DISTANCE AND CHEMICAL COMPOSITION OF HIGH-VELOCITY CLOUDS

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Abstract

This contribution reports results of recent absorption-line studies on La Palma and reviews earlier work done elsewhere. CaII has been found in absorption in five HVCs, mostly against extragalactic background sources. The CaII/HI ratios differ strongly, from 0.002 to 0.1 times solar, suggesting different origins of HVCs. Nondetections of CaII absorption in stellar spectra may provide lower limits to HVC distances, or be caused by small-scale structure or a low CaII/HI ratio in the HVC. Proper interpretation requires comparison of CaII/HI ratios in stellar and extragalactic probes, and use of high-resolution HI maps. No solid direct distance determinations of HVCs are available yet. The distance of Complex C is controversial.

1. Introduction

The cloud structure and associated motions of the interstellar medium were discovered by Beals (1936) and Adams (1943, 1949) through high-resolution observations of CaII absorption lines. Guido Münch (1953, 1957) was the first to measure the large-scale distribution of interstellar calcium and sodium clouds, confirming the spiral structure found in the distributions of emission nebulae (Morgan, Sharpless and Osterbrock 1952) and in the 21-cm neutral hydrogen maps (Van de Hulst 1953; Van de Hulst, Muller and Oort 1954).

Following these studies at low galactic latitudes, Münch and Zirin (1961) used the CaII and NaI lines in a first exploration of interstellar clouds at large distances from the plane. A five-year search for HI in the galactic halo led to the discovery of high-velocity clouds (Muller, Oort and Raimond 1963). In view of the wide distribution of HI at velocities up to $|V| > 70\,\mathrm{km\,s^{-1}}$ (Van Woerden, Takakubo and Braes 1962; Blaauw and Tolbert 1966), the Dwingeloo studies defined high-velocity clouds (HVCs) as HI clouds at $|b| > 10^\circ$ and $|V| > 70 - 80\,\mathrm{km\,s^{-1}}$ a velocity range significantly higher than that in earlier optical studies. (Velocities V throughout this paper are relative to the local standard of rest.)

A recent review (Van Woerden, Schwarz and Hulsbosch 1985) summarizes the HVC phenomena; cf. also Mirabel's paper in this volume. After 25 years of study, nature and origin of HVCs remain enigmatic. The key to better understanding lies in the determination of the distances of HVCs; estimates implied by various hypotheses concerning their origin range between 0.1 kpc (nearby supernova shells) and 500 kpc (protogalaxies in the Local Group). The distance also is an important parameter in determinations of physical properties of HVCs: sizes, masses, densities, velocity gradients, and time scales vary as distance to the power $+1, +2, -1, -1$ and $+1$; column densities, kinetic and spin temperatures are distance-independent.

The chemical composition of HVCs is another important item in discussions of their nature and origin. For instance, in a nearby supernova shell a high calcium abundance would be expected, while protogalaxies in the Local Group might be devoid of metals. Also,

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the composition plays a key role in attempts to determine the distance of HVCs, as will be shown below.

The present paper discusses the results of our recent work on the distance and composition of HVCs, carried out with the Isaac Newton Telescope (La Palma) and the Anglo-Australian Telescope, in collaboration with Aad Hulsbosch (Nijmegen) and Gordon Robertson (AAO). For perspective, we also summarize the results of other workers in this field, and we critically review methods, problems and prospects. We restrict the discussion to HVCs detected in the 21-cm line, leaving aside observations of high-velocity halo gas which have not been correlated with hydrogen HVCs.

2. The method and its problems

Many indirect methods have been followed to estimate the distance of HVCs, but their results differ by several orders of magnitude. Since no physical associations of HVCs with objects at well-known distances have been found, the only direct method available is through measurement of interstellar absorption lines in the spectra of stars lying at known distances projected onto HVCs.

The probe stars must have clean spectra so that the HVC absorption is not confused with or obliterated by stellar absorption lines. Early-type stars would be best, but these are extremely rare at distances >1 kpc in latitudes $|b| > 10°$. RR Lyrae stars have been well catalogued, and have reasonable magnitudes: +11 to +16 at distances of 1 to 10 kpc, but their stellar lines are in general too strong, except possibly for a brief interval around maximum brightness. The best probes are blue horizontal-branch (BHB), sdO and sdB stars; unfortunately, searches for these objects have so far been sparse, and the number known to lie within an HVC boundary remains small. Since absorption by HVCs at $|V| \gtrsim 100\,\mathrm{km\,s^{-1}}$ must be distinguished from that by gas at low and intermediate velocities, a velocity resolution of order $30\,\mathrm{km\,s^{-1}}$ is required. At magnitudes >12, spectra of $30\,\mathrm{km\,s^{-1}}$ resolution require a large telescope.

Detection of a CaII or NaI absorption line at the HVC velocity shows the cloud to be in front of the star, and hence places an upper limit on the HVC's distance. Nondetection of an HVC absorption line, however, may have several causes. The HVC may be behind the star; or it may be in front, but contain too few Ca^+ ions on the line of sight to the star. A lack of Ca^+ ions may be due to: 1) a preponderance of neutral or doubly ionized calcium, 2) a low calcium abundance, or 3) a low column density of hydrogen (and other) gas on the stellar sight-line. A test for causes 1) and 2) is provided by observation of an extragalactic probe, preferably one with a bright nucleus, such as a quasar or Seyfert galaxy; combination of the HVC CaII line strength in this spectrum with a 21-cm line profile measured in the same direction supplies a N(CaII)/N(HI) ratio, which one may then reasonably assume to be valid elsewhere in the same HVC. The chance that cause 3) applies is great: as shown elsewhere in this volume (Wakker 1989), HVCs are very rich in small-scale structure, and HI column densities may vary by factors of order 10 on scales of a few arcminutes. High-resolution maps, preferably obtained with a synthesis telescope (Westerbork or VLA), are required to test for this situation, and to provide a more reliable ratio N(CaII)/N(HI) in the direction of the extragalactic probe, for comparison with a — similarly measured! — upper limit derived from nondetection on a star.

The preceding arguments, summarized in Table 1, are of key importance in interpreting nondetections of metal absorptions in HVCs, as well as in deriving metal abundances in HVCs from detections. Only after the effects of causes B 1) 2) 3) have been assessed by the appropriate observations, can a nondetection yield a reliable lower limit to the distance of a HVC.

Table 1 Possible causes of non-detection of an HVC absorption line toward a star.

A. The HVC lies behind the star
B. The sight-line to the star contains too few Ca^+ ions
(1) low ratio N(CaII)/N(Ca) [ionisation equilibrium shifted: Ca predominantly in form of CaIII or CaI]
(2) low ratio N(Ca)/N(H) [i.e. low calcium abundance]
(3) low column density of hydrogen (and other atoms) [small-scale structure in HVC]
Checks for B1 and B2: Measure N(CaII)/N(HI) on extragalactic background source.
Check for B3: High-resolution HI map with synthesis telescope.

3. Calcium abundances in high-velocity clouds

Table 2 summarises the ratios of ionized calcium to neutral hydrogen measured in high-velocity clouds. The velocities v_{lsr} are from single-dish 21-cm observations at Dwingeloo (D), Parkes (P) or Villa Elisa, Argentina (VE). Except for one detection against an RR Lyrae star, only results on extragalactic probes have been listed. In view of the unknown ionisation equilibrium, the ratios N(CaII)/N(HI) have not been corrected to abundances N(Ca)/N(H). For comparison, the table also gives the ratios measured in various clouds at low and intermediate velocities, and the calcium abundance measured in the Sun.

So far, CaII detections have been reported for 5 different HVCs, all lying far apart on the sky. [In the spectrum of stars in the Magellanic Clouds many absorption lines at velocities between 0 and $+310\,\mathrm{km\,s^{-1}}$ have been observed. The relation of these lines with galactic HVCs remains uncertain, however; hence we have not listed these detections.] Clearly, the 5 HVCs detected do not consist of primordial gas, but are enriched in heavy elements. In several HVCs, the CaII/HI ratio is much higher than in low — or intermediate — velocity gas, showing that in these HVCs the calcium is not depleted by being locked up in dust grains. Alternatively, the dust may have been affected by the acceleration process that caused the HVCs, releasing the metals.

Table 2 Calcium II absorptions measured in high-velocity clouds.

Name of HVC	Probe Name, Type	l	b	v_{lsr} $\mathrm{km\,s^{-1}}$	N_{CaII}/N_{HI} 10^{-9}	Reference
Magell. Stream	Fairall 9, Sy	294	−58	+195 P	11	Songaila 1981
287+22+240	NGC 3783, Sy	287.5	+22.5	+240 VE	4.6	West *et al.* 1985
237+17+105	0837-120, Q	237.2	+17.4	+105 P	160	Robertson *et al.* 1989
						Van Woerden *et al.* 1986
Complex C	BT Dra, RR	99.4	+51.2	−154 D	120	Songaila *et al.* 1988
				−94 D	50	Songaila *et al.* 1988
String A	MK 106, Q	161.1	+42.9	−156 D	30	Schwarz *et al.* 1989
Various	, Q, Sy				?	Pettini 1986
For comparison:						
low-velocity gas	stars			<20	0.5-6	Pottasch 1985
IVCs	stars			20−60	6−30	Albert 1983
Sun					2200	Pottasch 1985

The CaII/HI ratio varies strongly from cloud to cloud. This indicates that different HVCs may have different origins, or different ionization conditions, and that it is important to measure the ratio in various clouds; for many clouds, no information is available yet. The variation in the CaII/HI ratio further indicates that, in interpreting CaII nondetections in terms of HVC distances, one cannot use CaII/HI ratios measured in other HVCs; it is necessary to compare upper limits obtained on stellar probes with ratios measured on extragalactic probes behind the same HVC.

Does the CaII/HI ratio vary within one HVC? At present we have no unequivocal answer to this question. In Complex C, there is apparent disagreement between the ratio measured against a stellar probe and the upper limits found on two more distant probes; however, as discussed in section 4, this disagreement may not be significant.

In view of the strong small-scale structure present in many HVCs (cf. the papers by Wakker and by Danly in this volume), the CaII/HI ratios listed in Table 2 must be considered with caution. Observations at high angular resolution are required to obtain more reliable ratios.

4. Distances of high-velocity clouds

From the above it will be clear that, in order to have any handle on the distances of HVCs, we must have either 1) a CaII (or any other suitable metal ion) absorption detected against a star; or 2) a CaII (etc.) detection against an extragalactic probe, accompanied by a nondetection against a star at a significantly lower level of CaII/HI. The first three HVCs listed in Table 2 do not fulfil this requirement: they show absorption against extragalactic probes, but no useful measurements on stellar probes have been obtained. Hence, for these three HVCs the only distance information is an upper limit of many megaparsecs. For the other two HVCs, String A and Complex C, both stellar and extragalactic probes have been measured. We discuss these objects in some detail.

4.1 String A

For this object, the first HVC discovered, a distance of a few kpc has often been assumed (e.g. Oort and Hulsbosch 1978). Pettini (1986, private communication), on the basis of a nondetection of CaII against a BHB star, derived a lower limit of 15 kpc. However, while a 1973 Green Bank map at ~10 arcmin resolution had this star lying within the boundary of Cloud A IV, our recent Westerbork map (Wakker and Schwarz 1989) shows no measurable HI in the direction of the BHB star. Hence, the nondetection of CaII is not significant and the 15 kpc distance limit spurious. Songaila *et al.* (1988), from a comparison of several stellar spectra, have tentatively suggested a distance of 1-2 kpc for String A, but the evidence is not strong.

Figure 1 illustrates two spectra obtained by us with the Isaac Newton Telescope on La Palma (Schwarz *et al.* 1989). The quasar MK 106, projected on cloud A VI, shows CaII absorption near the HVC velocity of $-156\,\mathrm{km\,s^{-1}}$; the derived ratio N(CaII)/N(HI) is $(30 \pm 9)\times10^{-9}$. The star 291-257, projected on cloud AIII, shows no absorption by the HVC; the upper limit on the CaII/HI ratio is 7×10^{-9}. Assuming this star to be on the BHB at absolute magnitude ~+1, we estimate its distance as 4 kpc. The nondetection of the HVC in the stellar spectrum is confirmed by an independent observation by Brown *et al.* (1989) who, from detailed analysis, find a spectral type B 1V for the star, and a distance of 31 kpc!

At face value, these results would indicate that cloud A III in chain A is beyond 4, or even 31, kpc distance. The latter limit especially is surprising, since chain A is rich in small-scale structure, suggestive of shocks and instabilities, and hence possibly of some kind of interaction. However, the lower distance limits found are no more than tentative, for several reasons. 1) The HVC absorption in the quasar spectrum is only just above 3σ and requires confirmation. 2) The small-scale structure in various clouds of String A is particularly strong; hence high-resolution HI maps are required before the CaII/HI ratios

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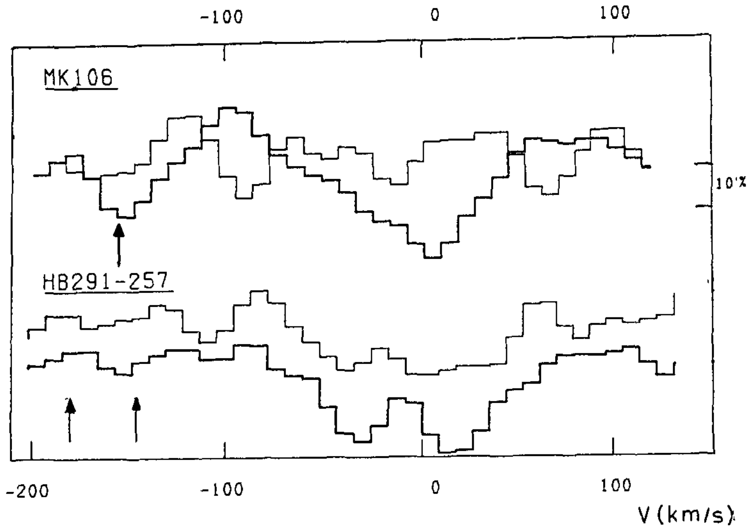

Figure 1. Spectrum portions around the CaII K line (fat line) and H line (thin line), measured at the Isaac Newton Telescope on La Palma, for 2 probes projected on string A. Spectra have been smoothed to obtain optimum signal/noise ratios. A 10% absorption scale is indicated. Arrows show HVC velocities measured at the probe positions. MK 106 is a quasar, 291-257 a blue horizontal-branch (or main-sequence) star at 4 (or 31) kpc distance. The star shows no HVC absorption, the quasar does. Absorption at low and intermediate velocities is seen in both spectra. Velocities are relative to the local standard of rest.

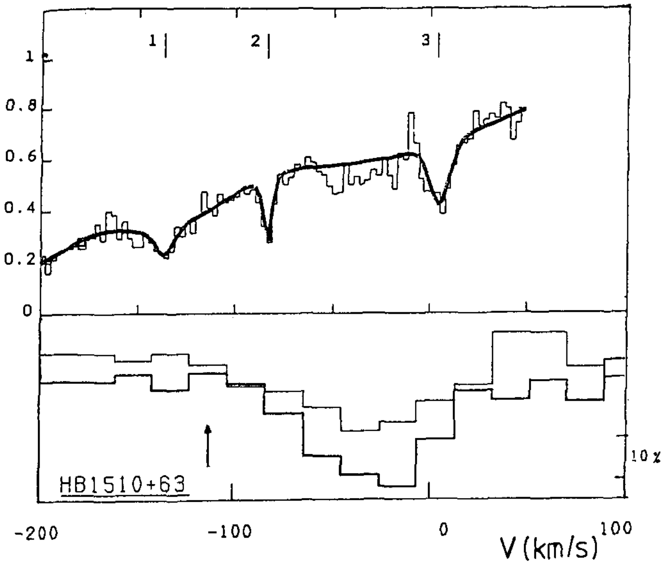

Figure 2. Top: Spectrum of the RR Lyrae star BT Dra at CaII K (histogram) and model fit (thick line) obtained by Songaila et al. (1988). Bottom: Spectrum of the horizontal-branch star 1510+63 at K (fat line) and H (thin line), observed with the Isaac Newton Telescope on La Palma (Schwarz et al. 1989). The stars lie 4° apart, both projected on Complex C. Arrows indicate HVC velocities.

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can be trusted. We have observed both fields at Westerbork and the analysis is in progress. 3) The quasar and the star are 13° apart and lie projected on different clouds in String A, which is highly fragmented; the CaII/HI ratio may well vary between these clouds, and it would be desirable to measure more extragalactic and stellar probes, closer together.

We conclude that more detailed observations, both optical and at 21 cm, are required before the distance of String A can be pinned down.

4.2 Complex C

This is the largest HVC, measuring about 70° ×20°; it may be connected with the "Outer Arm" of the Galaxy, which lies in a strongly warped portion of the disk.

Songaila, Cowie and Weaver (1988) have found absorption at $V = -136\,\mathrm{km\,s^{-1}}$ in the RR Lyrae star BT Dra at 2.1 kpc distance, a possible absorption at a similar velocity in SW Dra at 1.2 kpc, and no absorption in several stars at distances $\lesssim 0.8$ kpc. They conclude that Complex C must be at 1–2 kpc distance. [Songaila *et al.* (1985, 1988) also report CaII and NaI absorption at $V = -83\,\mathrm{km\,s^{-1}}$ in BT Dra. However, it is not clear whether gas at this velocity belongs to Complex C, or may rather be connected with the large complex at intermediate negative velocities ($-90 < V < -30\,\mathrm{km\,s^{-1}}$) described by Wesselius and Fejes (1973).]

Together with the Songaila *et al.* (1988) spectrum of BT Dra, Figure 2 shows the spectrum obtained by us with the Isaac Newton Telescope on the BHB star 1510+63 at 3.7 kpc distance, 5° from BT Dra. Combining the 3σ upper limit of 50 mÅ with N(HI) $= 12\times10^{18}\,\mathrm{cm^{-2}}$ obtained from special measurements at Dwingeloo by R.J. Habing, we find N(CaII)/N(HI) $\leq 50\times10^{-9}$, significantly lower than the 120×10^{-9} derived from the K-line detection by Songaila *et al.*. A noisier spectrum on the quasar 0.087, at 8° from BT Dra, also gives a significantly lower CaII/HI ratio.

Our upper limits for the CaII/HI ratio on a more distant star and on an extragalactic probe would appear inconsistent with the detection in BT Dra reported by Songaila *et al.* (1988). Contamination with stellar lines in the spectrum of the RR Lyr-type star might be a possible cause of the discrepancy. However, other possible causes include noise in the spectra, small-scale HI structure, and true variations in the CaII/HI ratio. Again, further observations will be required to settle the issue and firmly measure the distance of Complex C.

5. Concluding remarks

In several high-velocity clouds, CaII (and sometimes also NaI) has now reliably been detected. The ratios N(CaII)/N(HI) vary over a wide range, suggesting that different HVCs may have different origins.

Almost all CaII detections in HVCs have been made against extragalactic probes. This fact might suggest that most HVCs are at great distances (see also Wakker 1989), but that conclusion would be premature: firm distance limits based on stellar observations are lacking. As a consequence, the nature and origin of HVCs and the values of their physical properties remain open questions.

Progress in this field will require further optical spectra of high quality, for several probes per HVC. Detections and non-detections of HVC absorption are both useful, for distance as well as chemical composition of the clouds. In both cases, HI synthesis maps are required to obtain reliable abundances and distance estimates. These quantities are of great importance to theories of the origin of HVCs and their role in the evolution of our Galaxy. Finally, searches for suitable probes - blue horizontal branch stars, post AGB stars, quasars and seyferts - are badly needed.

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Discussion:

MÜNCH (Comment): In my opinion, to the two reasons you listed for an optical IS line, expected from a foreground cloud, not to appear on the spectrum of a distant star, the porosity of the HI medium should be added.