Hα EMISSION FROM HIGH-VELOCITY CLOUDS AND THEIR DistANCES

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ABSTRACT

We present deep Hα spectroscopy towards several high-velocity clouds (HVCs) which vary in structure from compact (CHVCs) to the Magellanic Stream. The clouds range from being bright (~640 mR) to having upper limits on the order of 30 to 70 mR. The Hα measurements are discussed in relation to their Hβ properties and distance constraints are given to each of the complexes based on \( f_{\text{esc}} \approx 6\% \) of the ionizing photons escaping normal to the Galactic disk (\( f_{\text{esc}} \approx 1-2\% \) 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. However, the Magellanic Stream is inconsistent with this model and needs to be explained. It has bright Hα emission and little [NII] emission and appears to fall into a different category than the currently detected HVCs. This may reflect the lower metallicities of the Magellanic Clouds compared to the Galaxy, but the strength of the Hα emission cannot be explained solely by photoionization from the Galaxy. The interaction of the Stream with halo gas or the presence of yet unassociated young stars may assist in ionizing the Stream.

Subject headings: Galaxy: halo – galaxies: individual (Magellanic Stream) – galaxies: ISM, intergalactic medium – cosmology: diffuse radiation

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 leftovers 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 & Wolfe 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 Hα 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 (Tuft et al. 1998; hereafter T98). 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.

In this paper we present HVC optical line emission observations to investigate the relationship between HVCs and the Galaxy. The paper begins by summarizing the Fabry-Perot and long slit Hα observations in §2, and presents the results of the observations in §3. In §4-5, we discuss our findings and interpret them in the context of the location and environment of the HVCs. The ionization of the Magellanic Stream is considered in §6 and an overview of the results is presented in §7.

2. OBSERVATIONS

The Fabry-Perot Hα observations were obtained in five Anglo-Australian Telescope (AAT) observing runs from December 1997 - June 1999 and one William Herschel Telescope (WHT) run in January 1999. At both sites, the TAURUS-2 interferometer was used in conjunction with the University of

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of Maryland 44μm etalon. Single orders of interference were isolated using 4-cavity blocking filters with high throughput (80–90%) and bandpasses well matched to the etalon free spectral ranges. The focal plane was baffled to give either a 10′ or, on the WHT (northern objects), a 5.0′ field. The resulting pattern covered about 45Å (Hα) at the AT&T and 20Å (Hα) at the WHT. The resolution is 1Å (or 46 km s⁻¹ at Hα). The repeated exposures were generally 10–20 minutes. A deep sky exposure was also made in a region 5°–20° away from the cloud, at a position that does not contain any high-velocity Hα based on HIPASS limits (< 2 × 10¹⁸ cm⁻²). The reduction and analysis is discussed in Bland-Hawthorn et al. (1998; hereafter B98).

HVCs and corresponding deep sky exposures were also observed with the Double Beam Spectrograph (DBS) on the Siding Spring Observatory 2.3 m telescope over 5 observing runs from August 1998 - April 2000. The DBS was set up with a 7′ long slit and a slit width of 2′, yielding a spectral resolution of 0.57 Å (26 km s⁻¹ at Hα). Spectral reduction was done using the VISTA and IRAF reduction packages. The two-dimensional spectra from the large sets of exposures obtained on target and sky were each reduced separately. The procedure involved bias subtraction using both bias frames and the overscan area on each exposure, flatfielding using QI lamp exposures, and cosmic ray removal with a 2.5-sigma rejection.

The resulting ring of sky lines in the object’s spectrum (only possible with the red order) and the NeAr lamp spectra obtained at the same air mass as, and immediately before or after, the object’s exposure. The spectra were put on an absolute flux scale using the spectra of flux standards obtained throughout the night. Each object’s exposures were added together after aligning the spectra using the closest skyline to the expected emission from the HVC as a guide. An example of a DBS spectrum is shown in Figure 1.

We examined the deep sky exposures closely for signs of Hα emission at a velocity similar to the closest detectable Hα and found no indication of emission. This was especially important to check considering the OVI that has been detected in absorption at the velocities of nearby HVCs, but off the Hα contours of these clouds (Sembach et al. 2003), and the extended low Hα column density emission found around cataloged HVCs (Lockman et al. 2002). We assume foreground Galactic extinction along a given sight line, measured from the COBE/DIRBE maps (Schlegel et al. 1998), and therefore correct all Hα emission measures (Eα) for dust extinction. We also include the uncorrected Eα values in Tables 1 and 2, as the dust correction may not be realistic for the low latitude clouds. Eα upper limits quoted throughout this paper are 2-sigma for the TAUROS data and 3-sigma for the DBS data. Our characteristic detection errors are approximately 10 mR if the Hα detection is at least 2Å from a skyline, but close to a skyline the errors can reach 15-30 mR. Future use of the nod+shuffle technique (Glazebrook & Bland-Hawthorn 2001) with the Fabry-Perot staring method may be able to reach levels of ~5 mR.

Many of the observed HVCs were first identified by HIPASS (see Putman et al. 2002a; hereafter P02). This is especially true of the CHVCs. The clouds observed were chosen because they have: Hα velocities which isolate an equivalent velocity Hα line from the skylines, a proposed extragalactic nature (e.g. the CHVCs), and/or an estimate has been made of their distance and/or origin (e.g. Complex M, Magellanic Stream). In the latter case, the observations could be used to clarify the nature of the Hα emission. Several positions observed by Weiner & Williams (1996; hereafter WW96) and T98 were repeated to compare observing and reduction methods.

3. RESULTS

The results of the observations are described in Table 1 and 2. Table 1 lists the positive detections and Table 2 the non-detections. The objects are grouped in terms of their high-velocity classification and are named either by their traditional name or by their P02 classification, which is the type of cloud (CHVC = Compact HVC, CHVC = slightly more extended than a CHVC, HVC = extended HVC, or XHVC = a HVC which has Hα emission that merges with Galactic velocities), followed by the intensity weighted Galactic longitude and latitude and the central LSR velocity. The Hα 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 B98, T98, and Tufte et al. (2002; hereafter T02) are also included in Table 1. The columns of Table 1 are: l and b coordinates of the Hα observation, HVC name, Hα column density, Hα velocity (LSR), Hα velocity width, 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, the [NII]λ6583/Hα ratio, the velocity of the Hα detection (LSR), and the predicted distance to the HVC based on its l, b, and extinction corrected emission measure (see §4). Some of the [NII]/Hα ratios are not included due to the observation not including the wavelength of the [NII]λ6583 line (i.e. the WHT and WHAM observations). Table 2 does not include the [NII]/Hα ratio or the predicted distance (see §5), but does include two limits on [OIII] emission.

The close relationship between Hα velocity and Hα velocity is shown in Figure 2 and the complete lack of correlation between the Hα emission measure and Hα column density is shown in Figure 3. This is what would be expected if the outer skin of the HVC is being ionized by an external ionizing radiation field. Figure 2 also shows that non-detections (open diamonds) span the entire range of high velocities. Though not shown, 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). Figure 3 shows that undetected clouds span the entire range of Hα column densities, i.e. there does not currently seem to be a lower or upper column density cutoff. The distribution of the Hα detections and non-detections on the sky in Galactic coordinates is shown in Figure 4, and a large number of the Hα observations are depicted on the Hα map of the Magellanic System shown in Figure 5. We now discuss the specific detections listed in Table 1 and the undetected clouds listed in Table 2. Pictures and spectra of most of the high-velocity complexes are shown in Putman (2000).

3.1. Detections

Complexes: Several of the HVCs detected in Hα are part of larger complexes which are defined by Wakker & van Woerden (1991). The Hα brightest of these is Complex L, a negative velocity HVC made up of several clumpy filaments, with several small clouds scattered amongst the filaments. The cloud mapped here is HVC341.6+31.4-142 in the P02 catalog and the brightest emission lies closest to the head of the cloud. Complex...
complex L has a highly elevated [NII]/Hα ratio (2.7). Along with the detections there was one non-detection in a very low column density (∼10^{18} \text{ cm}^{-2}) part of Complex L. All of the positions with bright detections have column densities between 1.6 - 3.6 \times 10^{19} \text{ cm}^{-2}.

The other detected complexes are: Complex M, which has an upper distance constraint of < 4 kpc (Ryans et al. 1997) and was detected at a similar level by T98, Complex H, which lies along the Galactic Plane making this detection more tentative (especially since the Hα velocity is offset by 30 km s^{-1} from the H\textsc{i} velocity), and Complex GCP (Smith Cloud) which was originally presented in B98 and now has a limit on the [OIII] emission at the position of Smith1 (< 70 mR; Table 2). We include the T98 detections of Complexes A and C with a model distance because they have direct distance limits of 4-10 kpc (van Woerden et al. 1999) and > 6 kpc (Wakker 2001), respectively.

The Magellanic Stream: The Magellanic Stream shown in Figure 5 is the result of the interaction of the Large and Small Magellanic Cloud with each other and the Galaxy. It trails the Magellanic Clouds for over 100◦ from head to tail (relative to the Local Standard of Rest; 400 km s^{-1} relative to the Galaxy). The Stream is a complicated network of filaments and clumps, but remains relatively continuous along its entire length (see Putman et al. 2003; hereafter P03). Stars have not yet been found in the Stream (e.g. Guhathakurta & Reitzel 1998), but Hα emission has been previously detected by WW96 at the level of 200 - 400 mR.

We observed several positions along the Magellanic Stream, including one repeat of a WW96 observation, with both TAU-RUS and the DBS. The repeat observation of MSIIa is approximately the same as WW96 with TAURUS, but is lower with the DBS. This could be due to the difference in the field of view of TAURUS and the DBS (a 10′ diameter FOV versus a 7′ × 2′ slit). [NII] was also detected and the ratio to Hα is low compared to the Smith Cloud and Complex L (0.15 vs. 0.6 - 2.7). MSIIa was subsequently observed in [OIII]λ5007 and no detection was obtained (< 52 mR; Table 2). As tabulated in Table 1, a new relatively weak Hα detection was made at the head of the Stream, (ℓ, b) = 304°, -67°, and at the position of the background QSO Fairall 9 where OVI absorption has also been detected (10^{14.3} \text{ cm}^{-2}; Sembach et al. 2003). There was also a non-detection at (ℓ, b) = 293.4°, -56.4° and at the tail of the Stream (MSV; (ℓ, b) = 96.5°, -53.9°) as tabulated in Table 2. As shown in Figure 5, there are large variations in the strength of the Hα emission along the Stream’s length, and so far there does not seem to be a correlation with the H\textsc{i} column density (Figure 3). However, one should consider that the beam used in the Hα observations is larger than the FOV of TAURUS (15.5′ vs. 10′). Though the number of observations remains limited, there also does not seem to be a gradient of Hα brightness along the Stream. Currently, the brightest detection is approximately at the South Galactic Pole in a region of complexity in terms of the high-velocity H\textsc{i} gas distribution (P03). The velocities of the H\textsc{i} and Hα lines generally closely agree (within ∼10 km s^{-1}; Figure 2). Several positions along the Magellanic Bridge and Leading Arm were also observed. All of the pointings were non-detections (see Table 2 and Figure 5), except for an extremely bright observation at the position of a known OB association (Bridge M in Table 1; see also Marcelin et al. (1985)).

Compact High-Velocity Clouds (CHVCs): Two compact high-velocity clouds (CHVCs) were detected with the DBS. CHVC197.0-81.8-184 is located ∼10° from the Stream where it passes through the South Galactic Pole (see Figure 5). The Hα detection of this cloud (Fig. 1) is at the level of many of the Stream detections. The second CHVC is a very small and isolated cloud located in the region leading the LMC (Figure 5). CHVC266.0-18.7+336 has a velocity which places the Hα line at the edge of a skyline, making the brightness of this detection somewhat less certain. The CHVC detections of T02 with model distances are also included in Table 1.

3.2. Non-Detections

There are several clouds which were not detected in this survey and are summarized in Table 2. Some of these clouds have detections reported in the conference proceedings of Weiner et al. (2001), but the precise coordinates of their observations have not yet been reported. This is not unusual considering the range of detections and non-detections noted in the previous section within the same high-velocity complex. Many of the HVCs which we have only non-detections for lie in approximately the same region of the sky (see Figure 4). The undetected clouds mostly lie in the Galactic Longitude range of ℓ = 250° - 320°, and include the length of the Leading Arm of the Magellanic System (Figure 5), several HVCs and CHVCs, and part of the Extreme Positive Velocity Complex. We note that many of these clouds (marked with a * in Table 2) have velocities that place the Hα line close to a skyline, making the non-detections somewhat less certain.

Additional non-detections include the high positive velocity cloud HIPASS J1712-64 (Kilborn et al. 2000) which has an Hα upper limit of 44 mR, and the clouds associated with the Sculptor dSph galaxy by Carignan et al. (1998) (cataloged as CHVC286.3-83.5+091 and CHVC290.6-82.8+095 in P02). It is unclear if these clouds are actually associated with the Sculptor dSph. The Hα maps of P03 and Carignan (1999) show the complexity of this region in high-velocity gas, with a high concentration of clouds at similar and very different velocities to the Sculptor dSph. There is an undetected negative velocity XHVC at approximately -145 km s^{-1} along our observed sightline to the clouds associated with the Sculptor dSph, as well as a nearby positive velocity XHVC, which was also undetected.

4. The Hα distance constraint

The Hα distance constraint is based on photoionizing radiation escaping from the Galactic disk and ionizing the surface of H\textsc{i} 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 constraints (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 pre-
dictions of B99 – updated in B02 to include spiral arms – which uses an escape fraction normal to the disk of $f_{\text{esc}} = 6\%$ ($f_{\text{esc}} \approx 1-2\%$ averaged over $4\pi$ sr). The escape fraction used in the B02 spiral arm model has been adopted based on its agreement with the direct distance determinations and H$\alpha$ emission measures for Complex A, M, C, and the IVC, Complex K. It has a factor of two uncertainty which could affect the predicted distances listed in Table 1 by 50%. Figure 6 shows the effect of using a model with spiral arms compared to exponential and uniform disk models. The halo ionization field is very different for a dusty spiral versus an exponential disk within 10 kpc of the Galactic disk.

All of the HVCs detected in H$\alpha$ 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 ~13 kpc using this distance determination method. The model prediction for a radius vector towards Complex L is shown in Fig. 7. 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, as expected for clouds within about 10 kpc (B02), but more sightlines are needed to confirm this.

Though the detection of H$\alpha$ 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 §6 and Bland-Hawthorn & Putman 2001, hereafter B01). We also note that Complex L and GCP (the Smith Cloud) not only have high H$\alpha$ emission measures (which makes sense, as they most likely lie inside the solar circle above the spiral arms), but also elevated [NII]/H$\alpha$ emission. The [NII] emission may be an indication of enhanced electron temperatures (Reynolds, Haffner & Tuft 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 2003a, 2003b). In essence, we can use the elevated [NII]/H$\alpha$ 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 H$\alpha$ structure of these clouds, each of which show possible extensions into Galactic H$\alpha$.

5. DO NON-DETECTIONS CORRESPOND TO LARGE DISTANCES?

If the H$\alpha$ normalization to local HVCs is valid, this may indicate that some HVCs which are faint or undetected in H$\alpha$, 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 $5\, \text{mR\,H} \alpha$ detection and would only begin to dominate over the Galactic ionizing radiation field approximately 100 kpc from our Galaxy. Considering the H$\alpha$ upper limits in some cases and the variations in intensity 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. H$\alpha$ mapping across an entire HVC to find the brightest H$\alpha$ emission, higher resolution H$\alpha$ observations to clarify the column density at the position of the H$\alpha$ 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 TAUURUS beam may also be important considerations. There may be an observed relationship between the strength of $E_\text{msg}$ and the position of the cloud above the Galaxy, as clouds at $\ell > 330^\circ$ and $\ell < 60^\circ$ have a slight tendency to be brighter and clouds between $\ell = 250 - 320$ remain largely undetected (Figure 4). This is expected from their line of sight over the Galaxy (see Taylor & Cordes 1993) and from the B02 model.

6. 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 H$\alpha$ velocity and the H$\alpha$ velocity for all clouds supports photionization. However, if ionizing photons from the Galaxy are reaching HVCs at distances of ~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? As shown in Figure 8, at a mean Stream distance of 55 kpc, the expected emission measure of a flat H$\alpha$ stream is 30–50 mR (B02), an order of magnitude fainter than the brightest detections. Figure 8 also shows that the contribution from the LMC will not play a dominant role in ionizing the majority of 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 H$\alpha$. 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$^\circ$ from the main filament of the Stream and is as H$\alpha$ bright as the Stream, possibly indicating a large spread of debris associated with Stream’s H$\alpha$ emission. Two of the T02 detected CHVCs (shown in Fig. 5) 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 possi-
bility of the Stream harboring young, ionizing stars.

7. OVERVIEW

The Hα observations presented here are a combination of
detections and non-detections on clouds with H I column den-
sities greater than a few times 10¹⁸ cm⁻². This represents the
complex nature of the ionized component of HVCs and the im-
portance of mapping across an entire cloud before accepting a
non-detection as meaningful for the entire high-velocity com-
plex. The results thus far show a population of clouds which
appear to extend out of Galactic H I 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 lon-
gitude and are relatively isolated from Galactic emission. The
detection of several CHVCs in both this paper and the T02 pa-
per 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 con-
straints are consistent with the surfaces of the clouds being ion-
ized by ~ 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 com-
pared 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 pres-
ence of yet unassociated young stars, is partially responsible
for the Stream’s elevated Hα emission. Through future Hα
observations which include mapping head-tail H I 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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Fig. 1. DBS spectrum of CHVC197.0-81.8-184 showing H$\alpha$ 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 H$\alpha$ strength of the CHVC overplotted (dashed line). The bottom plot shows the sky spectrum with the gaussian fit to the H$\alpha$ detection shown as the dashed line.

Fig. 2. The relationship between the H$\alpha$ and H$\text{I}$ velocity for all of the recently published HVC H$\alpha$ observations (this paper; WW96; T98; B98; T02). Crosses show the detections, diamonds the non-detections in H$\alpha$, and the triangle is the one high-velocity detection in H$\alpha$ but not H$\text{I}$ on the edge of Complex M (T98).
Fig. 3. The relationship between the Hα emission measure and the H I column density for the same data shown in Figure 2. Detections are represented by crosses and non-detections are represented by open diamonds. The Hα emission measures are NOT extinction corrected. Using the extinction corrected values does not greatly change this plot, as can be noted from the values listed in Table 1 and 2.
Fig. 4. The distribution of Hα detections (solid symbols) and non-detections (open diamonds) of the same data shown in Fig. 2 in Galactic coordinates.
Fig. 5. An H\textsc{i} map of the Magellanic System showing column densities greater than $2 \times 10^{18}$ cm$^{-2}$ (P03), with the H\textalpha{} detections and non-detections labeled as diamonds and circles, respectively. The size of the diamond represents the relative strength of the H\textalpha{} detection. The positions and strengths of the H\textalpha{} observations were labeled by eye, and are for general reference only. The detections include this work, the WW96 observations, and two of the CHVCs detected by T02 which are located near the northern tip of the Magellanic Stream.
Fig. 6. The halo ionizing flux for different disk distributions (uniform emissivity, exponential and spiral) compared to a simple inverse square law. The vertical distance is measured from the center of the disk along the polar axis. The top three curves are in the absence of dust and converge in the far field limit. The lower three curves include the effects of dust where $\tau_{LL} = 2.8$ ($f_{esc} = 6\%$).

Fig. 7. Predicted run of emission measure (in mR) as a function of radius (in kpc) along our sight line to Complex L. The light shaded model is the H\alpha signal due to an exponential disk of ionizing sources; the dark shading is for the spiral arm model. The horizontal line shows our brightest observed $E_m$ for Complex L. Note the spiral arm model can produce multiple solutions depending on the location of the HVC above the Galaxy. [We note that Weiner et al. (2001) detect emission measures of $\sim$1 R for a different cloud in Complex L, indicating the near field solution (above a spiral arm) is correct.] Plots of the model predictions for the other detected HVCs can be found at [ftp://www.aao.gov.au/pub/local/jbh/disk_halo]
Fig. 8 The predicted Hα emission measure along the Stream as a function of polar angle $\delta$ in units of log(mR) where $\delta = 90^\circ$ is the South Galactic Pole. The roman numerals refer to the specific Magellanic Stream complex defined by Mathewson et al. (1977). See P03 for the definitions of these complexes on the map shown in Figure 5. The short dashed curve includes the contribution of the LMC; the dotted curve includes the contribution of a UV-bright stellar bulge. The solid curve includes the effect of the LMC and a stellar bulge.
| Obs. | Commona | Name (10^{-19} cm\(^{-2}\)) | V\(_{lsr}\) (km s\(^{-1}\)) | \(\Delta V\) (km s\(^{-1}\)) | E\(_m\) (mR) | E\(_{obs}\) (mR) | [NII]/H\(\alpha\) | V\(_{lsr}\) (km s\(^{-1}\)) | D\(_{mod}\) (kpc) |
|------|----------|-----------------------------|-----------------------|---------------------|-----------|-----------|-------------|-----------------|------------------|
| 295.1+57.8 | MS I (Fairall 9) | 9.3 | 194 | 52 | 124(D) | 120 | < 0.25 | < 0.25 | < 0.25 |
| 304.0+68.3 | MS Ib | 29.0 | 81 | 54 | 296 | 280 | 0.3 - 3.3 |
| 342.6+79.6 | MS IIa | 11.1 | -120 | 37 | 407 | 386 | 0.15 | < 1.4 | < 1.4 |
| 342.2+79.9 | MS IIa | 3.4 | -116 | 34 | 228(D) | 220 | < 0.18 | < 0.18 | < 0.18 |
| 297.5+42.5 | Bridge M | 98.3 | 166 | 66 | 3796 | 3240 | 0.05 | 0.05 | 0.05 |
| 040.3-15.1 | Smiths | 16.0 | 86 | 38 | 450 | 300 | 0.60 | 0.60 | 0.60 |
| 040.6-15.5 | Smiths | 15.1 | 94 | 47 | 360 | 240 | 0.60 | 0.60 | 0.60 |
| 130.8+00.9 | Complex H\(\alpha\) | 18.2 | -200 | 16 | 3697 | 150 | - | - | - |
| 170.9+64.7 | Complex M W6 | - | - | - | 150 | 140 | - | - | - |
| 163.3+66.7 | Complex M W2 | 11.7 | -101 | 43 | 203 | 190 | - | - | - |
| 341.8+31.3 | Complex L2 | 1.6 | -146 | 58 | 263 | 168 | 2.5 | 2.5 | 2.5 |
| 343.1+32.0 | Complex L4 | 3.4 | -142 | 41 | 309 | 197 | 2.5 | 2.5 | 2.5 |
| 343.2+31.9 | Complex L5 | 3.4 | -145 | 39 | 637 | 406 | 2.7 | 2.7 | 2.7 |
| 343.4+32.0 | Complex L6 | 2.3 | -138 | 35 | 639 | 407 | 2.7 | 2.7 | 2.7 |
| 153.6+38.2 | Complex A\(\alpha\) | 1.3 | -177 | 23 | 108(W) | 90 | - | - | 1.6 |
| 084.3+43.7 | Complex C\(\alpha\) | 0.54 | 120 | 15 | 133(W) | 130 | - | - | 1.9 |
| 310.9+44.4 | HVC 310.5+44.2+187 | 0.37 | 187 | 40 | 99(D) | 80 | 1.3 | 1.3 | 1.3 |
| 322.0-15.8 | HVC 322.7-16.0+113 | 1.7 | 113 | 59 | 125(D) | 100 | < 0.30 | < 0.30 | < 0.30 |
| 104.2-48.0 | HVC 104.2-48.168 | 0.6 | -170 | 25 | 39(W) | 32 | - | - | 1.1 |
| 119.2-30.8 | CHVC 119.2-31.3-384 | 1.1 | -386 | 20 | 24(W) | 20 | - | - | 1.3 |
| 158.0-39.0 | CHVC 157.7-39.3-287 | 0.5 | -284 | 27 | 147(W) | 130 | - | - | 1.7 |
| 197.4-81.8 | CHVC 197.0-81.8-184 | 2.7 | -184 | 41 | 227(D) | 220 | < 0.30 | < 0.30 | < 0.30 |
| 266.0-18.7 | CHVC 266.0-18.7+336 | 1.42 | 336 | 31 | 190(D) | 140 | < 0.60 | < 0.60 | < 0.60 |
| 285.9+16.6 | XHVC 285.6+17.1+111 | 0.7 | 111 | 32 | 241(D) | 180 | - | - | 0.8 |

\(\alpha\) 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. \(\delta V\) at FWHM of HI line.

\(\beta\) The emission measure in milliRayleighs (mR) has D in parentheses if the result is from the DBS and W if the result is from WHAM. All values are extinction corrected.

\(\gamma\) Modeled distance based on E\(_m\), the HVC position and the model described in B02 (\(\hat{\phi}_{esc} = 6\%\) 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\(_{obs}\). Exceptions where the errors on the far field solutions are \(\sim 9\) 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.

\(\delta\) Weighted average for Complex L is E\(_{obs}\)=300 mR, [NII]/H\(\alpha\)=2.7, V\(_{lsr}\) = -140. \(\epsilon\) Emission line results from T98 and T02.

\(\zeta\) Velocity of this cloud places [NII]\(\lambda 6583\) right on a skyline.

Results published in B98. \(\chi\) Unable to model distance because of location in Galactic Plane. The dust correction may not be applicable at such low latitudes. \(\theta\) Weighted average for Complex L is E\(_{obs}\)=300 mR, [NII]/H\(\alpha\)=2.7, V\(_{lsr}\) = -140. \(\iota\) Emission line results from T98 and T02.
### Table of Hα Emission Limits and HI Properties of Undetected HVC Positions

| Obs. | $b$ | Commona | $N_H/ (10^{20} \text{ cm}^{-2})$ | $V_{lsr}$ (HI) | $\Delta V$ | $E_m$ (mR) | $E_m(\text{obs})^b$ (mR) | $V_{lsr}$ (Hα) |
|------|-----|----------|-------------------------------|----------------|------------|-------------|-----------------|----------------|
| 293.4–56.4 | MS I | 3.6 | 226, 158 | 25, 40 | < 59 | < 54 | < 55 | < 50 | 226, 158 |
| 342.2–79.9 | MS IIa | 3.4 | 116 | 34 | < 52[OIII] | < 52 [OIII] | -116 |
| 096.5–53.9 | MS V | 4.6 | -366 | 45 | < 153 | < 120 | -366 |
| 292.4–40.1 | Bridge1 | 50.1 | 184 | 53 | < 42 | < 35 | 184 |
| 290.2–37.6 | Bridge2 | 47.0 | 198 | 74 | < 79 | < 52 | 198 |
| 287.7–34.8 | Bridge3 | 26.8 | 204 | 41 | < 52 | < 40 | 204 |
| 291.7–32.0 | Lead Arm1 | 27.2 | 222 | 33 | < 71 | < 52 | 222 |
| 291.7–30.6 | Lead Arm2 | 19.4 | 236 | 43 | < 78 | < 52 | 236 |
| 292.1–29.7 | Lead Arm3 | 5.1 | 305 | 37 | < 30 | < 21 | 305 |
| 287.5–23.0 | Lead Arm4 | 11.3 | 238 | 36 | 70 | < 47 | 238 |
| 342.5+31.9 | Complex L1e | 0.1 | -126 | 20 | < 65 | < 43 | -126 |
| 248.5–12.2 | Pop EP1 | 0.6 | 334 | 58 | < 56 | < 16 | 334 |
| 262.7+13.5 | Pop EP2 | 1.6 | 160 | 38 | < 41 | < 26 | 160 |
| 280.1+04.0 | Pop EP3 | 6.9 | 163 | 35 | < 128 | < 35 | 163 |
| 271.2+29.4 | Pop EP4e | 0.2 | 184 | 29 | < 39 | < 30 | 184 |
| 326.5–14.6 | HIPASS J1712-64 | 0.4 | 458 | 41 | < 44 | < 30 | 458 |
| 040.6–15.5 | Smith1 | 15.1 | 94 | 47 | < 70[OIII] | < 70[OIII] | 94 |
| 039.3–13.8 | HVC039.3+13.8-233 | 3.1 | -233 | 29 | 213(D) | < 120 | -233 |
| 259.2–17.2 | HVC259.1-17.2+362 | 0.4 | 362 | 37 | < 171(D) | < 120 | 362 |
| 301.2+27.7 | HVC301.1+27.6+168 | 2.2 | 166 | 34 | < 37 | < 28 | 166 |
| 321.5+20.7 | HVC321.7+20.8+167 | 3.0 | 166 | 36 | < 53 | < 40 | 166 |
| 257.2+22.0 | HVC257.2+21.9+188 | 3.1 | 188 | 33 | < 93(D) | < 80 | 188 |
| 324.4+10.6 | HVC324.4+10.6+151 | 4.3 | 151 | 47 | < 167(D) | < 100 | 151 |
| 162.0+02.5 | CHVC161.6+02.7-186 | 1.2 | -180 | 28 | < 980 | < 28 | -180 |
| 284.6–16.1 | CHVC284.9-16.1+205e/f | 11.6 | 192 | 33 | < 48 | < 34 | 192 |
| 285.6–83.3 | CHVC286.3-83.5+091h | 1.3, 0.6 | 86, -144 | 35, 44 | < 26, 37 | < 26, 37 | 86, -144 |
| 289.7–83.0 | CHVC290.6-82.8-095e/h | 2.1, 1.6 | 95, -147 | 43, 37 | < 26, 70 | < 26, 70 | 95, -147 |
| 306.3–16.0 | CHVC305.9-16.1+185 | 2.5 | 183 | 38 | < 61 | < 37 | 183 |
| 321.0+14.9 | CHVC321.1+14.8+113 | 8.7 | 110 | 32 | < 73 | < 10 | 110 |
| 275.2–80.7 | XHVC275.5-80.8-132 | 10.7 | -139 | 82 | < 26 | < 26 | -139 |
| 290.9–76.3 | XHVC294.2-76.1+134h | 2.8, 0.03 | 141, -154 | 43, 15 | < 37, 30 | < 37, 30 | 141, -154 |

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a MS refers to a Magellanic Stream complex (Mathewson et al. 1977). Smith is also Complex CGP, most objects are named with their catalog name from P02. b $\Delta V$ at FW1M of HI line.

c The emission measure limit in miliRayleighs (mR) has D in parentheses if the result is from the DBS and [OIII] if it is a limit on the [OIII]$\lambda$5007 emission ($2\sigma$). All Hα limits are extinction corrected. d $E_m$ before the extinction correction. The characteristic detection errors are 10 mR, unless noted with a * . The * indicates the Hα line is within 2 $\AA$ of a skyline and the errors are between 15 - 30 mR. e Compromised by Fraunhofer lines from strong moonlight. f Also undetected by the DBS. g These clouds have been associated with the Sculptor dSph by Carignan et al. (1998). h There is also a negative velocity cloud, XHVC288.4-81.8-109, along this sightline.