SECTION II.8

OUTSKIRTS AND ENVIRONMENT

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Hugo van Woerden in his opening address as Chairman of the Scientific Organizing Committee CFD

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HIGHLIGHTS OF HIGH-VELOCITY CLOUDS

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1. INTRODUCTION

Twenty years after their first discovery at Dwingeloo (Muller, Oort and Raimond 1963), the nature and origin of high-velocity clouds (HVCs) remain enigmatic. Yet, much important progress has been made in the study of their properties, and prospects are brightening that the problem of their distances, which holds the key to their understanding, may soon be solved.

The present paper reviews recent results, partly unpublished. For earlier reviews, we refer to Davies (1974), Giovanelli (1978, 1980b), Hulsbosch (1975, 1979a, b), Mirabel (1981a), Oort and Hulsbosch (1978), Van Woerden (1976, 1979) and Verschuur (1975).

The structure of this paper is as follows. In Section 2, we define the HVC phenomenon and review the sky distributions of HVCs and their velocities. In Section 3, we summarize attempts at interpretation and evaluate the merits of Bregman's Galactic-Fountain model. Section 4 discusses new large-scale surveys, Section 5 the velocity structure of the largest HVC complex. Section 6 reviews the small-scale structure of HVCs, highlighting new results on Chain A. Sections 7 and 8 summarize recent work on the Magellanic Stream and on the clouds with very high velocities. Section 9 discusses attempts to determine the distances of HVCs, and the related problem of their chemical composition. Section 10 draws a few conclusions.

2. THE PHENOMENA - AN OVERVIEW

The HVCs were discovered in the 21-cm HI line, and, with few exceptions (Section 9), they have never been observed in any other way.

No sharp, generally accepted definition exists. HVCs may be defined as HI clouds whose velocities are inconsistent with the standard model of the galactic HI distribution: a thin, flat disk in differential

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rotation. In using this definition, one must of course account for the well-known warp of the HI layer (see e.g. Henderson et al. 1982), for the random motions (velocity dispersion in one coordinate $\sim$ 7 km/s) and for local, systematic non-circular motions (e.g. Burton, 1966) in the interstellar medium. At low galactic latitudes, the range of radial velocities (with respect to the local standard of rest) expected from differential galactic rotation may be considerable; for instance, for a flat rotation curve with circular velocities Θ_o out to radius xR_o, where R_o is the Sun's distance from the Galactic Centre, it reaches in the first galactic quadrant at longitude ℓ from $V = \Theta_o (1/x - 1) \sin \ell$ to $V = \Theta_o (1-\sin \ell)$, in the second quadrant from $V = \Theta_o (1/x - 1) \sin \ell$ to $V = 0$, with opposite values in the fourth and third quadrants. At latitudes $|b| > 15°$, however, the line of sight leaves the disk within about 1 kpc, and differential-galactic-rotation effects remain minor, facilitating the recognition of HVCs. In the analysis of HI surveys at $|b| > 15°$, it has become customary to call velocities $|V|$ between 20 and $\sim$ 80 km/s "intermediate velocities" (see e.g. Wesselius and Fejes 1973), and reserve the name "high-velocity clouds" for those with $|V| \gtrsim 80$ km/s.

The most recent compilation of HVC observations from various sources is that by Mirabel (1981a). Figure 1a (see page 6 of these Proceedings) shows the distribution of HVCs and of their velocities (coded in colour) over the sky. The map is based on surveys published up to 1980; however, later surveys - which we summarize in Section 4 - have not materially changed the picture.

The most striking feature of Figure 1a is the uneven distribution of both position and velocity over the sky. Negative velocities dominate at longitudes $30° < \ell < 210°$, positive velocities at $210° < \ell < 330°$. At first sight, this might be interpreted as an effect of galactic rotation, since the velocities shown are with respect to the local standard of rest (LSR). However, as emphasized by Oort and Hulsbosch (1978; also Hulsbosch 1979a), negative velocities also dominate near the galactic poles and in the Anticentre region, where galactic-rotation effects should be minor. Indeed, a plot of velocities corrected for the rotation of LSR about the Galactic Centre (Figure 2, taken from Giovanelli 1980b) also shows a preponderance of negative velocities. Although the observed radial velocities represent only one component of the space motions (cf. Kerr 1967), the dominance of negative values suggests an inflow of high-velocity gas into the Galaxy, in keeping with the early suggestions by Oort (1965, 1966, 1967, 1970) - or, at least, an inflow into its Disk (Bregman 1980, Mirabel 1981a). The inflow rate depends on assumptions as to the distance and thickness of HVCs, but most estimates are of order 1 $M_\odot$ per year (Oort 1967, Hulsbosch 1975, Mirabel 1981a).

Another major asymmetry is that HVCs appear much more numerous in the range $0° < \ell < 180°$ than at $180° < \ell < 360°$. A similar asymmetry exists in the intensities, but these are not shown in Figure 1a. In connection with the asymmetry in the distribution, it should be noted

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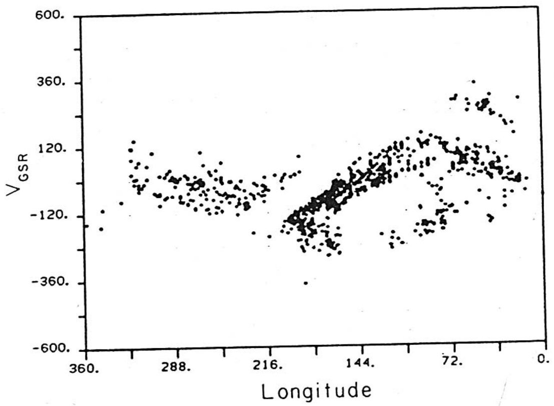

Figure 2. Velocities of HVCs with respect to the galactic standard of rest, V_{GSR} = V_{LSR} + 250 sin ℓ cos b km/s (Giovanelli 1980b).

that most of the longitude range 180° < ℓ < 360° lies in the southern celestial hemisphere, where surveys have been less complete and less sensitive than in the north. We return to this point in Section 4. However, the asymmetry is probably genuine. Obvious is the asymmetry between the positive and negative latitudes in this longitude range: the quadrant b > 0, 180° < ℓ < 360° contains many faint, scattered clouds - which are better shown in Figure 1 of Hulsbosch (1979a) -; the quadrant b < 0, 180° < ℓ < 360° is dominated by the gaseous envelope of the Magellanic Clouds, and by the Magellanic Stream: a long, narrow filament extending from the Clouds to the south galactic pole, and beyond to ℓ ∿ 90°, b ∿ -40°. We discuss the Magellanic Stream in Section 7.

Figure 1a shows several other elongated features. The best known is "Chain A", a narrow string of HVCs between ℓ = 132°, b = +23° and ℓ ∿ 165°, b ∿ +45°, which we shall discuss in detail in Section 6. "Complex C" is a broader feature between ℓ ∿ 70°, b ∿ +30° and ℓ ∿ 140°, b ∿ +55°, to which we return in Section 5. Long, narrow features also exist at southern latitudes in the Anticentre region (cf. Giovanelli 1980b, Figure 12). Each of these elongated features contains a number of condensations, "clouds", typically a few degrees in size (see Section 6).

One further asymmetry must be mentioned. Clouds with velocities $|V_{LSR}|$ > 200 km/s occur almost exclusively at **negative** velocities, in the quadrant b < 0, 0° < ℓ < 180°. Hulsbosch (1978a) pointed out that in this region the distribution of velocities relative to the **galactic** standard of rest, $V_{GSR} \equiv V_{LSR}$ + 250 sin ℓ cos b km/s, shows two distinct components, suggesting two separate categories of HVCs. Figure 3, taken from Giovanelli (1980b), shows that the distinction is also clear in a plot of V_{LSR} versus ℓ for HVCs in the southern galactic hemisphere. We discuss the "very-high-velocity clouds" (VHVCs) in Section 8.

Giovanelli (1980b) has estimated that about 10% of the sky is covered by HVCs. The masses involved depend on the distances. Hulsbosch (1979a) estimates that the sums of $M_{HI}d^{-2}$ over the whole sky are about

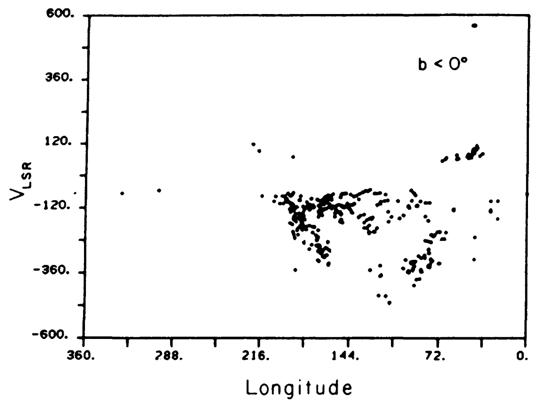

Figure 3. Velocities with respect to the local standard of rest, V_{LSR}, of HVCs in the southern galactic hemisphere (Giovanelli 1980b). Note the presence of two distinct components in the distribution; the clouds with more negative velocities are called "very-high-velocity clouds" (VHVCs, see Section 8).

$10^5\ M_\odot\ kpc^{-2}$ and $0.5 \times 10^4\ M_\odot\ kpc^{-2}$ for HVCs with negative and with positive velocities, respectively.

3. ATTEMPTS AT INTERPRETATION

A variety of models for the nature and origin of high-velocity clouds have been considered in the literature. We shall mention the more important models, with key references, but refrain from detailed discussion. Arguments pro and contra have been given in the reviews by Oort (1966, 1967), Davies (1974), Verschuur (1975), Giovanelli (1978), Oort (1978) and Oort and Hulsbosch (1978).

3.1. A general synopsis

A possible interpretation of HVCs as nearby supernova shells has been discussed in detail by Oort (1966) and by Verschuur (1971). Among the objections raised by Oort (1966, 1967, Oort and Hulsbosch 1978) are: the prohibitively high supernova rate required; the distances (> 1 kpc) estimated for a few HVCs; the straight, narrow shape of Chain A (cf. Section 6); the lack of correspondence between HVCs and the radio-continuum Loops (cf. also Verschuur 1975; however, Cohen (1981) suggests a relation between HVC 160-50-110 and the Cetus Arc, Loop II). Verschuur (1971) proposes a supernova model for the large HI complex with intermediate negative velocities at high northern latitudes; see also Wesselius and Fejes (1973) for discussion. Giovanelli (1980a) suggests that the Anticentre Stream between ℓ, b = 140°, -8° and 190°, -20° at V = -110 km/s may be due to a supernova explosion in the Perseus-Taurus region. Bruhweiler et al. (1980) have proposed that HI supershells of the type described by Weaver (1979) and Heiles (1979) form around evolving associations, and after breaking up into clouds may fall back as HVCs. In ultraviolet absorption lines, Cowie et al. (1979, 1981) have observed supershells of radii $\sim$ 100 pc and velocities $\sim$ 100 km/s around the Orion Association ("Orion's Cloak") and in Carina, but these have not been identified with HVCs.

Superexplosions in the Galactic Disk as a source of HVCs have been discussed by Oort (1966). His main objections were: the very high number of supernovae required, and the short lifetime of the structure in HVCs (Section 6) as compared with their long travel times from distant explosion sites.

Explosions in the Galactic Nucleus appear unsuitable (Oort 1966, 1978) because of the observed shortage of positive-velocity clouds, the lack of angular momentum caused by such ejecta, and again the short lifetime of HVC structure.

Condensations in a hot Galactic Corona have been briefly considered by Oort (1966, 1978), and in more detail by Bregman (1980) - see Section 3.2.

Oort (1965, 1966, 1967, 1969, 1970) has proposed that the HVCs are caused by an inflow of intergalactic gas into the Galaxy. The gas falls in at $\sim$ 500 km/s, but is decelerated in the Halo; the HVCs obtain their structure in the lower Halo. The total inflow would amount to $\sim 1\ M_\odot$ per year. The intergalactic gas density required is of order 10^{-4} cm^{-3}; streams of gas must come from various directions. The Halo must be replenished by explosions of supernovae in the Disk. Verschuur (1975) has sharply criticised this model. Davies (1974) points out that the positive-velocity clouds and the elongated strings remain unexplained. More recently, Oort and Hulsbosch (1978) have suggested that the long strings may have had their shapes before entering the Galaxy, possibly originating from old tidal debris in the Milky Way - Magellanic System. Holder (1980) discusses the thermal instabilities caused by radiative cooling of the infalling gas. Tenorio-Tagle (1981) has calculated the evolution of shocks caused by collisions of HVCs with the Galactic Disk.

Oort (1966, 1967) had considered, but rejected, a possible identification of the HVCs with satellites of our Galaxy. However, Kerr and Sullivan (1969) showed that the distribution of HVCs in ℓ, b and V could be well fitted by satellites with orbits having semi-major axes of 30-80 kpc, excentricities 0.5 to 0.8, and inclinations 40°-70°. The total mass required would be of order $10^8\ M_\odot$. The origin of these small satellites might lie in Galactic tidal action on the Magellanic Clouds during earlier passages (cf. the tidal models for the Magellanic Stream, Section 7). Similarly, Einasto et al. (1976) proposed to consider the HVCs as a system of companions in elliptical orbits about our Galaxy.

Following an early suggestion by Burke (1967), Verschuur (1969) showed that HVCs would be virially stable at distances of $\sim$ 400 kpc. With masses of order $10^9 - 10^{10}\ M_\odot$ for the HVC complexes at such distances, they might then be considered protogalaxies. The failure of Lo and Sargent (1979) and of Haynes and Roberts (1979) to find intergalactic HI clouds - other than in the form of tidal debris - in several nearby groups of galaxies has made this hypothesis unlikely.

Whether the new, much fainter clouds with very high velocities (VHVCs, see Sections 2 and 8) might be intergalactic clouds in the Local Group, as suggested by Oort and Hulsbosch (1978), deserves further analysis. Eichler (1976) has shown that, at distances of order 1 Mpc, stock thermal energy would be insufficient to support HVCs against collapse. Support might be provided by turbulence, by star formation, or by the presence of substructure.

After Habing (1966) and Kepner (1970) showed that the outer arms of the Galaxy have faint extensions to a few kpc ($b \sim 10°-20°$) above the plane, Davies (1972, 1973) and Verschuur (1973a, b) proposed that the HVCs must be interpreted as features in a highly warped outer spiral structure. Hulsbosch and Oort (1973) accepted that a Galactic warp could explain the HVCs at the lower latitudes, but pointed out that no reasonable rotation of the warped disk could produce the velocities observed at $b \gtrsim 45°$ and in the Anticentre region. Davies (1972, 1973) ascribed these phenomena to tidal debris from an encounter between Galaxy and Magellanic Clouds, but Oort and Hulsbosch (1978) outline some dynamical objections to this suggestion.

It seems likely to us that several of the models mentioned above are actually represented among observed HVCs. Distance determinations will be required to prove this.

A new, detailed model, allowing prediction of the velocity field of HVCs, has been worked out by Bregman (1980). We discuss this in the next subsection.

3.2. Bregman's "Galactic Fountain of High-Velocity Clouds"

Bregman (1980) has proposed that HVCs form by condensation in a hot, dynamic Corona above (and below) the galactic plane, and has modelled this process by hydrodynamic calculations. Supernova-heated gas rises or bubbles up from the Disk, and flows outward into the Corona. There, radiative cooling will lead to thermal instabilities and to condensation of neutral clouds; these clouds fall ballistically back toward their point of origin. The cloud velocities are explained through conservation of angular momentum. Bregman obtains an optimum reproduction of the HVC velocity field in a model with $T_o \sim 1 \times 10^6$ K, $n_o \sim 1 \times 10^{-3}$ cm^{-3} at the base of the Corona; the coronal mass is then 7×10^7 $M_\odot$ and the HVC mass flux onto the Disk 2.4 $M_\odot$/year. Differential rotation in the Corona will stretch the density perturbations and lead to the elongated appearance of HVC groups.

Figure 1b (in colour, see page 6 of these Proceedings) shows the velocity field of HVCs predicted by Bregman (1980, his Figure 6) on the basis of his model E1. It displays the predicted relative numbers of clouds in several velocity intervals at various positions in the sky. These predictions (which are symmetric with respect to the galactic equator) may be compared with the **observed** velocities of HVCs as summarized in Figure 1a (also page 6). In general, Bregman's predictions fit the observed velocity field fairly well. In particular, the predominance of negative velocities around the galactic poles and throughout the longitude range $30° \leqq \ell \leqq 210°$ (i.e., **beyond** the Anticentre) is well represented: in Bregman's model, just as in real nature, the HVC velocity field is not symmetric about the meridional plane through Sun and Galactic Anticentre, but rather about a plane $\ell \sim 210°$. However, the observed **structural** asymmetry between the hemispheres $30° < \ell < 210°$ and $210° < \ell < 390°$ is not predicted by the model; nor are the observed asymmetries between the northern and southern galactic hemispheres. Furthermore, the observed velocity distributions appear to deviate systematically in a few respects from those predicted: 1) The model predicts both positive and negative high velocities in every region of sky, but there are very few regions where both are observed in nature. 2) In comparison with HVCs at $80 < |V| < 130$ km/s, those at higher velocities $130 < |V| < 220$ km/s are more frequently observed than predicted. 3) Finally, the observed clouds with extreme velocities $|V| > 220$ km/s (VHVCs, Section 8) are not predicted and - as emphasized by Mirabel (1981a) - it is unclear how a Galactic Fountain could produce the extreme observed asymmetry of VHVCs with respect to the Galactic Disk.

Thus, although the Galactic-Fountain model gives, in part, a fair representation of HVCs, important features remain unexplained. In particular, the very-high-velocity clouds may represent a separate category located outside the Fountain.

4. NEW LARGE-SCALE SURVEYS

The overview given in Section 2 and Figure 1a was based on quite incomplete information. So far, HVC surveys have either covered large areas of sky with a coarse grid, or mapped small areas in detail, or lacked sensitivity (notably the early surveys). In Section 6 we shall mention new small-scale surveys (of areas $\lesssim 30°$). The most complete published large-scale survey is that by Giovanelli (1980b) with the NRAO 91-meter telescope. It covers the range $-10° < \delta \lesssim +50°$ with a grid of 2-3 degrees in α and δ, and spans the velocity range $-900 < V(LSR) < +900$ km/s with a resolution of 22 km/s. Its detection limit is about 0.06 K, corresponding to 3×10^{18} atoms/cm^2. The results of this survey have been incorporated in Figure 1a, and in the discussion of Sections 2 and 3. Unfortunately, Giovanelli's survey is still quite incomplete in its sky coverage, and biased against small clouds: with its 10' beam, it samples less than 1 percent of the large area (almost 20 000 deg^2) covered.

Much more complete is the new survey by Hulsbosch with the Dwingeloo 25-m telescope. With a $0\overset{\circ}{.}6$ beam, it covers the sky from $\delta = -18°$ to $+90°$ with grid spacings $\Delta b = 1°$ and $\Delta\ell \cos b \approx 1°$, sampling 40 percent of the 27 000 deg^2 sky area covered. The velocity range spanned is $V_{LSR} = -1000$ to $+1000$ km/s, with 16 km/s resolution. The detection limit is 2×10^{18} atoms/cm^2 for resolved structures, but of course poorer for small clouds. Partial results, including the discovery of a large number of VHVCs, have been reported by Hulsbosch (1978) and incorporated in Figure 1a. A map of results in the region $0° < \ell < 200°$, $-70° < b < +70°$ - i.e., about 70 percent of the survey area - is contained in the contribution (Hulsbosch 1985) immediately following this review. The survey has not disclosed any new large-scale structures. However, many new VHVCs and a number of positive-velocity clouds have been found. Also, the survey provides much improved information on the structure and extent of many HVCs and HVC-complexes, and on their mutual relationships. As an example, we discuss in the next section the velocity structure of "Complex C". In view of its relatively dense sampling, the new survey will further provide good statistics of cloud sizes, masses, velocities etc. For further details, we refer to the paper by Hulsbosch (1985).

Another important, though more limited, survey is that by Mirabel and Morras (1984, and these Proceedings) in a wide region around the Galactic Centre. Their survey covers the region $320° < \ell < 50°$, $-90° < b < +40°$, $\delta > -44°$ with a 2° grid (2000 positions) and a detection limit $\sim 5 \times 10^{18}$ cm^{-2}. We discuss the results of this survey, which has yielded many new VHVCs, in Section 8. Since most of these VHVCs are small (often < 1°), and the beamwidth (0°.35) was small compared to the grid spacing (2°), many VHVCs may still have been missed.

At southern declinations beyond the limits of northern radio telescopes, major surveys have been made by Mathewson et al. (1974) and by Mathewson (1976). A complete survey of the sky south of $\delta = -30°$ was carried out by Cleary with the Parkes 18-meter dish (beam 0°.8); the grid spacing was 1° at $b > -25°$ and 2° x 1° at $b < -25°$, the velocity resolution 7 km/s, and the detection limit 0.3 K, or $\sim 10^{19}$ atoms/cm^2 for HVCs. Within the velocity range -148 to +300 km/s at $b > -25°$, and -230 to +218 km/s at $b < -25°$, this survey has not turned up any new HVCs (Cleary et al. 1979).

5. LARGE-SCALE VELOCITY STRUCTURE IN COMPLEX C

In Section 2 we have drawn attention to the prominence of elongated features ("strings") in the sky distribution of HVCs. The most striking strings, Chain A and the Magellanic Stream, will be discussed in Sections 6 and 7. Complex C is a broad, long feature running from $\ell \sim 70°$, $b \sim +25°$ to $\ell \sim 130°$, $b \sim +60°$. Velocities range from -80 to -200 km/s, with an average of $\sim$ -130 km/s. Intensities are generally low. The full extent of this complex, about 70° long and 20° wide, is shown in the map of Hulsbosch (1985). At lower ℓ and b, the complex connects (or, at least, becomes confused) with the "Outer Arm" in the warped HI disk, which reaches up to $b \sim +20°$ at $\ell \sim 70°$ (Habing 1966). In fact, Davies (1972, 1973) and Verschuur (1973) have advocated that complex C and other HVCs be viewed as very strongly warped parts of the outermost spiral structure, possibly so deformed by tidal action of the Magellanic Clouds.

Figure 4 (in colour, page 7 in these Proceedings) shows the velocities measured by Hulsbosch (1985) on a 1° grid in this Complex. Velocities between -90 and -110 km/s (red) occur along the high-b top of the Complex, and near its low-b, low-ℓ end. Velocities -110 > V > -130 km/s (orange) are found throughout the Complex, but especially along its long axis and in the northern half. Velocities -130 > V > -150 km/s (yellow) are seen mostly at lower b and higher ℓ, but also in patches elsewhere. Velocities -150 > V > -170 km/s (green) are observed along the axis of the Complex and in its southern half. Finally, the highest negative velocities (blue) are found in patches along the axis.

Clearly, the velocity field cannot be simply described by e.g. rotation about a long or a short axis. In many places the line profiles contain two peaks, suggesting two velocity systems overlapping on the sky. On the Davies-Verschuur model, these might represent two warped spiral arms. An alternative possibility is that we see a number of HVCs of modest size projected on a large complex. The material has not yet been analyzed in detail, and clarification may require observations at higher velocity resolution. Also, distance determinations of the overlapping structures would be of great interest.

6. SMALL-SCALE STRUCTURE AND ASSOCIATED MOTIONS

6.1. HVCs in general

The large, elongated complexes discussed in Section 2 in general consist of a number of discrete clouds, with sizes of a few degrees and velocity widths of 20-40 km/s, embedded in a tenuous medium. In fact, the clouds were known (1963) before the larger complexes, and gave the HVC phenomenon its name. In Chain A, the cloud structure is particularly strong (Giovanelli et al. 1973, and Figure 5), and large jumps in velocity occur between neighbouring clouds (Oort 1978). Similar jumps have been found in the Anticentre Complex, but these may be due to overlap of clouds - cf. the situation in Complex C (Section 5). The Magellanic Stream also consists of a number of clouds (Mathewson 1976), but its velocity structure appears to be smoother.

Since 1973, observations at high angular resolution (≦ 10', more recently even 1', see Section 6.2) have revealed much detailed structure within the clouds. Most HVCs are found to consist of a small, dense core and an extended, tenuous halo or envelope (Greisen and Cram 1976; Cram and Giovanelli 1976; Schwarz et al. 1976; for further references see Hulsbosch 1979a, b). The cores have angular sizes below 10 arcmin, often unresolved, velocity halfwidths of 5-10 km/s, and brightness temperatures up to 65 K - fully comparable with those measured in low-velocity, even low-latitude hydrogen! The envelopes have sizes of a few degrees, velocity halfwidths of order 25 km/s, and brightnesses of a few K or indeed much less. Also, the clouds often have very steep edges (Giovanelli et al. 1973, Hulsbosch 1978b), suggestive of shock fronts. Collisions of infalling intergalactic material with gas in the Disk or lower Halo may have led to these shocks, and by further compression to instabilities and core formation (Giovanelli and Haynes 1977, Oort and Hulsbosch 1978).

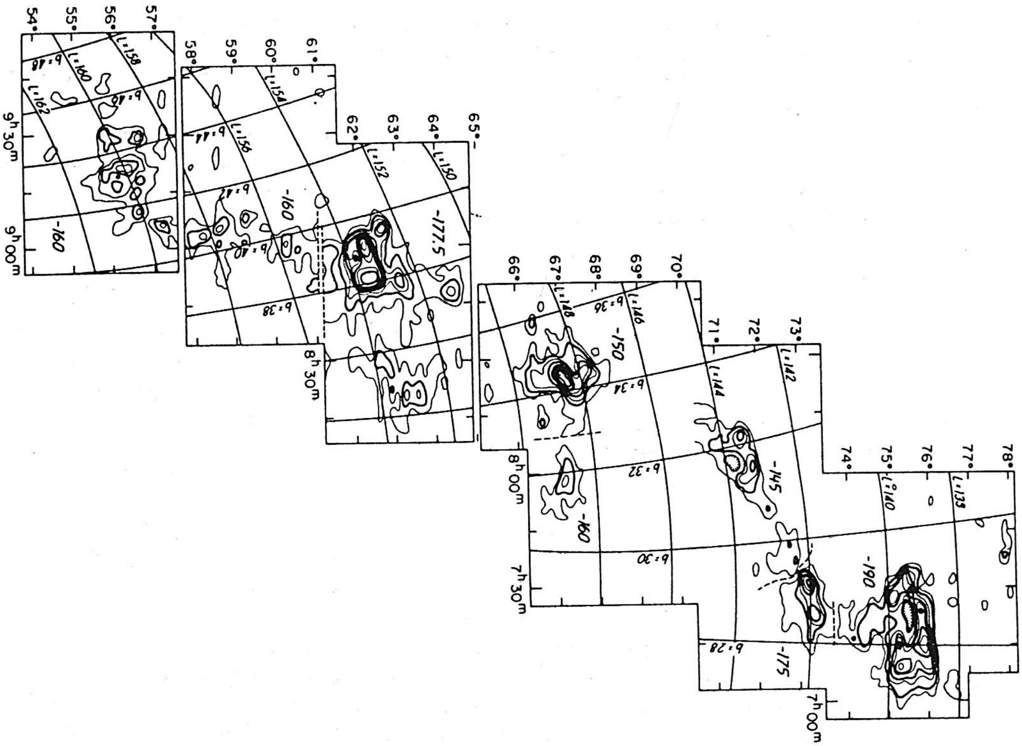

Figure 5. Cloud structure in part of Chain A (Giovanelli, Verschuur and Cram, 1973). The figure consists of a number of monochromatic contour maps, at velocities representative for the individual clouds; consequently, it does not show the full column-density distribution in Chain A. The velocity fields of the clouds at ℓ = 139°, b = +28° (AI) and at ℓ = 153°, b = +39° (AIV) are shown in Figures 7 and 8 (page 7 of these Proceedings).

While much of the above refers especially to Chain A, which has been studied in greatest detail (for a summary, see Oort 1978), it may well apply to HVCs in general. Cohen (1981) finds that HVC 160-50-110, a feature ≧ 25° in length, is similar to Chain A in some respects; and that it coincides with a low-velocity filament, suggesting collision of this HVC with Disk gas. Evidence for such collisions has also been reported by Mirabel (1982) and by Burton and Moore (1979). Core-envelope structure has also been found in several HVCs with **positive** velocities (Giovanelli and Haynes 1976, Cohen and Ruelas-Mayorga 1980, Morras and Bajaja 1983). However, the structure of VHVCs (Section 8) and of the Magellanic Stream (Section 7) appears to be different; this may indicate differences in origin and physical conditions, although one must watch out for possible differences in linear resolution caused by differences in distance.

The spin temperatures T_s of gas in HVCs can, in principle, be determined by measuring the absorption spectrum of a background radio source and comparing it with neighbouring emission spectra, measured at sufficiently high angular resolution. Payne et al. (1980) have very carefully applied the method to 8 sources located behind clouds with $|V_{LSR}| > 50$ km/s. However, the clouds detected in absorption are at low latitudes and would not normally be called high-velocity clouds. A measurement of T_s in cloud AI is discussed in Section 6.2.

6.2. New results in Chain A

The best-known string of HVCs is Chain A, which spans at least 33° from ℓ = 132°, b = +23° to ℓ = 161°, b = +46°. Oort (1978) gives a detailed discussion of its structure, internal motions, probable distance, space motion and possible origins. Figure 5 shows the location and velocities of condensations in a major portion of the Chain. The core-envelope structure of these clouds has been discussed above.

Hulsbosch (1978b) has mapped the cloud HVC 132+23-211, at the low-latitude end of the string, with 9 arcmin and 1 km/s resolution. This cloud contains a number of very bright cores. Schwarz et al. (1976) mapped part of this cloud at Westerbork, with 2 arcmin resolution, and found 3 clumps of 3 arcmin size on a long, narrow ridge. Figure 6 (in colour, page 6 of these Proceedings) is a new Westerbork map, obtained at 1 arcmin resolution (Schwarz, unpublished); it shows a filament of 6 arcmin width and ≥40 arcmin length, containing several small but bright condensations. The filament runs along a line of constant galactic latitude, and is crossed by another, fainter structure. Velocity variations (coded in colour) are small in this field.

Schwarz and Oort (1981) have mapped a field in HVC 139+28-190 (cloud AI in figure 5) with 50" and 2 km/s resolution. The field falls on the intense ridge and steep slope found by Giovanelli and Haynes (1977) at the edge of cloud AI. Schwarz and Oort find much fine structure, down to 1 arcmin scale, and often of a filamentary nature. These small structures typically have velocity halfwidths $\sim$ 5 km/s and column densities $\sim 1 \times 10^{20}$ atoms/cm^2, densities $\sim 100\ d^{-1}$ cm^{-3} and masses between 0.03 and 10 $d^{-2}\ M_\odot$, with d expressed in kpc. Their distribution in position and velocity (see Figure 7, page 7 of these Proceedings) is irregular, with a velocity dispersion of 7 km/s about the mean for the cloud. For the temperatures in 3 of the condensations both upper and lower limits can be given: kinetic temperature $T_k \lesssim 500$ K from the velocity widths, and spin temperature $T_s \gtrsim 25$ K from the lack of detected 21-cm absorption against background sources. The fine structure thus has T $\sim$ 100 K, within a factor $\sim$ 5, and it may be contained by the presence of the surrounding, more tenuous cloud of 2°

diameter, whose temperature can be estimated at 6000 K from the velocity dispersion. The doubling time scale for the cloud is 1 d Myr; for the filaments it would be an order of magnitude less, in the absence of pressure equilibrium with the cloud. A striking fact is that the filaments show no preferred direction of elongation, not even parallel to the steep slope. The orientation of the filament in Figure 6 might thus be a coincidence.

The chaotic structure of HVC 139+28-190 appears not to be unique: HVC 153+39-178 (Figure 8, page 7) shows similar filamentary features. We note in particular the velocity gradients across these filaments. The narrow filaments in Figures 7 and 8 are strongly suggestive of shock fronts, due to interaction of high-velocity gas with low-velocity material.

It is tantalizing that the physical conditions in these intriguing structures are still so poorly known, owing to the lack of distance information. Further detailed studies should be of great interest, but must be accompanied by strong efforts to obtain spin temperatures from 21-cm absorption and distances from optical absorption measurements (Section 9).

The high densities found invite the speculation that stars might be formed in the HVC cores or shock fronts. Dyson and Hartquist (1983) calculate that the internal motions within Chain A might be due to energization of the gas by young stars. So far, however, no direct evidence for such young stars has been found.

7. THE MAGELLANIC STREAM

This object will be extensively discussed at IAU Symposium 108 on the Magellanic Clouds (Van den Bergh and De Boer, 1984); hence, we shall review it only briefly here.

Originally known as the South Galactic Pole complex, this HVC was partly mapped by northern observers (see Wannier and Wrixon (1972) and references given there). Then Mathewson, Cleary and Murray (1974a, b) discovered its relationship to the Magellanic Clouds, named it the Magellanic Stream and mapped it more fully (see also Mathewson 1976). Since then, Haynes and Roberts (1979) have shown its extent and complexity in the Sculptor region, and Morras (1982) has observed a few, possibly related, HVCs on the opposite side of the Magellanic Clouds. McGee et al. (1983) have made sensitive measurements of 21-cm profile structure in the directions of Magellanic Clouds and Stream, compared these with ultraviolet absorption lines, and discussed implications for the haloes of Milky Way Galaxy and Magellanic Clouds.

Maps of the small-scale structure in the northern tip of the Stream have been made by Mirabel et al. (1979), Cohen (1982a), and Mirabel (1981a, c). The former observations show condensations of 0°.5 size, but at Arecibo (3!3 resolution) Mirabel (1981a, c) finds condensations of 5' size. In these various structures the velocity halfwidths are consistently ≧ 20 km/s; no narrow spectral components have so far been found. Towards its tip, the Stream appears to broaden, weaken and break up into clouds with velocity differences of order 30 km/s. Cohen (1982a) finds filamentary structures on scales from 10° to 0°.5, and velocity gradients both along the Stream (∿ 2 km/s per degree) and across it (∿ 6 km/s per degree); he claims that this favours a tidal interpretation.

Tidal models for the Stream, as debris from the Magellanic Clouds after a close encounter with the Galaxy, have been developed or advocated by Mathewson et al. (1974b), Fujimoto and Sofue (1976, 1977), Davies and Wright (1977), Lin and Lynden-Bell (1977, 1982), Fujimoto (1979), Kunkel (1979), and by Murai and Fujimoto (1980). The earlier models, with the Stream leading the Clouds, had trouble fitting its velocity field, but both Murai and Fujimoto (1980) and Lin and Lynden-Bell (1982) obtain good fits for a trailing Stream, caused through tidal action of a Milky Way Galaxy with a massive halo on the Clouds during a previous passage. Recently, Fujimoto and Murai (these Proceedings, Section III.1) have shown that a recent close encounter between the Large and Small Magellanic Clouds is required for a proper reproduction of the Stream.

Mathewson and Schwarz (1976) proposed to interpret the Stream as primordial gas clouds in the same orbit as the Magellanic Clouds. Similarly, Einasto et al. (1976) considered the Magellanic Stream as permanent members of the "Hypergalaxy" (the system of Galaxy and companions with total mass 1.2×10^{12} $M_{\odot}$), in elliptical orbits about the central Galaxy. Lo and Sargent (1979) consider the primordial interpretation unlikely, in view of their failure to detect intergalactic HI clouds - other than tidal debris - in several nearby galaxy groups. Later, Mathewson et al. (1977, 1979) interpreted the Stream as the result of thermal instabilities in the wake of the Magellanic Clouds on their passage through a hot halo around our Galaxy; but Bregman (1979) raised doubts about this model. The non-tidal models have not been discussed in recent years, and a tidal origin of the Stream now appears well established.

8. CLOUDS WITH VERY HIGH VELOCITIES

A few HVCs with exceptionally high velocity, in the range -250 to -450 km/s, were discovered by Wright (1974) near M33, by Davies (1975) near M31, by Cohen and Davies (1975) and by Shostak (1977). Then Hulsbosch (1978a, 1984) and Giovanelli (1980b) found large numbers of very-high-velocity clouds (VHVCs) in their sensitive surveys of large areas of sky, and Giovanelli (1981) defined the VHVCs as a separate population in (ℓ, b, V). Most of these objects are small, at most 1 or 2° in diameter, and almost all of them lie in the galactic quadrant 10° < ℓ < 190°, b < 0°. Mirabel (1981b) has found several VHVCs in a survey of a region of 34° x 18° around $\ell \sim 25°$, $b \sim -20°$; and Mirabel and Morras (1984) have recently found many more - see below.

Detailed maps of VHVCs have been made by Cohen (1982a, b), Cohen and Mirabel (1978, 1979), Giovanelli (1981), Mirabel (1981a, b) and Wright (1979 a, b). Most VHVCs appear to have simple structure, often with considerable velocity gradients indicating rotation. Two-component structure, with a small core having velocity halfwidth $W \sim 7$ km/s and an envelope with $W \sim 25$ km/s, has been found only in VHVCs 114-10-440 and 24-19-235 (Cohen and Mirabel 1979) and 17-25-230 (Mirabel 1981b). Steep edges suggesting shock fronts have not been observed. Thus, the structure of most VHVCs appears to differ from that in most northern ($b > 0$) HVCs at more modest velocities - or is this an effect of distance and resolution?

Two VHVCs of considerable size are known. Wright's (1974) cloud 128-33-400 near M33 extends over 7° x 5° and has much detailed structure (Wright 1979a). Its mass is 330 $d(\mathrm{kpc})^2$ $M_\odot$, or 2 x 10^8 $M_\odot$ if at the distance of M33. Although its edge is only 1° from that galaxy, Wright argues that it is too large to withstand the tides of M33, and too light to cause the warp in that galaxy, and hence it probably is an unrelated VHVC, seen close only in projection - unless it is a remnant of tidal interaction between M31 and M33.

The first VHVC discovered (by Meng and Kraus 1970, and Van Kuilenburg 1972, avant la lettre) is a large complex centred near $\ell = 165°$, $b = -45°$. According to a detailed study by Cohen (1982b), it has $\sim 12°$ diameter and spans the velocity range -360 to -190 km/s. This object, with a total mass 3800 d^2 $M_\odot$, contains many clumps of $\sim 0\overset{\circ}{.}5$ diameter, density $\sim 3\ d^{-1}\ \mathrm{cm}^{-3}$ and mass $\sim 30\ d^2\ M_\odot$, which should be investigated for smaller-scale structure. The velocity field is complex, with gradients both along and across the length of the object. Velocity halfwidths range from 18 to 54 km/s, with an average of 30 km/s. This object looks more like the northern HVCs than like the other VHVCs; its velocity, too, is not very different from that of Chain A.

The distribution of VHVCs in (ℓ, b, V) has been discussed by Giovanelli (1979, 1981). The pronounced difference of this distribution from that of other HVCs provides a clear distinction between the two categories. The small size of VHVCs and the proximity of a few early discoveries to M31 and M33 had suggested that the VHVCs might be intergalactic gas clouds in the Local Group (Hulsbosch 1978a). Whether this is compatible with the lack of detection of such clouds in other galaxy groups (Lo and Sargent 1979, Haynes and Roberts 1979) has not been fully assessed. However, Giovanelli (1981) finds that the (ℓ, b, V) distribution of VHVCs is quite different from that of galaxies in the Local Group, and is actually more similar to that of the Magellanic Stream. Rejecting both a local and a fountain-model interpretation on the basis of the observed velocities, Giovanelli (1981) proposes to explain the VHVCs as shreds of the Magellanic Stream, fragmented at its tip and now dispersed through a galactic quadrant. Similar suggestions have been made by Mirabel (1981a) and by Cohen (1982b). These suggestions appeared attractive as long as the Magellanic Stream was considered leading the Clouds, with a distance of $\sim$ 10 kpc at its tip - although the wide dispersion of fragments needed to be supported by orbit calculations. However, with the Magellanic Stream trailing as argued by Lin and Lynden-Bell (1982) and its tip at $\sim$ 60 kpc distance, the proposed explanation of VHVCs as Magellanic debris appears speculative. Giovanelli (1981) further suggests that collisions of (former) VHVCs with the Galactic Disk have decelerated them to HVCs with more modest velocities, and via shocks have caused the structures observed in these HVCs. This explanation of the HVCs in general meets severe difficulties (cf. Oort 1978, Oort and Hulsbosch 1978). Further objections to accretion of Magellanic Stream gas by the Galaxy have been raised by Bregman (1979).

In a new survey of a wide region around the Galactic Centre (cf. Section 4), Mirabel and Morras (1984, and these Proceedings) have found a large number of VHVCs. The great majority of these, about 85%, have negative velocities, also after correction for the rotation of LSR about the Galactic Centre (GC). Combining this finding with the fact that in the Anticentre (AC) region all VHVCs have $V < 0$, Mirabel and Morras conclude that the VHVCs fall towards the centre of the Galaxy. The small angular sizes observed in the GC region, smaller than in the AC region, support this view. The distances of VHVCs from the Centre may be of order 20 kpc, considering that two VHVCs (24-1.9-293 and 8.9-1.5-174) are observed at very low latitudes and yet have very high velocities, hence must probably still be outside the Disk. Mirabel and Morras (1984) estimate the inflow of gas with very high velocities - hence not yet decelerated - at about 0.2 $M_\odot$ per year.

9. DISTANCE AND CHEMICAL COMPOSITION

The problem of the distances of HVCs probably holds the key to their understanding. In derivations of size, density, mass, and various timescales the distance enters to the first or higher power. The distance of HVCs is also crucial in assessing their relationships to our Galaxy, its structural components such as spiral arms, stellar associations and supernova remnants, or to extragalactic objects.

The very definition of HVCs precludes the use of differential galactic rotation for their distance determination. Also, the claim by Giovanelli (1980b) and Mirabel (1981a), that one can roughly estimate the distances (nearby or distant) of HVC complexes or populations from the amplitude of variation of their LSR velocities with longitude, appears to us unfounded.

Until recently, no HVC had ever been detected outside the 21-cm line, and no convincing optical relationships had been found. In 35 hours of integration on Chain A, Giovanelli has not detected any CO or OH emission (Hulsbosch 1979a). Jura (1979) has pointed out that

Doppler-shifted Hα, due to scattering on dust grains, might be observable in HVCs, but no detection has been reported. In fact, the detailed infrared sky survey by IRAS should allow a careful search for correlations between the distributions of HVCs and dust in high latitudes. Dyson and Hartquist (1983) have suggested that OB stars might be formed in the dense cores of HVCs, but none have been found so far.

Attempts to determine the distance of HVC 131+1-200, which lies in the same direction as the galactic radio source 3C58, by measuring the absorption spectrum of this source at 21 cm wavelength, have given an ambiguous result (Hulsbosch 1975, Schwarz and Wesselius 1978). No absorption at the HVC's velocity was detected, hence either the HVC is behind 3C58 (which may be at 8 kpc distance) or its spin temperature is too high (T_s > 200 K).

Oort and Hulsbosch (1978), using various indirect arguments, estimate a distance of ∿ 2 kpc for Chain A. One of their arguments is the distance of intermediate-velocity clouds (IVCs), measured through the presence or absence of absorption lines of Ca^+ and Na in the spectra of early-type stars at high latitudes (cf. Münch and Zirin 1961). However, the relationship between IVCs and HVCs is uncertain, and may depend on assumptions as to the nature and origin of HVCs.

Indirect arguments have also been given by Cohen (1981) and by Watanabe (1981). Cohen estimates z = -200 ± 100 pc for HVC 160-50-110, which appears to be interacting with low-velocity gas in the disk (cf. Section 6). Watanabe (1981), assuming that the absence or presence of elongated structures in HVCs is due to tidal effects, derives lower and upper limits to HVC distances. We believe this procedure to be invalid, since processes other than tides may play a decisive role in shaping the structures.

The most promising method to determine distances appears to be through measurement of optical interstellar absorption lines in the spectra of early-type stars. Kepner (1968) published a list of potential probes, and Oort and Hulsbosch (1978) have reviewed the early unsuccessful attempts to use them. The basic problem is that young B-type stars are very rare at large distances z from the galactic plane. Hobbs et al. (1982) have measured the Ly α absorption line in 10 distant, high-latitude OB stars, and compared the HI column densities so measured in absorption with those found in the 21-cm emission line in the same directions. They find that the ratio $N_{HI}(\text{Ly }\alpha)/N_{HI}(21\text{cm})$ increases with stellar $|z|$, and that little HI exists above $|z|$ = 2 kpc; but this work carries no velocity information. In a very thorough study, Albert (1983) has measured Ti II, Ca II and Na I absorption lines in 9 pairs of distant (average $|z|$ = 1900 pc) and nearer ($<|z|>$ = 170pc) B-stars, and compared those with 21-cm emission profiles. He finds that gas with velocities $10 < |V| \lesssim 50$ km/s lies in the lower Halo, at $|z| > 170$ pc, but his spectra include no HVC lines.

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Interstellar absorption at velocities of order 100 km/s has been measured in the high-ionization UV lines, with IUE, and also in the lower-ionization UV and visible lines, on lines of sight to globular clusters, to the Magellanic Clouds and to other extragalactic objects, by Savage and De Boer; by Songaila, Cowie and York; by Blades and Morton; and by others. These absorptions are identified as due to hot, largely ionized gas in the galactic halo, and no convincing identifications with HVCs measured in the 21-cm line have been reported. De Boer reviews this work in a separate invited paper at this Symposium.

The best attack appears to be to search for suitable probes seen projected on known HVCs. An absorption line at the HVC's velocity then shows that the HVC is in front of the probe and yields an upper limit to the HVC's distance. Failure to find absorption at the proper velocity allows several interpretations: 1) the HVC may be behind the probe; 2) the HI column density in the HVC may be too low in the direction of the probe; 3) the chemical composition and physical conditions in the HVC may be such that the column density of the optical absorbers (Ca^+, Na, or other) is too low for detection. A high-angular-resolution 21-cm observation in the direction of the probe can be used to test for item 2); a spectrum of a nearby extragalactic probe (quasar, Seyfert) can serve to test item 3). Several teams of observers are working on this program. Songaila (1981) has found Ca II K absorption, at the velocity of the Magellanic Stream (MS), in a background galaxy (Fairall 9, distance 135 Mpc) but not in the globular cluster NGC 2808 (distance 9 kpc). This leaves the MS distance uncertain by ±2 orders of magnitude, but it is consistent with the - generally assumed - association of the MS with the Magellanic Clouds. It further shows that the chemical composition of the MS is not primordial, that in fact the ratio of Ca II and HI line strengths is much **higher** than in low-velocity gas. Pettini and Boksenberg (unpublished) have detected Ca II K absorption in two galaxies behind HVC-Complex C, again indicating a high ratio of Ca II and HI line strengths. They have, however, so far not found any HVC absorption in RR Lyrae stars in this direction. These preliminary results suggest that Complex C may be beyond 10 kpc distance.

Distance determinations will be required for several HVC complexes of different character and structural properties. Blue horizontal-branch stars and blue Population II giants will be the best stellar probes, since their spectra are much freer of stellar lines than those of RR Lyrae stars. Deep surveys for such stars, down to ∿ 17th magnitude, will be required in order to cover distances up to 20 kpc - if HVCs are at such great distances.

10. CONCLUDING REMARKS

The name high-velocity cloud covers a great variety of phenomena. The discussion in the previous sections suggests that these require a variety of explanations.

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An almost complete survey of HVCs north of -18° declination will now soon be available. A southern supplement is urgently needed. Such surveys can serve as a basis for statistical analysis of HVC properties, and for further small-scale studies. Aperture-synthesis maps are required to reveal the small-scale structures and the physical processes in HVCs.

Optical and ultraviolet absorption spectra may soon provide distances to several HVCs. As an immediate consequence, their physical properties, chemical composition, and relationships to our Galaxy and its constituents will then be clarified. Theories of the nature and origin of HVCs can then be put on a firmer basis.

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DISCUSSION

B.F. Burke: As a matter of principle, I object to presentation of anonymous data.

Van Woerden: What I showed is not anonymous. It was an unpublished spectrum of a background galaxy, with Complex C in absorption. I had to withhold the name of the galaxy, but the observation is by Pettini and Boksenberg, and Pettini has kindly allowed me to show this spectrum.

J.H. Oort: In his Green Bank survey Giovanelli found a remarkable thin feature at about -110 km/s extending over 50° in longitude between -10° and -20° galactic latitude. I have been puzzled by the nature of this object. Its width is no more than 3° to 4°.

Van Woerden: String A is a similarly intriguing, thin feature. I wonder whether these are shock fronts.

R.D. Davies: R.J. Cohen at Jodrell Bank has studied the feature mentioned by Oort, and suggested that its thinness was due to interaction between infalling gas and material in the upper Disk.

Oort: That may well be, but it extends over about 40 degrees!

Davies: He suggested that it might be very close to us.

Van Woerden: There is a misunderstanding. Giovanelli's Anticentre Stream runs from 140°-8° to 190°-20° (Giovanelli 1980a). Cohen's feature runs between 145°-50° and 180°-40° (Cohen 1981); it also has V = -110 km/s.

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W. Iwanowska: Are the high velocities of clouds shown in your map (Figure 1a of your paper) corrected for the solar galactic-rotation component? If the clouds do not participate in the galactic rotation, many of them may show negative radial velocities.

Van Woerden: That is quite correct. Figure 1a shows velocities relative to the local standard of rest. Velocities relative to the galactic standard of rest (i.e. after correction for the Sun's rotation about the Galactic Centre) are shown in Figure 2 of my paper. In that figure, there is still a slight preponderance of negative velocities. In the interpretation one must, of course, take the effects of galactic rotation into account.

I.F. Mirabel: There is a clear preponderance of very-high-velocity clouds with inward motions in the Galactic Centre and Anticentre regions of the sky. Since the solar-motion component in these two directions is small, these findings are evidence for inflow of HI toward the Milky Way. Cf. my poster paper.

J.P. Ostriker: I think it very unlikely that there is a significant infall of mass into the Galaxy from large distances. Infall of $1 M_\odot$/yr corresponds to 10^{41} erg/s released gravitationally, which is two orders of magnitude more than the total X-ray luminosity of a similar galaxy like NGC 4565. Fountain models or other supernova-driven processes are acceptable.

Mirabel: The large infall velocities of up to 250 km/s of some HVCs are an indication that these clouds with extreme velocities are coming from great distances above the galactic plane. This kind of very-high-velocity clouds contribute a rate of accretion much smaller than 1 solar mass per year.

Ostriker: If the accretion rate is 2 orders of magnitude less, it would be consistent with the X-ray observations.