Summary of Recent Progress in Understanding HVCs

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Summary of Recent Progress in Understanding HVCs

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1. Introduction

The study of high-velocity clouds has progressed much since the appearance of the review article by Wakker & van Woerden (1997), less than two years ago. Much of this progress is described in these workshop proceedings. Here we update the review article, summarizing the topics discussed at the workshop as well as covering the recent literature. We follow the outline of the review, describing HI properties in Sect. 2 and 3, interactions between HVCs and other gas in Sect. 4, observations at wavelengths other than 21-cm in Sects. 5 and 6, absorption-line studies of metallicities and distances in Sects. 7 and 8, extra-galactic HVCs in Sect. 9, the Magellanic Stream in Sect. 10, and a discussion of HVC origins in Sect. 11.

Key contributions of the past two years include (a) the first determination of a distance *bracket* for an HVC: d=4–10 kpc for complex A (van Woerden et al. 1999); (b) the first determinations of a true metallicity: $\sim$0.25 $Z_\odot$ for HVC 287+22+240 (Lu et al. 1998), and $\sim$0.1 $Z_\odot$ for complex C (Wakker et al. 1999); (c) the recognition of a leading counterpart to the Magellanic Stream (Gardiner & Noguchi 1996, Lu et al. 1998, Putman et al. 1998), indicative of a tidal origin; (d) the quickly growing number of optical emission line observations (primarily Hα) of HVCs, led by Tufte et al. (1998) and Bland-Hawthorn et al. (1998); and (e) the proposal by Blitz et al. (1998) that HVCs are intergalactic remnants of the formation of the Local Group.

2. Distribution and structure of HVCs

While all-sky HI surveys for HVCs have existed since the late 1980s, a major step forward in ensuring uniformity in spatial and velocity resolution can be expected after the release of the Villa Elisa Southern Sky Survey (Arnal et al. 1996), a direct analog to the Leiden-Dwingeloo Survey (LDS) (Hartmann & Burton 1997) in the north. Together, these will cover the sky at 30′ and 1 km s^{-1} resolution. For clouds between declinations of $-90°$ and 0°, higher angular resolution (16′ on a sub-Nyquist sampled spatial grid, with 13 km s^{-1}

velocity resolution) will ultimately be available when the Parkes Multibeam Survey (Staveley-Smith 1997) completes its scans of the sky.

A crucial first step in the analysis of the combined surveys will be the creation of a catalogue for all of the anomalous-velocity gas. Blitz reported that this work is in progress. The catalogue will contain all of the gas at velocities incompatible with a simple model of differential galactic rotation, and for the first time will contain reliable information on linewidths, making it possible to address some of the questions raised in the review of Wakker & van Woerden (1997, Sects. 2.3–2.7). Cross-correlation with the Parkes Multibeam HVC Survey will shed light on any residual compact, isolated HVCs missed by the somewhat coarser LDS and VESSS.

Using these new surveys, the questions of HVC sky coverage and the distributions of brightness temperature, cloud flux and cloud area can be addressed again. A proper discussion of the selection effects for low brightness temperatures and small clouds should allow to decide whether the apparent turnovers at low values in these distributions are real or not. Blitz et al. (1998) argue they are real and thus conclude that HVCs have a typical size of 1.5 degrees, typical distance 1 Mpc and a typical HI mass of $3\times10^7\,M_\odot$. Wakker & van Woerden (1997, Sect. 2.5) point out that the turnover in the N(HI) distribution found by Giovanelli (1980) appears to shift to lower N(HI) for the Hulsbosch & Wakker (1988) data. Including the limited, but more sensitive results of Murphy et al. (1995) makes the turnover move to even lower values of N(HI), indicating that selection effects are probably important.

3. Small-scale structure

3.1. High-resolution observations

Putman et al. (priv. commm.) reported the initiation of a long-term high-resolution ($\sim1'$) study of a number of southern HVCs with the Australia Telescope Compact Array (ATCA) at Narrabri. Wakker et al. (these proceedings) report on the ATCA observations of HVC 287+22+240. The ATCA has also mapped a HVC serendipitously: Oosterloo et al. (1996) found a small HI cloud in the field of the newly discovered Tucana Local Group dwarf; this cloud (HVC323−48+135) is probably associated with the Magellanic Stream. Several Anti-Center HVCs were mapped at $3'$ resolution by Tamanaha (1995, 1997). A few northern HVCs were mapped with the Westerbork Synthesis Radio Telescope (WSRT), including a field in complex L, HVC 100−7+100 (Stoppelenburg et al. 1998), and the Mark 290 field (see Sect. 7).

The primary use of such data often is the derivation of accurate HI column densities in the direction of extragalactic and stellar probes, in order to determine accurate metallicities and to establish significant limits on non-detections, allowing the derivation of lower limits to distances. A second important use is the study of fine structure in the ISM.

The importance of high angular resolution for abundance studies was clearly shown by Lu et al. (1998) for the case of HVC287+22+240. In the direction of the background Seyfert galaxy NGC 3783 the value of N(HI) derived from a $21'$ beam (Green Bank 140-ft) is a factor 1.5 higher than the value derived from a $1'$ beam (ATCA), changing the derived sulphur abundance from 0.15 to 0.25 times solar. The latter value indicates Magellanic-Cloud like metallicities. Since this cloud is in a part of the sky where the tidal model for the Magellanic Stream of Gardiner & Noguchi (1996) predicts Magellanic gas to be present, the abundance result supports a relation to the Magellanic Stream. Using the uncorrected value would have given more weight to the idea that HVC287+22+240 could be an independent intergalactic object.

3.2. Analyses of high-resolution maps

High-resolution maps of high-velocity clouds provide a convenient laboratory to study fine structure in the ISM, as the HVCs are relatively isolated both in velocity and position, and thus there is little confusion with foreground and background emission. The simplest analysis is to look at column density contrasts. Wakker & Schwarz (1991) and Wakker et al. (1999) find that the structure is hierarchical, consisting of cores embedded in a smoother background. At the cores, the column density contrast can be as high as a factor 5 over a few arcminutes. Off the cores factors of 2 on arcminute scales are common. A slightly more complex analysis was done by Vogelaar & Wakker (1994), who find that the structure can be described by a fractal with dimension 1.4, similar to the values found for molecular clouds (Falgarone et al. 1991). Other methods of analysis based on the Fourier plane or Minkowski functionals have been suggested, but not yet implemented.

A new use for high-angular-resolution maps of HVCs was suggested by Ivezić & Christodoulou (1997) and Christodoulou et al. (1997). The former paper looked for Young Stellar Objects (YSOs) associated with the small HI cores in cloud MI and the core of complex H that were observed by Wakker & Schwarz (1991). Ivezić & Christodoulou (1997) point out the coincidence of the only YSO in the MI field with the brightest HI knot (MI core 4 in Wakker & Schwarz 1991). Three further YSOs are found in the core of complex H. Christodoulou et al. (1997) analyze the likelihood of forming stars inside HVCs by means of the collision of cloudlets and find that at most a few stars should form over several Gyr, consistent with the observed numbers. However, no estimate was made of the probability that these coincidences are due to chance superpositions.

3.3. Observational determination of pressure

Theoretically, the gas pressure is one of the most important concepts. Wolfire et al. (1995) show how the assumption that the clouds are confined by an external pressure leads to a two-phase core-envelope structure. However, it is not trivial to measure the cloud pressure observationally. A possible way of deriving pressure using high-resolution HI data will be described by Wakker et al. (1999). This method is summarized here. First, use the maps to derive the volume density for each core (see details below); second, fit one or more gaussians to the profile at each pixel and convert the FWHM linewidth(s) W to a temperature: $T(x,y)=21.8\,W^2(x,y)$; third, for each core make a histogram of the product $P(x,y) = n(x,y)\,T(x,y)$. The derived pressure is then given by the median of this distribution. To derive the volume density $n(x,y)$, start by defining a box around each core, then calculate the number of pixels with N(HI) above 0.5 times the maximum value in that core, and convert to a core diameter

($\alpha = \sqrt{\frac{4}{\pi}\,N_{\rm pix}} \times$ gridspacing). Assuming that the line-of-sight density profile is gaussian, then $n(x,y)$ = N(HI)(x,y) / [1.064 α 3.08$\times$10^{21} D(kpc)].

In practice, one finds that the derived radius increases with the square root of the angular resolution (θ), while the peak column density decreases as $\theta^{1/2}$. Thus, the pressure derived in this manner varies as $1/\theta$. Further, within a single core the pressure histograms tend to be wide (rms dispersion/median ~0.3 in the best cases). The interpretation of this result is unclear. It may imply that the cores are unresolved; or the pressure may vary throughout the core, so that at different resolutions different averages are found; or the density structure may be more complex than that of a gaussian. At the highest resolution ($1'$) the values that are found for the cores are of order 20000/D(kpc) K cm^{-3}. This is a combination of the thermal and "turbulent" pressure. Assuming a temperature of 50 K (as measured for complex H by Wakker et al. 1991), the thermal pressure in the core (which is the number to be compared to the Wolfire et al. (1995) models) would be $1500/\theta$(arcmin)/D(kpc) K cm^{-3}. If one does the same exercise for the large-scale structure of the HVCs, pressures of order 5000/D(kpc) K cm^{-3} are derived for the cloud envelopes. These are clearly lower than the pressures found from the highest-resolution data. A more detailed analysis of observational selection effects and biases is required to understand the problems mentioned above.

4. Interactions between HVCs and other gas

Many papers claim evidence for interactions between HVCs and gas in the galactic disk (see Sect. 2.9 in Wakker & van Woerden 1997 and below). In almost all cases this is based on a comparison of the morphology of the HVC with that of lower-velocity gas, combined with a consistency argument concerning the energetics. However, hard evidence will require knowledge of the distances to all HI features in the regions studied.

On the theoretical side, many models of impacting clouds exist (e.g. Comeron & Torra 1992, 1994), whose phenomenology can be compared to the observations. A different approach was taken by Benjamin & Danly (1997), who studied the effects of drag. They argued that many of the clouds falling towards the Galactic plane in the solar neighborhood are traveling at or near terminal velocity, which is determined by balancing the drag of the intercloud medium with the gravitational attraction of the Galaxy. This model is expected to work best for the closer IVCs (see contribution by Gladders et al.), where gas density and thus drag are highest. For the more distant high velocity clouds, the effects of drag on the dynamics of infall should be considered, as it will affect how quickly the orbits of extra-galactic infalling objects, such as the Magellanic Stream, will decay.

Observationally, Tamanaha (1995, 1996, 1997) used Arecibo to map (at $3'$ resolution) the Anti-Center Shell (an arc at (l,b,$v_{\rm LSR}$)= (180,0,−70) found by Kulkarni et al. 1985), ACI ((l,b,$v_{\rm LSR}$)= (182,−11,−180)), ACII ((l,b,$v_{\rm LSR}$)= (185,−15,−200)), and the Cohen Stream ((l,b,$v_{\rm LSR}$)= (165,−46,−260)). In this series of papers evidence is presented that the HVCs and IVCs in the anti-center are falling onto the disk. In particular, the shape of the apparent cavity in the disk gas is similar to that expected from an oblique impact in the models of Comeron & Torra (1992).

The possibility that infalling HVCs triggered star formation in the Orion region was discussed at the workshop by Lepine (see also Lepine & Duvert 1994), who showed suggestive maps of the distribution of the OB associations, relative to that expected from an infalling cloud sheared by differential galactic rotation. This is the same area of sky studied by Tamanaha, although the suggested direction of infall is opposite. This may not be a problem, as the ACI, ACII, etc clouds may be more distant than the Orion star-forming region.

Finally, Morras et al. (1998) present an Effelsberg map of complex H, and argue that the edge of the galactic HI distribution has a hole in this direction, caused by the infall of complex H. The evidence is weak, however.

5. Optical emission lines

Pre-1996 attempts at measuring ionized hydrogen at high velocity, through measurement of its Hα emission, were summarized by Wakker & van Woerden (1997, Sect. 3.2). Two processes are capable of producing Hα emission; discriminating between these two can lead to a fuller appreciation of the environment in which the HVCs reside. If photoionization dominates, the Hα intensity directly reflects the Lyman continuum flux incident upon the cloud; if collisional ionization dominates, the Hα intensity would be a reflection of the ambient density and the relative velocities between the cloud and the medium through which it moves. Unfortunately, determining which is dominant is generally not possible based upon Hα alone, but requires emission line ratios (e.g. [NII],[OIII],[SII]/Hα).

The past year has seen rapid progress being made in this field, driven observationally by two instruments — the Wisconsin Hα Mapper (WHAM) (Tufte et al. 1998) and TAURUS-2 (Bland-Hawthorn et al. 1998). An important attribute of WHAM is its association with a dedicated 0.6 m telescope. The aperture advantage of TAURUS-2 on the 4 m AAT and WHT is tempered by the oversubscription rates of both telescopes. For HVC work, a major advantage enjoyed by WHAM is its velocity resolution ($\sim$12 km s^{-1}, vs 45 km s^{-1} for TAURUS-2), which is well suited for resolving the typically $\sim$20 km s^{-1} Hα linewidths. On the other hand, TAURUS-2 has a larger bandpass ($\sim$50 Å vs $\sim$5 Å), allowing simultaneous observations of several emission lines. The large field-of-view of WHAM ($\sim$1°) is superior for mapping the large complexes, while the 5′ field-of-view of TAURUS-2 is superior for compact HVCs and situations for which emission measures close to a given line-of-sight are desired.

Tufte et al. (1998) report Hα detections toward complexes M, C and A. For complex M, I(Hα) ranges from 60 to 200 mR, for complex A it is 85 mR, and for the single complex C pointing, 130 mR. The quoted measurement errors are typically $\sim$10–20%. In two complex M directions [SII]λ6716 was also observed, in an attempt at constraining the ionization mechanism. The [SII]/Hα ratios are 0.64$\pm$0.14 for the direction with the highest N(HI), and $<$0.11 one degree away, where there is little HI. The former is suggestive of photoionization, while the latter is consistent with a shock-induced origin. Clearly, there exist significant variations in the ionization conditions within Complex M.

WHAM was also employed by Wakker et al. (these proceedings) along the complex C sightline sampled by the background Seyfert galaxy Mark 290. An I(Hα) of 190 mR was found, as well as a 3σ upper limit of 20 mR on [SII]λ6716. This is the first study to combine the constraints imposed by (i) non-depleted elemental abundances, (ii) 21-cm synthesis column densities, (iii) emission line intensities, and (iv) stellar probe distance limits, providing unique insight into the physical conditions (e.g. ionization fraction, temperature, thermal pressure) at play in the Galactic halo.

Parallel to the WHAM Team's efforts, the TAURUS-2 Team presented their first results (Bland-Hawthorn et al. 1998). They detected Hα (270 mR) and [NII]λ6548 (127 mR) emission lines from HVC#360 in complex GP (Wakker & van Woerden (1991), also known as the Smith Cloud. This gives a ratio of 0.47, which is enhanced by a factor of two relative to the Reynolds layer; the enhancement is close to a factor of four at the core of the line. A 3σ upper limit to the [OIII] line intensity of 120 mR was also found. Arguments in support of photoionization as the dominant ionization mechanism were presented.

The newly released model of Bland-Hawthorn & Maloney (1998) of the Galactic Halo ionizing radiation field allows to predict HVC distances, under the assumption that the optical emission lines from HVCs arise due to ionization from photons leaking from the Galactic Disk (with some assumptions about the geometry). In that case the number of emitted Hα photons is proportional to the number of incoming ionizing photons. Bland-Hawthorn et al. (1998) apply this to the detections of HVC#360 and derive an implied distance of $\sim$26 kpc. They suggest that at this distance an association with the Sagittarius dwarf is possible. Further testing of the Bland-Hawthorn & Maloney radiation field model will be a natural byproduct of both the WHAM and TAURUS-2 surveys.

Bregman (these proceedings) points out that Weiner & Williams (1996) also report directions in the Magellanic Stream where no Hα is detected, although HI emission is seen in these directions (at low angular resolution). They used these non-detections to argue that the Hα emission originates from ram-pressure heating by the movement of the clouds through a tenuous halo. If it can be shown that there are no holes in the HI (using higher-angular resolution data such as those from the Parkes Multibeam survey), these non-detections imply that the ionizing radiation field reaching the Stream is much lower than expected. This requires an extra optical depth of 1.2 near 14 eV, or an halo HI column density of 3×10^{17} cm^{-2}. Then the Hα intensity can no longer be used to estimate cloud distances.

6. A connection between HVCs and energetic radiation?

Blom et al. (1997) suggest that a feature in the distribution of 0.75–3 MeV γ-ray radiation may be generated by the interaction of HVCs with disk gas. These authors find a γ-ray emission enhancement in the Ursa Major Window (Lockman et al. 1986) (l,$b$$\sim$150°,55°), whose edges are lined by the HVC complexes A, M and C. However, it is unclear whether the Ursa Major Window is associated in any way with the HVCs, also leaving open the association between HVCs and γ-rays.

At the workshop, Mebold reported on the work of Kerp et al. (1998), who analyzed ROSAT data for four ∼30°x30° fields containing HVCs (the low- and high-latitude ends of complex C, the complex WA region and a region near the GCN complex). They show that the large-scale features of the X-ray maps are well explained by a simple model of foreground emission associated with the Local Hot Bubble (LHB, Cox & Reynolds 1987), combined with background emission associated with a Galactic halo, which is absorbed by all or most of the HI column density; within each field the foreground and background intensities are assumed constant. Kerp et al. (1998) point out excess emission in the region l=100°–130°, b=50°, which is near the main line of complex C cores. This excess X-ray emission may originate in an interaction between complex C and gas in the lower Galactic halo. If so, Zimmer et al. (1997) provide an explanation for the X-ray emission in terms of the dissipation of magnetic fields in the Galactic halo. However, a connection between the X-ray excess and intermediate-velocity gas or small-scale structure in the Galactic halo cannot be completely ruled out.

This X-ray excess was originally interpreted as due to variations in the shape of the Local Hot Bubble (Cox & Reynolds 1987). A major part of the argument for a local origin is based on a comparison of the expected X-ray optical depths in two energy bands (B-band, 75–200 eV and C-band, 100–300 eV) of pre-ROSAT observations (McCammon & Sanders 1990). The low-velocity HI (presumably at z<500 pc) has a column density of $\sim 10^{20}$ cm^{-2}. Then the optical depth in B-band is <1, while that in C-band is >5. Yet, the B-band and C-band images look similar, which is hard to explain if the enhancement originates at z>1 kpc. ROSAT did not have the spectral resolution to address this problem.

7. Metallicities

Wakker & van Woerden (1997, Sect. 4.3) discussed the measurement of SII absorption associated with HVC287+22+240 in the spectrum of the Seyfert galaxy NGC 3783. Sulphur is one of a few elements that are not depleted onto dust in the ISM, and thus can provide an absolute metallicity measurement. Lu et al. (1994) derived an abundance of 0.15 times solar, but this was based on a low-resolution HI observation. Wakker et al. (these proceedings) observed the HVC at 1′ resolution, using which a sulphur abundance of 0.25±0.07 times solar was derived by Lu et al. (1998). Elsewhere in these proceedings, Wakker et al. report the second detection of sulphur in a HVC. They find [S/H]=$0.094\pm0.019^{+0.022}_{-0.018}$ times solar for complex C, using Mark 290 as the background probe. This is a very low value, and Wakker et al. argue that complex C represents the infall of low-metallicity gas onto the Galaxy. So far, an absolute metallicity has been found only for these two HVCs, and both results are much lower than the solar value. While suggestive, it is premature to conclude that all HVCs therefore have strongly sub-solar metallicities.

For instance, the [SII]/Hα ratio of 0.64 measured for cloud MI by Tufte et al. (1998) can be used to argue that the metallicity of MI is near solar. Assuming solar abundance a temperature of ∼7000 K is required, within the range of expected values (6000–8000 K; Reynolds 1985). Pressure equilibrium with a hot halo (for which Wolfire et al. 1995 give P(z)) would occur at a distance of 3 kpc. If the abundance were 0.1 or 0.5 solar, then T=20,000 K (very unlikely) or 9000 K (unlikely but possible), respectively, would be required to get the observed level of [SII] emission.

Sahu & Blades (1997) and Sahu (1998) present low-resolution ($120\,\mathrm{km\,s^{-1}}$) data on SiII, SiIII and NI for HVC 487, probed by the starburst galaxy NGC 1705. This cloud is probably a shred of the Magellanic Stream. Unfortunately, the low resolution and the fact that the lines are saturated do not allow measurements of the metallicity.

Much progress on HVC metallicities, dust depletion patterns and ionization structure is expected from the Far Ultraviolet Spectroscopic Explorer (FUSE), set to be launched in May 1999. The capabilities of FUSE for HVC metallicity work were described at the workshop by Sembach. This satellite can detect lines from the dominant ionization stage of several undepleted elements (O, N, P, Ar), lines of many depleted elements (C, Mg, Al, Si, Cl, Cr, Mn, Fe, Ni), lines of different ionization stages of the same element (especially C, N, P, S and Fe), many molecular lines (H_2, HD, CO), as well as lines originating in hot gas (OVI, PV, SIV, SVI). Long integrations are planned for probes of the Magellanic Stream, complex A, complex M, complex C (8 probes), HVC287+22+240, and of highly-ionized HVCs. Other HVCs may also be observed, if the candidate probes prove to be sufficiently bright.

8. Distances

Work on HVC distances is proceeding at an accelerated rate. The first distance bracket has now been found, for complex A (see van Woerden's article in these proceedings). CaII absorption in the spectrum of the RR Lyrae star AD UMa (l,b=160°,43°) sets an upper limit of 10±1 kpc. A lower distance limit of 4±1 kpc is provided by the non-detection of MgII absorption toward PG 0859+593 (l,b=157°,40°) (Wakker et al. 1996). This lower limit may have been confirmed by Ryans et al. (1997b), using PG 0832+676. They give 4.6 kpc for its distance, although earlier estimates varied from 1.6 to 18 kpc (Schwarz et al. 1995, Brown et al. 1989). Using N(HI) derived from a combination of Effelsberg and Westerbork data (Schwarz et al. 1995), and the Ca^+ abundance for complex A (Schwarz et al. 1995), the expected value of N(CaII) is $5\times10^{11}\,\mathrm{cm^{-2}}$, which would have yielded a 10σ detection.

For two other HVCs an upper distance limit has been set. Clouds MII/MIII have been shown to be less distant than 4.0 kpc (Danly et al. 1993, Keenan et al. 1995), while a tiny HVC in the direction of 4 Lac is less distant than 1.2 kpc (Bates et al. 1990). No lower distance limits are known for these clouds.

The case of MII/MIII in particular shows the difficulty of interpreting non-detections, especially in sightlines with faint HI. An upper distance limit of ~4 kpc is set from the detection of absorption toward BD+38 2182, a lower limit of 1.7 kpc was inferred from the absence of absorption toward HD 93521, 25′ away. However, as summarized by Wakker & van Woerden (1997, Sect. 4.4), and discussed more fully by Ryans et al. (1997a), with sufficiently high angular resolution no associated HI emission is found in the direction of HD 93521. Thus a lower distance limit can no longer be inferred. Danly (priv. comm.) points out the possibility of ionized hydrogen in the HD 93521 sightline; the absence of the strong UV absorption lines would then still imply a lower distance limit.

The third upper distance limit known is for HVC100−7+100, which is seen in absorption toward 4 Lac (distance 1.2 kpc; Bates et al. 1990). Stoppelenburg et al. (1998) map this HVC at 1.′8x2.′3 resolution and show that the cloud is within the Galactic disk ($|z|$<150 pc) and has a mass of only 0.6 (D/1 kpc)^2 $M_\odot$.

Some progress has been made for HVC complex C, for which van Woerden et al. (these proceedings) increase the lower distance limit from 2.5 to 5 kpc. Finally, Tamanaha (1996) determined lower limits to the distances of AC0 (160 pc), AC I (650 pc) and the Cohen Stream (=HVC168−43−260; 350 pc).

At the workshop, distances were also reported for a number of Intermediate-Velocity Clouds (IVCs) and high-latitude molecular clouds, which may or may not be inextricably linked with the HVCs. Gladders et al. (1998) report that the distance of the Draco molecular cloud (Herbstmeier et al. 1996 and references therein) at (l,b,v_{LSR})= (90,+39,−25) is between 450 and 650 pc. This is the same object for which Burrows & Mendenhall (1991) found a clear X-ray shadow. The new distance determination thus sets a strict lower limit of 300 pc to the z-height of part of the X-ray emission.

Further progress in determining HVC and IVC distances will be made by a coordinated effort that was initiated at the workshop to a) find suitable probe stars in HVC fields, b) obtain intermediate-resolution spectroscopy for classification and c) do high-resolution spectroscopy at any of the new 8-m class telescopes coming on-line in the next five years. Beers (this volume) gave an overview of the possibilities and problems. In most of the southern sky finding suitable probes may become relatively easy. The Parkes Multibeam Survey (Staveley-Smith 1997) will provide high-quality HVC data, while the Hamburg ESO survey (Wisotzki et al. 1996) covers 10000 square degrees at $\delta<0°$ down to 16.5 magnitude.

9. HVCs associated with other galaxies

Observations of extra-galactic HVC-analogues have provided more evidence for a connection between high- (and/or intermediate-) velocity gas and star formation intensity, probably via a galactic-fountain-type phenomenon. Schulman et al. (1997a) use the VLA to show that UGC 12732, a face-on galaxy with low star formation rate, does not have high-velocity HI gas. On the other hand, two face-on galaxies with high star formation rate do contain such high-velocity gas: NGC 5668 (Schulman et al. 1996) and NGC 1300 (Schulman et al. 1997b). The edge-on galaxy NGC 891 was shown by Swaters et al. (1997) to have HI up to 5 kpc. These authors also find that the distribution of high-z HI correlates with that of Hα and the radio-continuum.

10. The Magellanic Stream

While *technically* just one of the 17 HVC complexes defined by Wakker & van Woerden (1991), the Magellanic Stream occupies a rather special niche on the HVC family tree. Beyond the obvious (it being perhaps the single most striking structure in the HI sky, cutting a swath >100° along a Great Circle through the South Galactic Pole), a large part of its special nature can be traced to the fact that it is the only HVC of which we know the source: the Magellanic System.

Since its discovery (Mathewson et al. 1974), the debate on the origin of the Stream has focused on the mechanism whereby this gas attained its present-day distribution. In the mid-1990s two alternative models seemed feasible: ram-pressure stripping due to an extended gaseous Galactic halo (Moore & Davis 1994), or tidal disruption of the Magellanic System due to its interaction with the Galaxy (Gardiner & Noguchi 1996). The strongest discriminants between these two alternatives are that the tidal model predicts the existence of a leading counter-feature to the trailing Stream, as well as the presence of stars in the Stream, while the ram-pressure model predicts that such features are absent. The non-detection of a stellar Stream as well as the apparent absence of a leading arm made the ram-pressure model seem likely.

However, this situation has now changed. At the workshop, Gardiner reported on the dissertation of Yoshizawa (1998). Building upon the models of Gardiner & Noguchi (1996), he incorporated gas dynamics into the existing n-body framework (embedding initially compact stellar disks in more extended diffuse gaseous halos). This demonstrates that stars will not be drawn out along the Stream in appreciable numbers. Some stellar tidal debris is expected, but it is generally restricted to a $\sim 10^\circ$–15° region surrounding the LMC and appears clump-like, or in two-to-three dispersed streams. Observationally, Ostheimer et al. (1997) and Majewski et al. (1999) identified giant stars down to V$\sim$19 in an annulus around the Magellanic Clouds, and obtained luminosity classifications and radial velocities with follow-up spectroscopy. These observers tentatively report an excess of giants at distances expected for tidal debris from the Clouds. It is intriguing that observed excesses appear in the regions where the simulations of Yoshizawa (see Figure 1 of Gardiner in these proceedings) predict that stellar tidal debris should appear.

Two further observational pieces of evidence appeared during the past year, offering definitive proof for the tidal origin of the Magellanic Stream. First, for HVC 287+22+240 an accurate absolute metallicity of $\sim 0.25\,Z_\odot$ was found (Lu et al. 1998; see also the paper by Wakker et al. in these proceedings), which is similar to the sulphur abundance of the Magellanic Clouds. This result is especially noteworthy, because HVC 287+22+240 lies spatially and kinematically in a region where the Gardiner & Noguchi (1996) and Yoshizawa (1998) models predict gaseous tidal debris to reside.

Second, using the first data from the HI Parkes All-Sky Survey (HIPASS), Putman et al. (1998) concluded that what appeared to be disconnected and discrete HVCs in the region between the Magellanic Clouds and the Galactic Plane, was in fact a continuous feature. These HVCs are connected by a tendril of HI emanating from the SMC/Bridge region and extend continuously (both spatially and kinematically) at least as far as the Galactic Plane (>25° away). Gardiner presented a new grid of pure n-body models incorporating drag forces (based loosely upon the older Gardiner & Noguchi 1996 models). These nicely match this feature. However, this version of the model cannot simultaneously match the details of the Putman et al. HI feature and retain the HI debris in the region near HVC 287+22+240; better models are obviously needed.

Both the Lu et al. (1998) metallicity determination and the Putman et al. (1998) leading HI feature are consistent with the tidal models of Gardiner and collaborators, but not with ram-pressure models. The problem of the absence of a stellar stream was solved by Yoshizawa (1998). Thus, we can conclude that in the past year the tidal origin of the Magellanic Stream has been established beyond reasonable doubt.

11. Models

11.1. General comments

The most notable recent development concerning the origin of HVCs has been the revival of the idea that some (or all) of them are extra-galactic. This has been most clearly expressed in the proposal by Blitz et al. (1998) that HVCs are remnants of the formation of the Local Group. Mallouris et al. (1998 and these proceedings) propose a connection with Lyα absorbers seen in the spectra of background QSOs; in this case the HVCs would still be in the sphere of influence of the Galaxy, rather than in the Local Group at large, similar to the model originally proposed by Oort (1970).

The idea of extra-galactic origins gets strong observational support from the metallicity of $\sim$0.1 times solar derived for complex C (see Sect. 7 above), and also by the ionization properties found for complex GCN (Sembach et al. 1998). Toward Mark 509 and PKS 2155$-$304 they find strong CIV absorption, but no detectable CII or SiII absorption, nor HI emission. A photo-ionization model yields low density ($<10^{-4}$ cm^{-3}) and pressure ($\sim$2 K cm^{-3}), favoring a location in the Local Group or very distant halo (the semi-empirical formula for the halo pressure given by Wolfire et al. (1995) gives 2 K cm^{-3} at $z\sim$60 kpc).

However, it would be premature to conclude that *all* HVCs must be extra-galactic. The 3-D hydrodynamical models of de Avillez (these proceedings) may allow to set limits on which HVCs can be accommodated by the Galactic Fountain and which cannot. We now discuss these developments in more detail.

11.2. HVCs as Local Group objects

Blitz et al. (1998) propose that HVCs are spread across the Local Group, concentrating in a filament running through M 31 and the Galaxy. They conclude that a typical HVC has an HI mass of 3×10^7 M$_\odot$ and a diameter of 28 kpc, that the ratio of HI mass to total mass is 0.15, and that the distance scale of the ensemble is about 1 Mpc. Previously, this possibility was not considered because of the following arguments: a) the predicted kinematics are incompatible with the data; b) the typical distance at which the clouds are gravitationally stable if all the mass is in the form of neutral hydrogen and helium is 1–75 Mpc; c) the presence of two-phase structure requires a substantial external pressure; d) there are small velocity gradients (a few km s^{-1}) over what would be large linear distances (50 kpc); e) no analogues in other galaxy groups have been found.

Blitz et al. try to answer these objections. Against a) they show that the sky and velocity distributions can be explained from a simple model of Local Group formation. They solve b) by pointing out that 90% of the matter may be dark, as it is in the outer parts of galaxies; this reduces the stability distances to 0.1–5 Mpc. A large ionized fraction can further reduce these. Objection c) is answered by suggesting that the dark matter in the cores cools, settles and the gas becomes self-shielded from the ionizing radiation field, producing a core of neutral gas. The strongest argument against the HVCs being very distant has been point d) (see Giovanelli 1977); as a consistency argument Blitz et al. note that Lyα-forest absorbers also seem to have small velocity gradients over large scales.

Objection e) was discussed at the workshop. In this context the results of Zwaan et al. (1997) are particularly relevant. They used Arecibo to conduct a blind HI survey, but found no free-floating starless HI clouds down to a mass of about 5×10^7 $M_\odot$. Assuming that the Blitz et al. model is correct, one can estimate the mass, distance and radius for each HVC, and the volume out to which such a cloud could have been detected. Comparing to the effective detection volume for the Zwaan et al. (1997) survey then allows a prediction for the number of analogous clouds that should have appeared in their survey. Because of several technical issues, and because a number of free parameters remain, this is not the appropriate place for a complete discussion of the resulting predictions. It appears, however, that the Blitz et al. model in its original form is incompatible with the Zwaan et al. data; it can be made compatible by substantially decreasing the relative proportion of HI and thus substantially decreasing the distance scale of the ensemble. It is as yet unclear whether these changes will completely exclude a relation between the HVCs and the Local Group.

A crucial test of the Blitz et al. model may be provided by the WHAM and TAURUS-2 Teams, by means of observations of Hα emission of individual clouds. If these clouds are in the Local Group at large distances, then the incident radiation field should be weak and the Hα emission becomes undetectable. On the other hand positive detections of Hα emission for the large majority of clouds would falsify the Blitz et al. model.

11.3. HVCs as Lyα-forest analogues

Mallouris et al. (1998 and these proceedings) normalize the distribution of the number of HVCs per Mpc^3 as a function of column density, and find that both the slope and the absolute normalization fit in the gap in the distribution between low-redshift Lyα forest clouds (N(HI)$<10^{17}$ cm^{-2}) and damped Lyα absorbers (N(HI)$>10^{20}$ cm^{-2}). This model implies that there should not be a turnover in the distribution of column density, contrary to the interpretation of Blitz et al. (1998). The suggestion is made that the source of the Lyα clouds in general, as well as that of the HVCs in particular, lies in the tidal disruption of dwarf galaxies. The HVCs would thus be Local Group objects, though not necessarily as distant as in the Blitz et al. model.

11.4. The Galactic Fountain

Much progress was also made on the interpretation of HVCs as galactic objects. De Avillez (this volume) presents the first three-dimensional hydrodynamic models of the Galactic Fountain. See his Sects. 1.2–1.3 for a summary of the basics of the Fountain, and for a discussion of the problems with two-dimensional models. He solves the full equations of motion of the gas in a gravitational field provided by the stars and dark matter, using the ideal-gas law for the equation of state and an approximation for the cooling curve. Supernovae are set off in a manner that is tied to the distribution of early-type stars, allowing superbubbles to form.

The model reproduces many of the general features of the distribution of cold, cool, warm and hot gas in the Galaxy. A dynamic equilibrium is set up between upward and downward flowing gas with a rate of $4.2\times10^{-3}\,M_{\odot}\,kpc^{-2}\,yr^{-1}$, equivalent to $6\,M_{\odot}\,yr^{-1}$ when integrated over the disk. Chimneys are generated from superbubbles forming at z>100 pc. The ionized gas forms a layer with a scaleheight of about 1 kpc, and is fed by the chimneys and other ascending hot gas. This warm gas then escapes buoyantly upward, setting up a fountain flow. I.e., the fountain originates at z=1–1.5 kpc, rather than in the disk (z=0 kpc). From an analytical model, using parameters based on the model, this fountain gas is predicted to reach z-heights of up to 10 kpc.

Some of the model predictions are relevant to HVC studies. Infalling clouds form from cooling instabilities in the hot gas in places where shock waves intersect, creating density variations. The sizes of the cool clouds thus formed range from a few pc to hundreds of pc in size. The bulk of these clouds have (infalling) vertical velocities of 20 to $90\,km\,s^{-1}$, a small fraction has $v_z<20\,km\,s^{-1}$, and a few have higher velocities (up to $-300\,km\,s^{-1}$). Most of these clouds occur in a layer between z=1 and 2 kpc. This height corresponds to a cool layer that is in unstable equilibrium with the warmer gas below. Clouds form in complexes with different velocities, and internal dispersions of order $20\,km\,s^{-1}$. At higher z a small number of HI clouds are predicted to occur, because the cooling times get longer. However, the numerical model only extends up to z=±4 kpc, so the number of high-z high-velocity clouds is difficult to estimate.

Thus, it appears that many (or all) of the intermediate-velocity clouds with $|v_{LSR}|<100\,km\,s^{-1}$ can be understood as cool condensations in the dynamic equilibrium between gravity and supernovae, whereas this would be the case for only some of the high-velocity clouds. More analysis of the model results is necessary to determine which fraction of the HVCs can be understood as part of a fountain flow, and to determine the distribution of LSR velocities on the sky. Also, it remains to be seen whether the positive velocities of the clouds at $l>180°$ can be explained as due to projection effects, or whether these clouds require a separate explanation.

12. Future prospects

In this final section, we summarize the prospects for future work.

From the whole-sky HI surveys (Leiden-Dwingeloo Survey and Villa Elisa Southern Sky Survey) a more complete catalogue of the HVCs will be made. Most importantly, this catalogue will also contain the intermediate-velocity clouds. For the first time such a catalogue will allow detailed studies of cloud kinematics, linewidths, velocity gradients, as well as a proper statistical analysis.

An important type of study for which little progress was made in the past few years is to find HI absorption toward background 21-cm continuum sources, in order to derive spin temperatures. Unlike measurements of HI linewidths, these provide the kinetic temperatures that are used in model calculations such as those of Wolfire et al. (1995).

We foresee much progress in the study of ionized hydrogen at high velocity, using WHAM. Of particular interest are the following questions: a) is photoionization the main source of ionization? b) can we estimate cloud distances by combining the Hα intensity with a model of the galactic radiation field? c) does the ionized hydrogen form a shell around a neutral core, or is it pervasive? d) how important is H^+ in deriving abundances? By combining observations of optical emission lines with UV absorption lines it will also become possible to measure the temperature and density of the ionized gas, as well as constrain the cloud structure. Combining [NII]/Hα with [SII]/Hα (both dependent on abundance and temperature) will allow to set constraints on abundances. The Hα measurements alone will give strong constraints on the possibility that the HVCs are Local Group objects.

Further progress on metal abundances is expected with FUSE, especially for complex C, the Magellanic Stream and HVC287+22+240, and possibly for complexes A and M. FUSE will also provide much data on depleted elements, and thus allow a comparison of the depletion pattern with other kinds of gas (such as cool disk gas, warm disk gas and halo gas). FUSE data on high-velocity OVI will provide a better understanding of the hot gaseous halo of the Galaxy. More HST data for SII in different HVCs and IVCs could provide better insight into whether clouds have a galactic (Fountain) or an extra-galactic (Accretion) origin.

Work on distance determinations should profit from a more organized approach to finding and observing suitable background probes. While for several large HVCs significant lower distance limits are available or may be readily obtained, special probe searches will be required in order to establish upper distance limits, and also to obtain constraints on the distances of smaller HVCs.

The recognition of the leading counterpart to the trailing Magellanic Stream has provided the possibility of improved dynamical work on the Magellanic System. The positions and velocities of these leading-bridge clouds give extra constraints on the orbits of the Magellanic Clouds. The addition of gas dynamics to n-body models gives the possibility of studying the structure of the outer Galactic Halo. The fact that small-scale structure is present in the Stream in a probable outer-Halo environment should provide constraints on models for the physical conditions in that Halo.

The study of the relation to the underlying galaxy of high-velocity cloud analogues in nearby spiral galaxies (such as M 31, M 33, M 51, M 83, M 101, NGC 628, NGC 891, NGC 1300, NGC 5668) can provide more information about the relative importance of the Fountain vs Accretion.

In summary, in the next few years we expect to see substantial progress in measuring the properties of high-velocity gas, such as distances, metallicities, depletion patterns, and kinematics. Dynamical models of the Galactic Fountain, Magellanic Stream and Accretion will allow progress on understanding the origins of HVCs.

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