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Hα Distances to High Velocity Clouds

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Abstract. Several observing teams have now obtained deep Hα spectroscopy towards high-velocity clouds (HVCs) which vary in structure from compact (CHVCs) to the Magellanic Stream. Our team has observed clouds which range from being bright (~640 mR) to having upper limits on the order of 30 to 70 mR. The Hα measurements can be interpreted as a distance constraint if we adopt a halo ionization model based on $\hat{f}_{\rm esc} \approx 6\%$ of the ionizing photons escaping normal to the Galactic disk ($f_{\rm esc} \approx 1-2\%$ when averaged over solid angle). The results suggest that many HVCs and CHVCs are within a ~40 kpc radius from the Galaxy and are not members of the Local Group at megaparsec distances. We refer the reader to Putman *et al.* (2003) for the full version of the paper presented here.

1. Introduction

The smooth accretion of gas onto galaxies allows for continuous galaxy evolution and star formation. The intergalactic gas which feeds galaxies is seen in absorption against a bright background source along filaments of galaxies (e.g. Penton, Stocke & Shull 2002) and is predicted by simulations of the "cosmic web" (e.g. Davé *et al.* 1999). When this gas reaches a certain radius from the galaxy, it may be able to condense and cool, and in the case of our own Galaxy, the gas could become observable in 21-cm emission. Together with the remnants of Galactic satellites, these objects may be represented by the high-velocity clouds (Oort 1966).

High-velocity clouds are concentrations of neutral hydrogen which do not fit into a simple model of Galactic rotation and cover 30-40% of the sky (e.g. Wakker & van Woerden 1991; Lockman et al. 2002). There have been several models which propose that HVCs are the primordial building blocks of galaxies, the left-overs along the supergalactic filaments. Blitz *et al.* (1999) and Braun & Burton (1999) proposed HVCs, in particular the compact HVCs (CHVCs), represent the missing satellites of the Local Group, at mean distances of ~1 Mpc. These models have been called into question (e.g. Zwaan 2002; Sternberg, McKee & Wolfire 2002; Maloney & Putman 2003).

Hα observations provide a direct test of whether HVCs are infalling members of the Local Group at large distances from the Galaxy. Models of the Galactic ionizing radiation field indicate that ionizing photons are capable of reaching distances on the order of 100 kpc; HVCs can act as an HI screen and the Hα emission measure reflects the ionizing photon flux reaching the cloud (Bland-Hawthorn & Maloney 1999, hereafter B99; Bland-Hawthorn & Maloney 2002, hereafter B02). This is confirmed by recent Hα observations of large high velocity complexes which have direct distance bounds of < 10 kpc (Tufte *et al.* 1998, hereafter T98; Weiner *et al.* 2001). If any of the HVCs are at distances on the order of 1 Mpc they should not be detectable, as the cosmic ionizing background is too low; therefore, any detection of Hα emission brings the HVCs within the extended Galactic Halo. Hα observations of HVCs with known distances also provide insight into how the ionizing radiation escapes from the Galactic disk, other ionization processes present in the Galactic halo, and the nature of the halo/IGM interface.

2. Results

A summary of our results is shown in Table 1; the non-detections are given in Putman *et al.* (2003, hereafter P03). The objects are grouped in terms of their high-velocity classification and are named either by their traditional name or by their classification in Putman *et al.* (2002, hereafter P02), which is the type of cloud (CHVC = Compact HVC, :HVC = slightly more extended than a CHVC, HVC = extended HVC, or XHVC = a HVC which has HI emission that merges with Galactic velocities), followed by the intensity weighted Galactic longitude and latitude and the central LSR velocity. The HI properties are from P02 (excluding the northern targets which are from the LDS (e.g. Complexes H and M)) and are always taken along the sightline of the Hα observation. The results of T98 and Tufte et al. (2002; hereafter T02), and Bland-Hawthorn *et al.* (1998, hereafter B98) are also included in Table 1. The columns of Table 1 are: ℓ and b coordinates of the Hα observation, HVC name, HI column density, HI velocity (LSR), the extinction corrected Hα emission measure with W or D in parentheses if the result is from WHAM or the DBS respectively, the value of the Hα emission measure before the extinction correction, and the predicted distance to the HVC based on its ℓ, b, and extinction corrected emission measure.

A detailed discussion of the observations and detections is given in P03. We find that there is a close relationship between HI velocity and Hα velocity and no correlation between the Hα emission measure and HI column density. This is what would be expected if the outer skin of the HVC is being ionized by an external ionizing radiation field. The non-detections span the entire range of high velocities and HI column densities – there does not currently seem to be a lower or upper column density cutoff. There is also no relationship between the strength of the Hα emission and the velocity of the HVC (in the LSR or GSR reference frame). Pictures and spectra of most of the high-velocity complexes are shown in Putman (2000); an example detection is shown in Fig. 1.

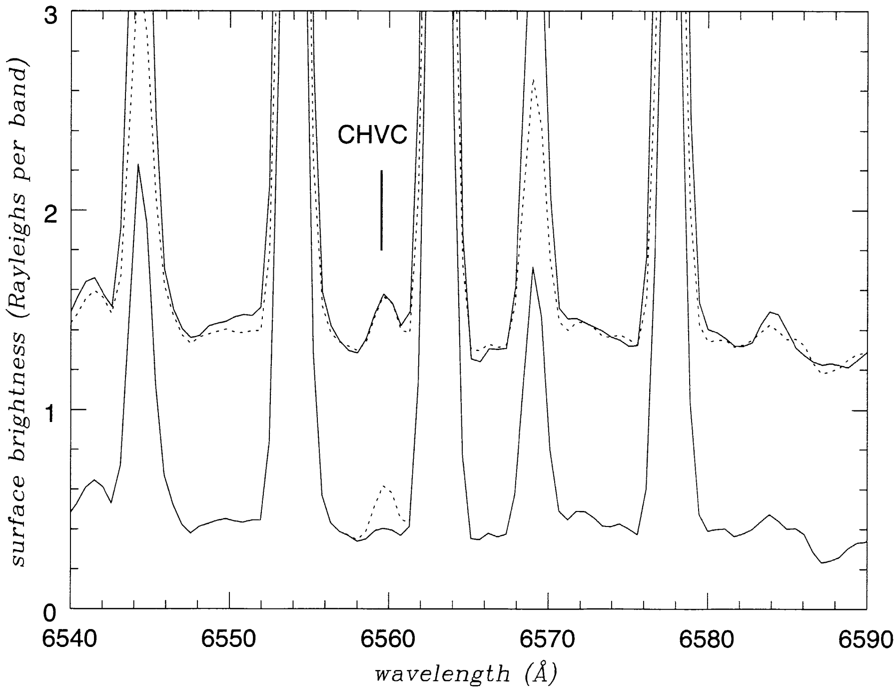

Figure 1. DBS spectrum of CHVC197.0-81.8-184 showing Hα emission at the level of 220 mR. The top spectrum is the CHVC observation (solid line) with the sky observation with a gaussian fit at the velocity and Hα strength of the CHVC overplotted (dashed line). The bottom plot shows the sky spectrum with the gaussian fit to the Hα detection shown as the dashed line.

3. The Hα Distance Constraint

The Hα distance constraint is based on photoionizing radiation escaping from the Galactic disk and ionizing the surface of HI clouds within the Galactic halo (B98). It relies on our knowing the strength and morphology of the halo ionizing field, and can be affected by a cloud's covering fraction, topology, and orientation to our line of sight (B02). Variations in Hα brightness across a single HVC may be due to these issues, and we stress that the Hα brightest point on the HVC (i.e. the point on the cloud receiving the most ionizing photons from our Galaxy) is the measure that should be used when estimating the HVC distance. Since we will not know if we have observed the brightest point on a particular HVC until we are able to do large scale Hα mapping of each cloud, our far field distance estimates in Table 1 currently serve as upper limits. Several HVCs with strong direct distance contraints (see Wakker (2000) for a summary) have now been detected in Hα by WHAM (T98), Weiner *et al.* (2001), and this survey. There is also an IVC (Complex K; Haffner *et al.* 2001) that has been completely mapped in Hα emission and has a distance constraint. The Hα emission measures from these clouds are consistent with the model predictions of B99 – updated in B02 to include spiral arms – which uses an escape fraction normal to the disk of $\hat{f}_{\rm esc} = 6\%$ ($f_{\rm esc} \approx 1 - 2\%$ averaged over 4π sr). The escape fraction used in the B02 spiral arm model has been adopted since it gives roughly the right Hα emission measures for Complex A, M, C, and the IVC, Complex K, for the observed distance brackets. It has a factor of two uncertainty which could affect the predicted distances listed in Table 1 by 50%. The halo ionization field is very different for a dusty spiral versus an exponential disk within 10 kpc of the Galactic disk (B02).

All of the HVCs detected in Hα emission would be at distances within 40 kpc in the context of this model. The detection of two CHVCs indicates that some fraction of this population falls within the extended Galactic halo. This is supported by the CHVC detections of T02. These CHVCs would be within $\sim$13 kpc using this distance determination method. The model prediction for a radius vector towards Complex L is shown in Fig. 7 of P03. Note that the spiral arm model predicts that Complex L lies directly over a spiral arm, but there is a near and far field solution, depending on its exact position. There is some indication that HVCs along sightlines over spiral arms are brighter, *e.g.* Complex K. This is expected for clouds within about 10 kpc (B02), but more sightlines are needed to confirm this.

Though the detection of Hα emission argues for HVCs being within the Galactic halo, the brightness of the Magellanic Stream detections needs to be understood before the distance constraint can be considered fully reliable (see Bland-Hawthorn & Putman 2001, hereafter B01). We also note that Complex L and GCP (the Smith Cloud) not only have high Hα emission measures (which makes sense, as they most likely lie inside the solar circle above the spiral arms), but also elevated [NII]/Hα emission. The [NII] emission may be an indication of enhanced electron temperatures (Reynolds, Haffner & Tufte 1999), rather than the presence of an alternative source of ionization (*e.g.* shocks). There are a variety of ways to produce this effect (*e.g.* photoelectric heating (Wolfire *et al.* 1995)), and the enhanced low-ionization emission is also seen in the high latitude gas of spirals (Haffner *et al.* 1999; Veilleux *et al.* 1995; Miller & Veilleux *et al.* 2003). In essence, we can use the elevated [NII]/Hα to argue that some HVCs are more than several kiloparsecs from the plane, and comprise part of the extended ionized atmosphere seen in external galaxies. Further support comes from HI structure of these clouds, each of which show possible extensions into Galactic HI.

4. Do non-detections correspond to large distances?

If the Hα normalization to local HVCs is valid, this may indicate that some HVCs which are faint or undetected in Hα, particularly those at high latitude, are dispersed throughout the extended halo on scales of 50 kpc or more. The cosmic ionizing background radiation ($\sim 10^4$ phot/s; Maloney & Bland-Hawthorn 1999) would correspond to a 5 mR Hα detection and would only begin to dominate over the Galactic ionizing radiation field approximately 100 kpc from our Galaxy. Considering the Hα upper limits in some cases and the variations in in-

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tensity across the HVCs, it remains to be seen whether most of the clouds which have non-detections are actually at large distances from the Galactic Plane. Hα mapping across an entire HVC to find the brightest Hα emission, higher resolution HI observations to clarify the column density at the position of the Hα observation, and the development of models of the escape of ionizing radiation from the Galactic Plane will help resolve the non-detection issue. It may be that some clouds will remain undetected in certain directions if they lie at too low an angle from our viewpoint, or do not lie above spiral arms or HII regions. Shadowing and the size of the TAURUS beam may also be important considerations. There may be an *observed* relationship between the strength of $\mathcal{E}_m$ and the position of the cloud above the Galaxy, as clouds at $\ell > 330°$ and $\ell < 60°$ have a slight tendency to be brighter and clouds between $\ell = 250 - 320$ remain largely undetected. This is expected from their line of sight over the Galaxy (see Taylor & Cordes 1993) and from the B02 model.

5. What is ionizing the Magellanic Stream?

The Stream is brightest at the South Galactic Pole and fainter towards the head and tail. This would be expected for halo gas ionized by an opaque disk where ionizing photons escape preferentially along the Galactic poles (B99). The match between the HI velocity and the Hα velocity for all clouds supports photoionization. However, if ionizing photons from the Galaxy are reaching HVCs at distances of $\sim$10 kpc, why are Stream positions near the South Galactic Pole, which most likely lie at distances between 20 – 100 kpc (Gardiner 1999; Moore & Davis 1994), consistently brighter than the HVCs? At a mean Stream distance of 55 kpc, the expected emission measure of a flat HI stream is 30–50 mR (B02), an order of magnitude fainter than the brightest detections. The contribution from the LMC will not play a dominant role in ionizing the majority of the Stream. It seems likely that another mechanism must be at play in the Stream.

Is it possible that sections of the Stream are just that much closer to the Galaxy disk than the Magellanic Clouds? With the detection of the head of the Stream (Fairall 9 sightline), this possibility seems unlikely, as the head of the Stream is presumed to be close to the Magellanic Clouds (50-60 kpc). Thus the distances predicted in Table 1 for the Stream sightlines are not relevant and we need to look for another source of ionization in the Stream. The detection of O VI absorption in and around the Stream may provide some clues (Sembach *et al.* 2003). Interaction with a halo medium could provide some pre-ionization which could elevate the Stream's Hα. The outer halo medium may well be clumpy, particularly at the poles, from the leftovers of other satellites or from self-interaction of the Stream (B01; P03). CHVC197.0-81.8-184 may represent some of this debris. This CHVC is only 10° from the main filament of the Stream and is as Hα bright as the Stream, possibly indicating a large spread of debris associated with Stream's Hα emission. Two of the T02 detected CHVCs may also represent the spread of ionized Stream debris.

Another possibility is that there are stars associated with the Stream which have yet to be detected. Recent results have found small isolated HII regions in interacting systems that can be ionized by a few O stars (*e.g.* Gerhard *et* *al.* 2002; Ryan-Weber *et al.* 2003). This indicates that isolated star formation can be triggered in low density interactive debris, which could in turn play an important role in ionizing this material. A single massive O star 1 kpc from the Stream could lead to an emission measure of 40 mR. If the star was actually embedded in the Stream this contribution would obviously be much higher. White dwarfs would not significantly contribute to the ionization of the Magellanic Stream unless their density was much higher than that found in the solar neighborhood (Bland-Hawthorn, Freeman & Quinn 1997). Thus far, only limited areas of the Stream have been surveyed for stars. Ongoing and future stellar surveys will provide further insight into the possibility of the Stream harboring young, ionizing stars.

6. Overview

Our Hα observations are a combination of detections and non-detections on clouds with HI column densities greater than a few times 10^{18} cm^{-2}. This represents the complex nature of the ionized component of HVCs and the importance of mapping across an entire cloud before accepting a non-detection as meaningful for the entire high-velocity complex. The results thus far show a population of clouds which appear to extend out of Galactic HI emission, are Hα bright, and show an elevated [NII]/Hα ratio, as well as an undetected population which tend to be in a specific region of Galactic longitude and are relatively isolated from Galactic emission. The detection of several CHVCs in both this paper and the T02 paper indicates that many of these clouds are indeed within the Galactic halo. The non-detections of some CHVCs cannot be used to argue for a greater distance until the origin of the non-detections in other complexes is understood.

The Hα emission measures of the clouds with distance constraints are consistent with the surfaces of the clouds being ionized by $\sim$ 6% of the Galaxy's ionizing photons. All of the clouds detected here are within 40 kpc of our Galaxy based on their level of Hα emission. The Magellanic Stream appears to fall into a different category than the currently detected HVCs, with bright Hα emission but little or no [NII] emission, possibly due to the lower metallicities of the Magellanic Clouds compared to the Galaxy. The strength of the Hα emission cannot be easily explained by photoionization from the Galaxy alone, and it is possible that interaction with halo debris, or the presence of yet unassociated young stars, is partially responsible for the Stream's elevated Hα emission. Through future Hα observations which include mapping head-tail HI clouds, the length of the Magellanic Stream, OVI absorption sightlines, and complexes of known distance, and the development of models which trace the path of the escaping photons from the Galactic Plane, we may come to a consensus on the origin of the Hα emission in all high-velocity clouds.

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TABLE OF Hα EMISSION LINE RESULTS, HI PROPERTIES, AND DISTANCES TO DETECTED HVCS

Obs. ℓ b	Common[a] Name	N_{HI} (10^{19} cm^{-2})	V_{lsr} (HI)	E_m[b] (mR)	$E_{m(obs)}$[c] (mR)	D_{mod}[d] (kpc)
295.1−57.8	MS I (Fairall 9)	9.5	191	128(D)	120*	0.5 - 25.7
304.0−68.3	MS Ib	29.0	81	99	95	0.5 - 33.2
342.6−79.6	MS IIa	11.1	-120	407	386	1.7 - 9.7
342.2−79.9	MS IIa	3.4	-116	228(D)	220	0.8 - 19.9
297.5−42.5	Bridge M	98.3	166	3796	3240	-
040.3−15.1	Smith2[f]	16.0	86	450	300	1.2 - 12.7
040.6−15.5	Smith1[f]	15.1	94	360	240	1.2 - 13.4
130.8+00.9	Complex H[g]	18.2	-200	3697	150	-
170.9+64.7	Complex M W6	-	-	150	140*	1.7 - 9.6
163.3+66.7	Complex M W2	11.7	-101	203	190*	2.2 - 6.7
341.8+31.3	Complex L2[h]	1.6	-146	263	168	0.5 - 19.9
343.2+32.1	Complex L3	3.6	-136	499	320	0.6 - 15.2
343.1+32.0	Complex L4	3.4	-142	309	197	0.6 - 19.0
343.2+31.9	Complex L5	3.4	-145	637	406	0.7 - 11.2
343.4+32.0	Complex L6	2.3	-138	639	407	0.7 - 11.1
153.6+38.2	Complex A[i]	1.3	-177	108(W)	90	1.6 - 5.0
084.3+43.7	Complex C[i]	0.54	120	133(W)	130	1.9 - 14.2
310.9+44.4	HVC310.5+44.2+187	0.37	187	99(D)	80*	0.4 - 27.5
322.0−15.8	HVC321.7-16.0+113	1.7	113	125(D)	100	0.5 - 18.5
104.2−48.0	:HVC104.2-48-168[i]	0.6	-170	39(W)	32	1.1 - 27.8
118.5−58.2	CHVC118.2-58.1-373[i]	3.1	-374	152(W)	140	1.9 - 10.6
119.2−30.8	CHVC119.2-31.1-384[i]	1.1	-386	24(W)	20	1.3 - 13.2
158.0−39.0	CHVC157.7-39.3-287[i]	0.5	-284	147(W)	130	1.7 - 4.3
197.4−81.8	CHVC197.0-81.8-184	2.7	-184	227(D)	220	1.4 - 12.9
266.0−18.7	CHVC266.0-18.7+336	1.42	336	190(D)	140*	1.2 - 6.1
285.9+16.6	XHVC287.6+17.1+111	0.7	111	241(D)	180	0.8 - 9.9

[a] MS refers to a Magellanic Stream complex (Mathewson et al. 1977), Smith is also Complex GCP, many objects are named with their catalog name from P02. [b] The emission measure in milliRayleighs (mR) has D in parentheses if the result is from the Double Beam Spectrograph at the MSO 2.3m, and W for the Wisconsin Hα Mapper (WHAM); all other observations are from Taurus at the AAT 3.9m. All values are extinction corrected. [c] E_m before the extinction correction. The characteristic detection errors are 10 mR, unless noted with a ∗. The ∗ indicates that the Hα line is within 2Å of a skyline and the errors are between 15 - 30 mR. [d] Modeled distance based on E_m, the HVC position and the model described in B02 ($\hat{f}_{\rm esc}$ = 6% normal to the disk). There is a near and far field solution based on the location of the HVC over the spiral arms. The error on the distance is generally less than 0.5 kpc for the near field solutions and less than 4 kpc for the far field solutions and this incorporates the difference in using E_m or $E_{m(obs)}$. Exceptions where the errors on the far field solutions are ∼9 kpc include :HVC104.2-48-168 and CHVC119.2-31.1-384. Plots of the model predictions and specific error values can be found at ftp://www.aao.gov.au/pub/local/jbh/disk_halo. [f] Results published in B98. [g] Unable to model distance because of location in Galactic Plane. The dust correction may not be applicable at such low latitudes. [h] Weighted average for Complex L is $E_{m(obs)}$=300 mR. [i] Emission line results from T98 and T02.

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