

H α EMISSION FROM HIGH-VELOCITY CLOUDS AND THEIR DISTANCES

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Received 2002 September 16; accepted 2003 July 11

ABSTRACT

We present deep H α spectroscopy toward several high-velocity clouds (HVCs), which vary in structure from compact HVCs (CHVCs) to the Magellanic Stream. The clouds range from being bright (~ 640 mR) to having upper limits on the order of 30–70 mR. The H α measurements are discussed in relation to their H I 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 H α emission and little [N II] 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 H α emission cannot be explained solely by photo-ionization from the Galaxy. The interaction of the Magellanic Stream with halo gas or the presence of yet unassociated young stars may assist in ionizing the Magellanic Stream.

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

1. INTRODUCTION

The smooth accretion of gas onto galaxies allows for continuous galaxy evolution and star formation. The intergalactic gas that 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 (HVCs; Oort 1966).

HVCs are concentrations of neutral hydrogen that 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 that 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 that 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 2001; Sternberg, McKee, & Wolfire 2002; Maloney & Putman 2003).

H α 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 H I screen, and the H α emission measure (EM) reflects the ionizing photon flux reaching the cloud (Bland-Hawthorn & Maloney 1999, hereafter BM99; Bland-Hawthorn & Maloney 2002, hereafter BM02). This is confirmed by recent H α observations of large high-velocity complexes that have direct distance bounds of less than 10 kpc (Tufté, Reynolds, & Haffner 1998, hereafter TRH98). 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 H α emission brings the HVCs within the extended Galactic halo. H α 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/intergalactic medium (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 H α observations in § 2 and presents the results of the observations in § 3. In §§ 4 and 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 H α observations were obtained in five Anglo-Australian Telescope (AAT) observing runs from

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1997 December to 1999 June and one William Herschel Telescope (WHT) run in 1999 January. At both sites, the TAURUS-2 interferometer was used in conjunction with the University of Maryland 44 μm etalon. Single orders of interference were isolated using four-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 ring pattern covered about 45 Å (H α , [N II] λ 6583) at the AAT and 20 Å (H α) at the WHT. The resolution is 1 Å (or 46 km s $^{-1}$ at H α). 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 H I based on H I Parkes All Sky Survey (HIPASS) limits ($<2 \times 10^{18}$ cm $^{-2}$). The reduction and analysis are 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 five observing runs from 1998 August to 2000 April. 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 H α). 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, flat-fielding using QI lamp exposures, and cosmic-ray removal with a 2.5 σ high/low filter. S-distortions and illumination effects along the slit were removed at this stage using the positions and intensity profiles of the skylines. The central 240 rows of each two-dimensional spectrum were extracted and then wavelength calibrated based on the positions of the skylines in the object's spectrum (only possible with the red spectra) 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 objects' 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 H α emission at a velocity similar to the closest detectable H I and found no indication of emission. This was especially important to check considering the O VI that has been detected in absorption at the velocities of nearby H I HVCs, but off the H I contours of these clouds (Sembach et al. 2003), and the extended low H I 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, Finkbeiner, & Davis 1998), and therefore correct all H α EMs for dust extinction. We also include the uncorrected EM values in Tables 1 and 2, as the dust correction may not be realistic for the low-latitude clouds. EM upper limits quoted throughout this paper are 2 σ for the TAURUS data and 3 σ for the DBS data. Our characteristic detection errors are approximately 10 mR if the H α detection is at least 2 Å 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.

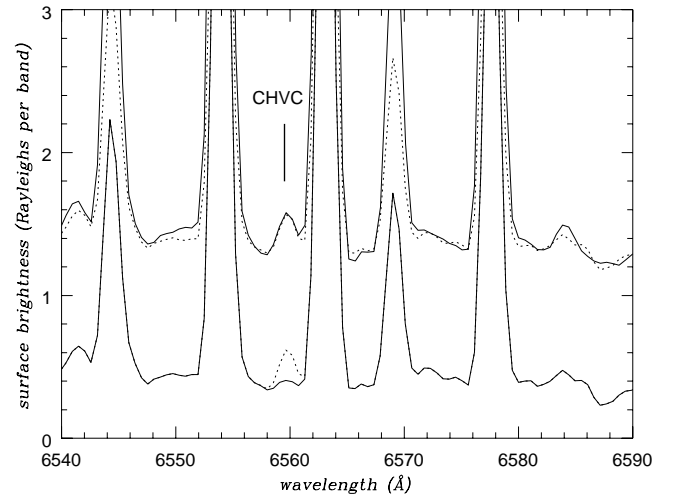


FIG. 1.—DBS spectrum of CHVC 197.0–81.8–184 showing H α emission at the level of 220 mR. The top spectrum is the CHVC observation (solid line) with the sky observation with a Gaussian fit at the velocity and H α strength of the CHVC overplotted (dashed line). The bottom plot shows the sky spectrum with the Gaussian fit to the H α detection shown as the dashed line.

Many of the observed HVCs were first identified by HIPASS (see Putman et al. 2002, hereafter P02). This is especially true of the CHVCs. The clouds observed were chosen because (1) they have H I velocities that isolate an equivalent velocity H α line from the skylines, (2) they have a proposed extragalactic nature (e.g., the CHVCs), and/or (3) 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 H α emission. Several positions observed by Weiner & Williams (1996, hereafter WW96) and TRH98 were repeated to compare observing and reduction methods.

3. RESULTS

The results of the observations are described in Tables 1 and 2. Table 1 lists the positive detections and Table 2 the nondetections. 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; \pm HVC = slightly more extended than a CHVC; HVC = extended HVC; or XHVC = an HVC that has H I emission that merges with Galactic velocities), followed by the intensity-weighted Galactic longitude and latitude and the central LSR velocity. The H I 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 sight line of the H α observation. The results of B98, TRH98, and Tufte et al. (2002, hereafter T02) are also included in Table 1. The columns of Table 1 are as follows: HVC name, l and b coordinates of the H α observation, H I column density, H I velocity (LSR), H I velocity width, the extinction-corrected H α emission measure with W or D in parentheses if the result is from WHAM or the DBS, respectively, the value of the H α emission measure before the extinction correction, the [N II] λ 6583/H α ratio, the velocity of the H α detection (LSR), and the predicted distance to the HVC based on its l , b , and extinction-corrected emission measure (see § 4). Some of the

TABLE 1
H α EMISSION LINE RESULTS, H I PROPERTIES, AND DISTANCES TO DETECTED HVCs

Common Name ^a	l (deg)	b (deg)	$N_{\text{H I}}$ ($\times 10^{19} \text{ cm}^{-2}$)	V_{LSR} (H I)	ΔV^b (km s^{-1})	EM ^c (mR)	EM _{obs} ^d (mR)	[N II]/H α	V_{LSR} (H α)	D_{mod}^e (kpc)
MS I (Fairall 9)	295.1	-57.8	9.5	191	52	128 (D)	120*	<0.25	200	0.5–25.7
MS Ib	304.0	-68.3	29.0	81	35	99	95	<0.30	93	0.5–33.2
MS IIa	342.6	-79.6	11.1	-120	37	407	386	0.15	-124	1.7–9.7
MS IIa	342.2	-79.9	3.4	-116	34	228 (D)	220	<0.18	-116	0.8–19.9
Bridge M	297.5	-42.5	98.3	166	66	3796	3240	0.05	146	...
Smith2 ^f	040.3	-15.1	16.0	86	38	450	300	0.60	80	1.2–12.7
Smith1 ^f	040.6	-15.5	15.1	94	47	360	240	0.60	100	1.2–13.4
Complex H ^g	130.8	+00.9	18.2	-200	16	3697	150	...	-170	...
Complex M W6	170.9	+64.7	150	140*	...	-90	1.7–9.6
Complex M W2	163.3	+66.7	11.7	-101	43	203	190*	...	-90	2.2–6.7
Complex L2 ^h	341.8	+31.3	1.6	-146	58	263	168	2.5	-124	0.5–19.9
Complex L3	343.2	+32.1	3.6	-136	36	499	320	2.7	-129	0.6–15.2
Complex L4	343.1	+32.0	3.4	-142	41	309	197	2.5	-146	0.6–19.0
Complex L5	343.2	+31.9	3.4	-145	39	637	406	2.7	-140	0.7–11.2
Complex L6	343.4	+32.0	2.3	-138	35	639	407	2.7	-140	0.7–11.1
Complex A ⁱ	153.6	+38.2	1.3	-177	23	108 (W)	90	...	-178	1.6–5.0
Complex C ⁱ	084.3	+43.7	0.54	120	15	133 (W)	130	...	-111	1.9–14.2
HVC 310.5+44.2+187	310.9	+44.4	0.37	187	40	99 (D)	80*	1.3	187	0.4–27.5
HVC 321.7-16.0+113	322.0	-15.8	1.7	113	59	125 (D)	100	<0.50	113	0.5–18.5
HVC 104.2-48-168 ⁱ	104.2	-48.0	0.6	-170	25	39 (W)	32	...	-168	1.1–27.8
CHVC 118.2-58.1-373 ⁱ	118.5	-58.2	3.1	-374	28	152 (W)	140	...	-369	1.9–10.6
CHVC 119.2-31.1-384 ⁱ	119.2	-30.8	1.1	-386	20	24 (W)	20	...	-382	1.3–13.2
CHVC 157.7-39.3-287 ⁱ	158.0	-39.0	0.5	-284	27	147 (W)	130	...	-290	1.7–4.3
CHVC 197.0-81.8-184	197.4	-81.8	2.7	-184	41	227 (D)	220	<0.30	-180	1.4–12.9
CHVC 266.0-18.7+336	266.0	-18.7	1.42	336	31	190 (D)	140*	<0.60	336	1.2–6.1
XHVC 287.6+17.1+111 ^j	285.9	+16.6	0.7	111	32	241 (D)	180	...	111	0.8–9.9

^a MS refers to a Magellanic Stream complex (Mathewson et al. 1977), Smith is also complex GCP, and many objects are named with their catalog name from P02.

^b ΔV at FWHM of H I line.

^c 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.

^d EM before the extinction correction. The characteristic detection errors are 10 mR, unless noted with an asterisk. The asterisk indicates that the H α line is within 2 Å of a skyline and the errors are between 15 and 30 mR.

^e Modeled distance based on EM, the HVC position, and the model described in BM02 ($\hat{f}_{\text{esc}} = 6\%$ 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 EM or EM_{obs}. Exceptions where the errors on the far field solutions are ~ 9 kpc include HVC 104.2-48-168 and CHVC 119.2-31.1-384. 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 EM_{obs} = 300 mR, [N II]/H α = 2.7, $V_{\text{LSR}} = -140$.

ⁱ Emission-line results from TRH98 and T02.

^j Velocity of this cloud places [N II] $\lambda 6583$ right on a skyline.

[N II]/H α ratios are not included as a result of the observation not including the wavelength of the [N II] $\lambda 6583$ line (i.e., the WHT and WHAM observations). Table 2 does not include the [N II]/H α ratio or the predicted distance (see § 5) but does include two limits on [O III] emission.

The close relationship between H I velocity and H α velocity is shown in Figure 2, and the complete lack of correlation between the H α emission measure and H I 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 nondetections (*open diamonds*) span the entire range of high velocities. Although not shown, there is also no relationship between the strength of the H α emission and the velocity of the HVC (in the LSR or galactic standard of rest [GSR] reference frame). Figure 3 shows that undetected clouds span the entire range of H I column densities; i.e., there does not currently seem to be a lower or upper column density cutoff. The distribution of the H α detections and nondetections on

the sky in Galactic coordinates is shown in Figure 4, and a large number of the H α observations are depicted on the H I 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 H α are part of larger complexes that are defined by Wakker & van Woerden (1991). The H α brightest of these is complex L, a negative velocity HVC made up of several clumpy filaments, with several small clouds scattered among the filaments. The cloud mapped here is HVC 341.6+31.4-142 in the P02 catalog, and the brightest emission lies closest to the head of the cloud. Complex L has a highly elevated [N II]/H α ratio (2.7). Along with the detections there was one nondetection in a very low column density ($\sim 10^{18} \text{ cm}^{-2}$) part

TABLE 2
H α EMISSION LIMITS AND H I PROPERTIES OF UNDETECTED HVC POSITIONS

Common Name ^a	l	b	$N_{\text{H I}}$ ($\times 10^{19} \text{ cm}^{-2}$)	V_{LSR} (H I)	ΔV^b (km s^{-1})	EM ^c (mR)	EM _{obs} ^d (mR)	V_{LSR} (H α)
MS I.....	293.4	-56.4	3.6, 9.6	226, 158	23, 40	<59, <54	<55*, <50	226, 158
MS IIa.....	342.2	-79.9	3.4	-116	34	<52 [O III]	<52 [O III]	-116
MS V.....	096.5	-53.9	4.6	-366	45	<153	<120*	-366
Bridge 1.....	292.4	-40.1	50.1	184	53	<42	<35*	184
Bridge 2.....	290.2	-37.6	47.0	198	74	<79	<52*	198
Bridge 3.....	287.7	-34.8	26.8	204	41	<52	<40*	204
Lead Arm 1.....	291.7	-32.0	27.2	222	33	<71	<52*	222
Lead Arm 2.....	291.7	-30.6	19.4	236	43	<78	<52*	236
Lead Arm 3.....	292.1	-29.7	5.1	305	37	<30	<21*	305
Lead Arm 4.....	287.5	+23.0	11.3	238	36	<70	<47*	238
Complex L1 ^e	342.5	+31.9	0.1	-126	20	<65	<43	-126
Pop EP1.....	248.5	-12.2	0.6	334	58	<56	<16*	334
Pop EP2.....	262.7	+13.5	1.6	160	38	<41	<26	160
Pop EP3.....	280.1	+04.0	6.9	163	35	<128	<35	163
Pop EP4 ^e	271.2	+29.4	0.2	184	29	<39	<30*	184
HIPASS J1712-64.....	326.5	-14.6	0.4	458	41	<44	<30	458
Smith 1.....	040.6	-15.5	15.1	94	47	<70 [O III]	<70 [O III]	94
HVC 039.3-13.8-233.....	039.3	-13.8	3.1	-233	29	<213 (D)	<120	-233
HVC 259.1-17.2+362.....	259.2	-17.2	0.4	362	37	<171 (D)	<120	362
HVC 301.1+27.6+168.....	301.2	+27.7	2.2	166	34	<37	<28	166
HVC 321.7+20.8+167.....	321.5	+20.7	3.0	166	36	<53	<40	166
:HVC 257.2+21.9+188.....	257.2	+22.0	3.1	188	33	<93 (D)	<80*	188
:HVC 324.4+10.6+151.....	324.4	+10.6	4.3	151	47	<167 (D)	<100	151
CHVC 161.6+02.7-186.....	162.0	+02.5	1.2	-180	28	<980	<28	-180
CHVC 284.9+16.1+205 ^{e,f}	284.6	-16.1	11.6	192	33	<48	<34*	192
CHVC 286.3-83.5+091 ^{g,h}	285.6	-83.3	1.3, 0.6	86, -144	35, 44	<26, <37	<26, <37	86, -144
CHVC 290.6-82.8+095 ^{g,h}	289.7	-83.0	2.1, 1.6	95, -147	43, 37	<26, <70	<26, <70	95, -147
CHVC 305.9-16.1+185.....	306.3	-16.0	2.3	183	38	<61	<37*	183
CHVC 321.1+14.8+113.....	321.0	+14.9	8.7	110	32	<73	<17	110
XHVC 275.5-80.8-132.....	275.2	-80.7	10.7	-139	82	<26	<26	-139
XHVC 294.2-76.1+134 ^h	290.9	-76.3	2.8, 0.03	141, -154	43, 15	<37, <30	<37, <30	141, -154

^a MS refers to a Magellanic Stream complex (Mathewson et al. 1977), Smith is also complex GCP, and most objects are named with their catalog name from P02.

^b ΔV at FWHM of H I line.

^c The emission measure limit in millirayleighs (mR) has D in parentheses if the result is from the DBS and [O III] if it is a limit on the [O III] $\lambda 5007$ emission (2σ). All H α limits are extinction corrected.

^d EM before the extinction correction. The characteristic detection errors are 10 mR, unless noted with an asterisk. The asterisk indicates that the H α line is within 2 Å of a skyline and the errors are between 15 and 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, XHVC 288.4-81.8-109, along this sight line.

of complex L. All of the positions with bright detections have column densities in the range $(1.6-3.6) \times 10^{19} \text{ cm}^{-2}$.

The other detected complexes are as follows: complex M, which has an upper distance constraint of less than 4 kpc (Ryans et al. 1997) and was detected at a similar level by TRH98; complex H, which lies along the Galactic plane, making this detection more tentative (especially since the H α velocity is offset by 30 km s^{-1} from the H I velocity); and complex GCP (Smith Cloud), which was originally presented in B98 and now has a limit on the [O III] emission at the position of Smith1 (<70 mR; Table 2). We include the TRH98 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 greater than 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 Clouds with each other and the Galaxy. It trails the Magellanic Clouds for over 100° through the south

Galactic pole and has a velocity gradient of 700 km s^{-1} from head to tail (relative to the LSR; 400 km s^{-1} relative to the Galaxy). The Magellanic 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 Magellanic Stream (e.g., Guhathakurta & Reitzel 1998), but H α 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 TAURUS and the DBS. The repeat observation of MS IIa 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 (FOV) of TAURUS and the DBS (a 10' diameter FOV vs. a 7' \times 2" slit). [N II] was also detected, and the ratio to H α is low compared to the Smith Cloud and complex L (0.15 vs. 0.6-2.7). MS IIa was subsequently observed in [O III] $\lambda 5007$, and no detection was obtained

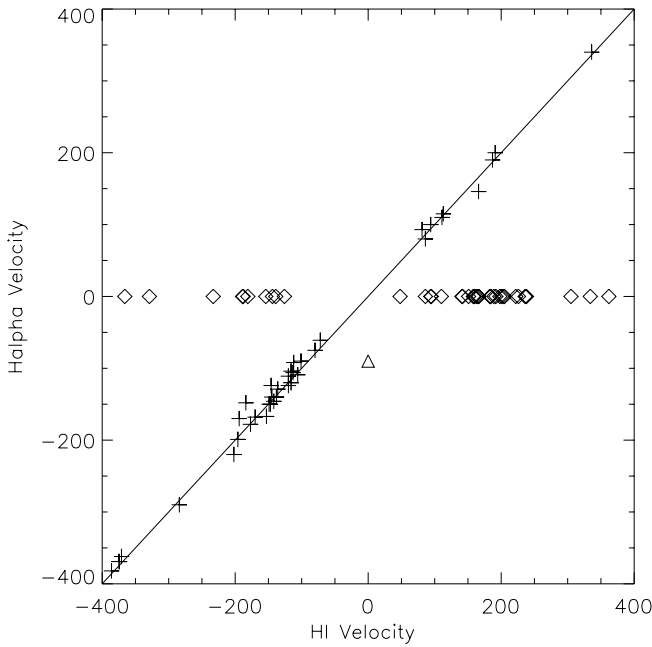


FIG. 2.—Relationship between the $H\alpha$ and $H\text{ I}$ velocity for all of the recently published HVC $H\alpha$ observations (this paper; WW96; TRH98; B98; T02). Crosses show the detections, diamonds the nondetections in $H\alpha$, and the triangle the one high-velocity detection in $H\alpha$ but not $H\text{ I}$ on the edge of complex M (TRH98).

(<52 mR; Table 2). As tabulated in Table 1, a new relatively weak $H\alpha$ detection was made at the head of the Magellanic Stream, $(l, b) = (304^\circ, -67^\circ)$, and at the position of the background QSO Fairall 9 where O VI absorption has also

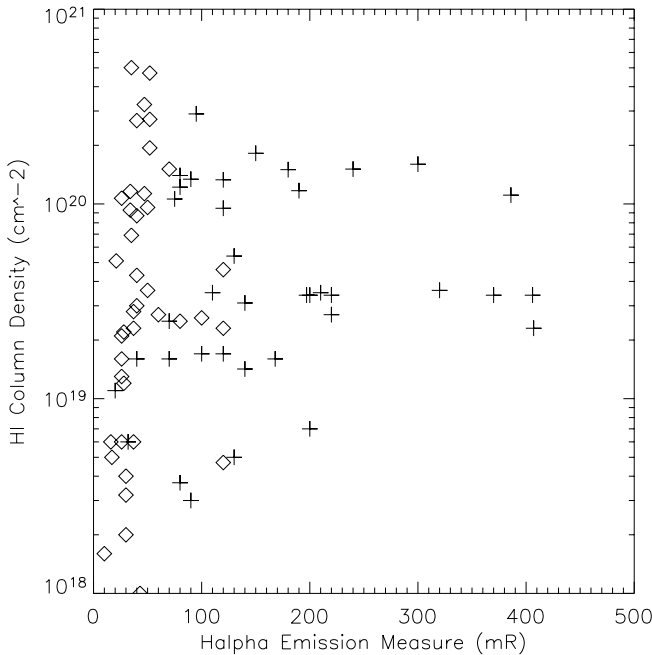


FIG. 3.—Relationship between the $H\alpha$ emission measure and the $H\text{ I}$ column density for the same data shown in Fig. 2. Detections are represented by crosses and nondetections are represented by open diamonds. The $H\alpha$ emission measures are *not* extinction corrected. Using the extinction-corrected values does not greatly change this plot, as can be noted from the values listed in Tables 1 and 2.

been detected ($10^{14.3}\text{ cm}^{-2}$; Sembach et al. 2003). There was also a nondetection at $(l, b) = (293.4, -56.4)$ and at the tail of the Magellanic Stream [MS V; $(l, b) = (96.5, -53.9)$] as tabulated in Table 2. As shown in Figure 5, there are large variations in the strength of the $H\alpha$ emission along the Magellanic Stream's length, and so far there does not seem to be a correlation with the $H\text{ I}$ column density (Fig. 3). However, one should consider that the beam used in the $H\text{ I}$ observations is larger than the FOV of TAURUS (15.5 vs. $10'$). Although the number of observations remains limited, there also does not seem to be a gradient of $H\alpha$ brightness along the Magellanic Stream. Currently, the brightest detection is approximately at the south Galactic pole in a region of complexity in terms of the high-velocity $H\text{ I}$ gas distribution (P03). The velocities of the $H\text{ I}$ and $H\alpha$ lines generally closely agree (within $\sim 10\text{ km s}^{-1}$; Fig. 2). Several positions along the Magellanic Bridge and Leading Arm were also observed. All of the pointings were nondetections (see Table 2 and Fig. 5), except for an extremely bright observation at the position of a known OB association (bridge M in Table 1; see also Marcelin, Boulesteix, & Georgelin 1985).

Compact High-Velocity Clouds.—Two CHVCs were detected with the DBS. CHVC 197.0–81.8–184 is located $\sim 10^\circ$ from the Magellanic Stream where it passes through the south Galactic pole (see Fig. 5). The $H\alpha$ detection of this cloud (Fig. 1) is at the level of many of the Magellanic Stream detections. The second CHVC is a very small and isolated cloud located in the region leading the LMC (Fig. 5). CHVC 266.0–18.7+336 has a velocity that places the $H\alpha$ 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. Nondetections

There are several clouds that 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, Vogel, & Williams (2001), but the precise coordinates of their observations have not yet been reported. This is not unusual considering the range of detections and nondetections noted in the previous section within the same high-velocity complex. Many of the HVCs that we have only nondetections for lie in approximately the same region of the sky (see Fig. 4). The undetected clouds mostly lie in the Galactic longitude range of $l = 250^\circ$ – 320° and include the length of the Leading Arm of the Magellanic System (Fig. 5), several HVCs and CHVCs, and part of the Extreme Positive Velocity Complex. We note that many of these clouds (marked with an asterisk in Table 2) have velocities that place the $H\alpha$ line close to a skyline, making the nondetections somewhat less certain.

Additional nondetections include the high positive velocity cloud HIPASS J1712–64 (Kilborn et al. 2000), which has an $H\alpha$ upper limit of 44 mR, and the clouds associated with the Sculptor dSph galaxy by Carignan et al. (1998) (cataloged as CHVC 286.3–83.5+091 and CHVC 290.6–82.8+095 in P02). It is unclear if these clouds are actually associated with the Sculptor dSph. The $H\text{ I}$ 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 sight line to the

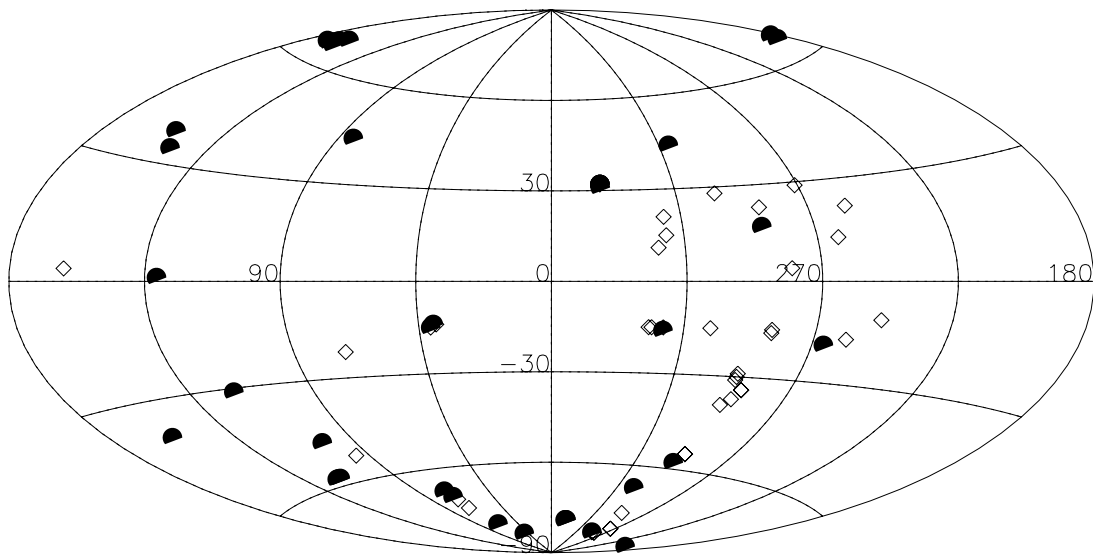


FIG. 4.—Distribution of H α detections (*filled symbols*) and nondetections (*open diamonds*) of the same data shown in Fig. 2 in Galactic coordinates

clouds associated with the Sculptor dSph, as well as a nearby positive velocity XHVC, which was also undetected.

4. THE H α DISTANCE CONSTRAINT

The H α distance constraint is based on photoionizing radiation escaping from the Galactic disk and ionizing the surface of H 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 (BM02). Variations in H α brightness across a single HVC may be due to these issues, and we stress that the H α 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 H α 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 2001 for a summary) have now been detected in H α by WHAM (TRH98), Weiner et al. (2001), and this survey. There is also an IVC (complex K; Haffner, Reynolds, & Tufté 2001) that has been completely mapped in H α emission and has a distance constraint. The H α emission measures from these clouds are

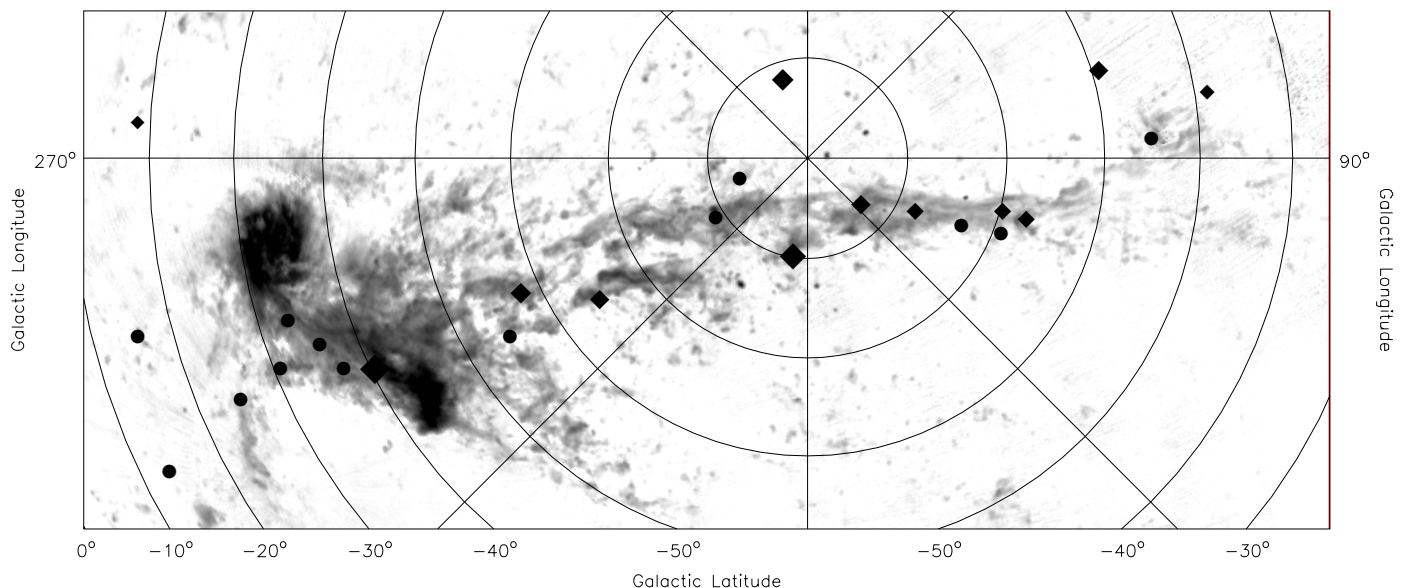


FIG. 5.—H I map of the Magellanic System showing column densities greater than $2 \times 10^{18} \text{ cm}^{-2}$ (P03), with the H α detections and nondetections labeled as diamonds and circles, respectively. The size of the diamond represents the relative strength of the H α detection. The positions and strengths of the H α 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.

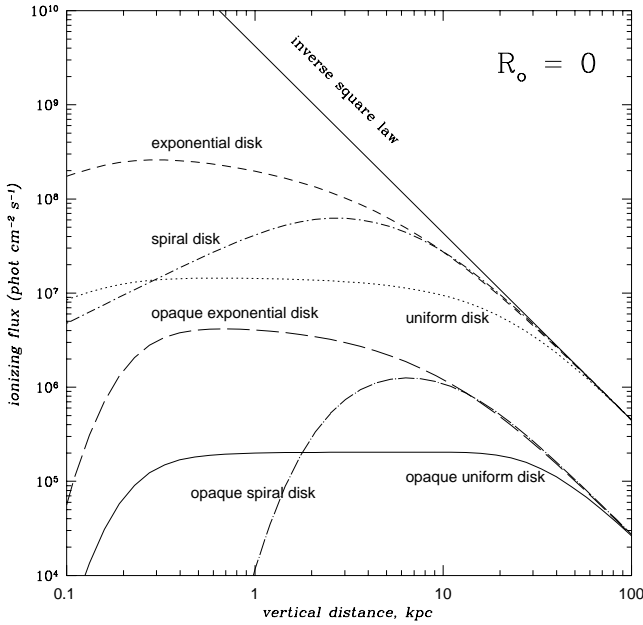


FIG. 6.—Halo ionizing flux for different disk distributions (uniform emissivity, exponential and spiral) compared to a simple inverse square law. The vertical distance is measured from the center of the disk along the polar axis. The top three curves are in the absence of dust and converge in the far field limit. The lower three curves include the effects of dust where $\tau_{LL} = 2.8$ ($f_{esc} = 6\%$).

consistent with the model predictions of BM99 (updated in BM02 to include spiral arms), which uses an escape fraction normal to the disk of $f_{esc} = 6\%$ ($f_{esc} \approx 1\% - 2\%$ averaged over 4π sr). The escape fraction used in the BM02 spiral arm model has been adopted based on its agreement with the direct distance determinations and $H\alpha$ emission measures for complexes A, M, C, and the IVC, complex K. It has a factor of 2 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 toward complex L is shown in Figure 7. Note that the spiral arm model predicts that complex L lies directly over a spiral arm, but there is a near and a far field solution, depending on its exact position. There is some indication that HVCs along sight lines over spiral arms are brighter, as expected for clouds within about 10 kpc (BM02), but more sight lines are needed to confirm this.

Although 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 BP01). We also note that complexes L and GCP (the Smith Cloud) not only have high $H\alpha$ emission measures (which

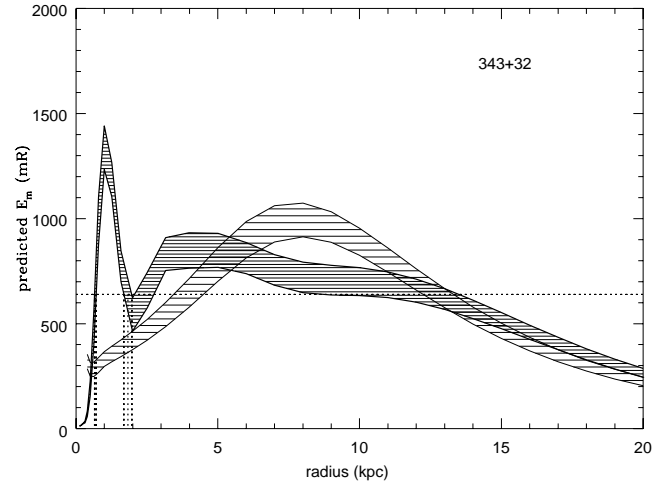


FIG. 7.—Predicted run of emission measure (in mR) as a function of radius (in kpc) along our sight line to complex L. The light shaded model is the $H\alpha$ signal due to an exponential disk of ionizing sources; the dark shading is for the spiral arm model. The horizontal line shows our brightest observed EM for complex L. Note that 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 ~ 1 R for a different cloud in complex L, indicating that 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.

makes sense, as they most likely lie inside the solar circle above the spiral arms) but also elevated $[N II]/H\alpha$ emission. The $[N II]$ 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, Reynolds, & Tufte 1999; Veilleux, Cecil, & Bland-Hawthorn 1995; Miller & Veilleux 2003a, 2003b). In essence, we can use the elevated $[N II]/H\alpha$ 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 I structure of these clouds, each of which shows possible extensions into Galactic H I.

5. DO NONDETECTIONS CORRESPOND TO LARGE DISTANCES?

If the $H\alpha$ normalization to local HVCs is valid, this may indicate that some HVCs that 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 ($\sim 10^4$ photons s^{-1} ; Maloney & Bland-Hawthorn 1999) would correspond to a 5 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 that have nondetections 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 I 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 H II regions. Shadowing and the size of the TAURUS beam may also be important considerations. There may be an *observed* relationship between the strength of EM and the position of the cloud above the Galaxy, as clouds at $l > 330^\circ$ and $l < 60^\circ$ have a slight tendency to be brighter and clouds between $l = 250^\circ$ and 320° remain largely undetected (Fig. 4). This is expected from their line of sight over the Galaxy (see Taylor & Cordes 1993) and from the BM02 model.

6. WHAT IS IONIZING THE MAGELLANIC STREAM?

The Magellanic Stream is brightest at the south Galactic pole and fainter toward 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 (BM99). The match between the H I velocity and the H α velocity for all clouds supports photoionization. However, if ionizing photons from the Galaxy are reaching HVCs at distances of ~ 10 kpc, why are Magellanic Stream positions near the south Galactic pole, which most likely lie at distances between 20 and 100 kpc (Gardiner 1999; Moore & Davis 1994), consistently brighter than the HVCs? As shown in Figure 8, at a mean Magellanic Stream distance of 55 kpc, the expected emission measure of a flat H I stream is 30–50 mR (BM02), 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 Magellanic Stream.

Is it possible that sections of the Magellanic Stream are just that much closer to the Galaxy disk than the Magellanic

Clouds? With the detection of the head of the Magellanic Stream (Fairall 9 sight line), this possibility seems unlikely, as the head of the Magellanic Stream is presumed to be close to the Magellanic Clouds (50–60 kpc). Thus, the distances predicted in Table 1 for the Magellanic Stream sight lines are not relevant, and we need to look for another source of ionization in the Magellanic Stream. The detection of O VI absorption in and around the Magellanic Stream may provide some clues (Sembach et al. 2003). Interaction with a halo medium could provide some preionization that could elevate the Magellanic Stream's H α . The outer halo medium may well be clumpy, particularly at the poles, from the leftovers of other satellites or from self-interaction of the Magellanic Stream (BP01; P03). CHVC 197.0–81.8–184 may represent some of this debris. This CHVC is only 10° from the main filament of the Magellanic Stream and is as H α bright as the Magellanic Stream, possibly indicating a large spread of debris associated with the Magellanic Stream's H α emission. Two of the T02-detected CHVCs (shown in Fig. 5) may also represent the spread of ionized Magellanic Stream debris.

Another possibility is that there are stars associated with the Magellanic Stream that have yet to be detected. Recent results have found small isolated H II 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 Magellanic Stream could lead to an emission measure of 40 mR. If the star was actually embedded in the Magellanic 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 Magellanic Stream have been surveyed for stars. Ongoing and future stellar surveys will provide further insight into the possibility of the Magellanic Stream harboring young, ionizing stars.

7. OVERVIEW

The H α observations presented here are a combination of detections and nondetections on clouds with H I 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 nondetection as meaningful for the entire high-velocity complex. The results thus far show a population of clouds that appear to extend out of Galactic H I emission, are H α bright, and show an elevated $[\text{N II}]/\text{H}\alpha$ ratio, as well as an undetected population of clouds that 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 T02 indicates that many of these clouds are indeed within the Galactic halo. The nondetections of some CHVCs cannot be used to argue for a greater distance until the origin of the nondetections in other complexes is understood.

The H α 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

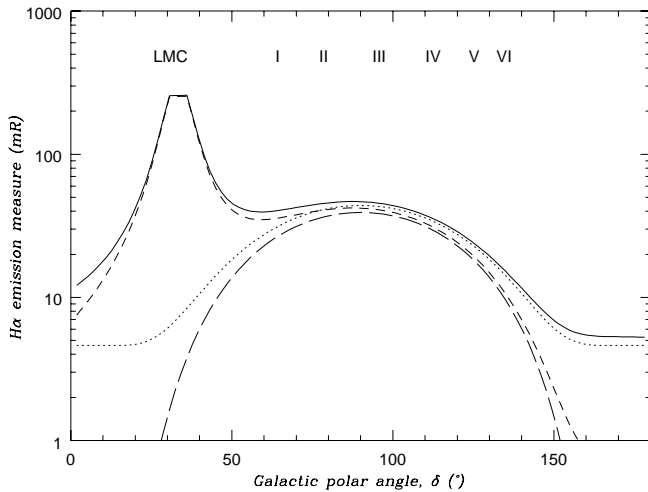


FIG. 8.—Predicted H α emission measure along the Magellanic Stream as a function of polar angle δ in units of $\log(\text{mR})$ where $\delta = 90^\circ$ is the south Galactic pole. The roman numerals refer to the specific Magellanic Stream complex defined by Mathewson, Schwarz, & Murray (1977). See P03 for the definitions of these complexes on the map shown in Fig. 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.

based on their level of $H\alpha$ emission. The Magellanic Stream appears to fall into a different category than the currently detected HVCs, with bright $H\alpha$ emission but little or no $[N\ II]$ emission, possibly as a result of the lower metallicities of the Magellanic Clouds compared to the Galaxy. The strength of the $H\alpha$ 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 $H\alpha$ emission. Through future $H\alpha$ observations that include mapping head-tail $H\ I$ clouds, the length of the Magellanic Stream, $O\ VI$ absorption sight lines, and complexes of known distance, as well as the development of models that trace the path of the escaping photons from the Galactic plane, we may come to a consensus on the origin of the $H\alpha$ emission in all HVCs.

We thank our referees, Robert Benjamin and an anonymous reviewer, for many useful comments and Ben Weiner and Mike Shull for helpful discussions. M. E. P. acknowledges support by NASA through Hubble Fellowship grant HST-HF-01132.01 awarded by the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. S. V. is indebted to the California Institute of Technology and the Observatories of the Carnegie Institution of Washington for their hospitality and is grateful for partial support of this research by a Cottrell Scholarship awarded by the Research Corporation, NASA/LTSA grant NAG 56547, and NSF/CAREER grant AST 98-74973. B. K. G. acknowledges the support of the Australian Research Council, through its Large Research Grant and Discovery Project schemes.

REFERENCES

- Bland-Hawthorn, J., Freeman, K. C., & Quinn, P. J. 1997, *ApJ*, 490, 143
 Bland-Hawthorn, J., & Maloney, P. R. 1999, *ApJ*, 510, L33 (BM99)
 ———. 2002, in *ASP Conf. Ser.* 254, *Extragalactic Gas at Low Redshift*, ed. J. S. Mulchaey & J. Stocke (San Francisco: ASP), 267 (BM02)
 Bland-Hawthorn, J., & Putman, M. E. 2001, in *ASP Conf. Ser.* 240, *Gas and Galaxy Evolution*, ed. J. E. Hibbard, M. Rupen, & J. van Gorkom (San Francisco: ASP), 369 (BP01)
 Bland-Hawthorn, J., Veilleux, S., Cecil, G. N., Putman, M. E., Gibson, B. K., & Maloney, P. R. 1998, *MNRAS*, 299, 611 (B98)
 Blitz, L., Spergel, D. N., Teuben, P. J., Hartmann, D., & Burton, W. B. 1999, *ApJ*, 514, 818
 Braun, R., & Burton, W. B. 1999, *A&A*, 341, 437
 Carignan, C. 1999, *Publ. Astron. Soc. Australia*, 16, 18
 Carignan, C., Beaulieu, S., Cote, S., Demers, S., & Mateo, M. 1998, *AJ*, 116, 1690
 Davé, R., Hernquist, L., Katz, N., & Weinberg, D. 1999, *ApJ*, 511, 521
 Gardiner, L. T. 1999, in *ASP Conf. Ser.* 166, *Stromlo Workshop on HVCs*, ed. B. Gibson & M. Putman (San Francisco: ASP), 292
 Gerhard, O., Arnaboldi, M., Freeman, K. C., & Okamura, S. 2002, *ApJ*, 580, L121
 Glazebrook, K., & Bland-Hawthorn, J. 2001, *PASP*, 113, 197
 Guhathakurta, P., & Reitzel, D. B. 1998, in *ASP Conf. Ser.* 136, *Galactic Halos: A UC Santa Cruz Workshop*, ed. D. Zaritsky (San Francisco: ASP), 22
 Haffner, L. M., Reynolds, R. J., & Tufte, S. L. 1999, *ApJ*, 523, 223
 ———. 2001, *ApJ*, 556, L33
 Kilborn, V., et al. 2000, *AJ*, 120, 1342
 Lockman, F. J., Murphy, E. M., Petty-Powell, S., & Urlick, V. J. 2002, *ApJS*, 140, 331
 Maloney, P. R., & Bland-Hawthorn, J. 1999, *ApJ*, 522, L81
 Maloney, P. R., & Putman, M. E. 2003, *ApJ*, 589, 270
 Marcelin, M., Boulesteix, J., & Georgelin, Y. P. 1985, *Nature*, 316, 705
 Mathewson, D. S., Schwarz, M. P., & Murray, J. D. 1977, *ApJ*, 217, L5
 Miller, S. T., & Veilleux, S. 2003a, *ApJ*, 592, 79
 ———. 2003b, *ApJS*, 148, 383
 Moore, B., & Davis, M. 1994, *MNRAS*, 270, 209
 Oort, J. H. 1966, *Bull. Astron. Inst. Netherlands*, 18, 421
 Penton, S., Stocke, J., & Shull, J. M. 2002, *ApJ*, 565, 720
 Putman, M. E. 2000, Ph.D. thesis, Australian National Univ.
 Putman, M. E., Staveley-Smith, L., Freeman, K. C., Gibson, B. K., & Barnes, D. G. 2003, *ApJ*, 586, 170 (P03)
 Putman, M. E., et al. 2002, *AJ*, 123, 873 (P02)
 Reynolds, R. J., Haffner, L. M., & Tufte, S. L. 1999, *ApJ*, 525, L21
 Ryans, R. S. I., et al. 1997, *MNRAS*, 289, 83
 Ryan-Weber, E., et al. 2003, *ApJ*, submitted
 Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
 Sembach, K., et al. 2003, *ApJS*, 146, 165
 Sternberg, A., McKee, C. F., & Wolfire, M. G. 2002, *ApJS*, 143, 419
 Taylor, J. H., & Cordes, J. M. 1993, *ApJ*, 411, 674
 Tufte, S. L., Reynolds, R. J., & Haffner, L. M. 1998, *ApJ*, 504, 773 (TRH98)
 Tufte, S. L., Wilson, J. D., Madsen, G. J., Haffner, L. M., & Reynolds, R. J. 2002, *ApJ*, 572, L153 (T02)
 van Woerden, H., et al. 1999, *Nature*, 400, 138
 Veilleux, S., Cecil, G. N., & Bland-Hawthorn, J. 1995, *ApJ*, 445, 152
 Wakker, B. 2001, *ApJS*, 136, 463
 Wakker, B., & van Woerden, H. 1991, *A&A*, 250, 509
 Weiner, B. J., Vogel, S. N., & Williams, T. B. 2001, in *ASP Conf. Ser.* 240, *Gas and Galaxy Evolution*, ed. J. E. Hibbard, M. Rupen, & J. van Gorkom (San Francisco: ASP), 515
 Weiner, B. J., & Williams, T. B. 1996, *AJ*, 111, 1156 (WW96)
 Wolfire, M. G., et al. 1995, *ApJ*, 453, 673
 Zwaan, M. 2001, *MNRAS*, 325, 1142