

A MAP OF THE IONIZED COMPONENT OF THE INTERMEDIATE-VELOCITY CLOUD COMPLEX K

L. M. HAFFNER AND R. J. REYNOLDS

Department of Astronomy, University of Wisconsin–Madison, 475 North Charter Street, Madison, WI 53706;
haffner@astro.wisc.edu, reynolds@astro.wisc.edu

AND

S. L. TUFTTE

Department of Physics, Lewis and Clark College, Portland, OR 97219; tuftte@lclark.edu

Received 2001 April 9; accepted 2001 June 14; published 2001 July 5

ABSTRACT

The Wisconsin H-Alpha Mapper (WHAM) Northern Sky Survey is revealing that many intermediate-velocity ($|v_{\text{LSR}}| \leq 100 \text{ km s}^{-1}$) neutral clouds and complexes have an associated ionized component. We present the first map of the $\text{H}\alpha$ emission from an intermediate- or high-velocity structure: Complex K. This large, high-latitude feature stretches from $l \approx 10^\circ$ to 70° , $b \approx +30^\circ$ to $+70^\circ$ and peaks in velocity over $v_{\text{LSR}} \approx -60$ to -80 km s^{-1} . The neutral and ionized gas generally trace each other quite well in the complex, but the detailed structure is not identical. In particular, the $\text{H}\alpha$ emission peaks in brightness at slightly higher Galactic longitudes than corresponding 21 cm features. The ionized gas has a peak $\text{H}\alpha$ intensity of 0.5 R, corresponding to an emission measure of $1.1 \text{ cm}^{-6} \text{ pc}$. Structures in the complex are traced by WHAM down to about 0.1 R ($0.2 \text{ cm}^{-6} \text{ pc}$). Typical line widths of the $\text{H}\alpha$ emission are $\sim 30 \text{ km s}^{-1}$, limiting temperatures in the ionized gas to less than 20,000 K. If radiation is the primary ionizing mechanism, the Lyman continuum flux required to sustain the most strongly emitting ionized regions is $1.2 \times 10^6 \text{ photons cm}^{-2} \text{ s}^{-1}$. There appears to be no local, stellar source capable of maintaining the ionization of the gas; however, the required ionizing flux is consistent with current models of the escape of Lyman continuum radiation from OB stars in the disk and of ionizing radiation produced by cooling supernova remnants.

Subject headings: Galaxy: halo — H II regions — ISM: atoms — ISM: clouds — ISM: individual (IVC K) — ISM: structure

1. INTRODUCTION

Optical emission lines are a new tool for the exploration of high- and intermediate-velocity clouds (HVCs and IVCs), traditionally discovered and studied in the 21 cm line of H I or through absorption-line observations. The $\text{H}\alpha$ intensity from such structures is typically a few tenths of a rayleigh ($1 \text{ R} = 10^6/4\pi \text{ photons cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} = 2.4 \times 10^{-7} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) and has only recently been accessible through modern detectors. With such faint emission, previous studies of emission lines such as $\text{H}\alpha$, [S II], and [N II] from HVCs and IVCs have been limited to single, pointed observations, although they have gleaned some of the first information about the ionization, temperature, and metallicity of these gas structures (Weiner & Williams 1996; Tuftte, Reynolds, & Haffner 1998; Bland-Hawthorn et al. 1998; Wakker et al. 1999). Since most of the known HVCs and IVCs are at high latitudes and many are distant ($d > 500 \text{ pc}$) structures, studies of their ionized component reveal information not only about the clouds themselves but also about the environment of the Galactic halo and the escape of radiation from the Galactic plane.

With high sensitivity and velocity resolution, the recently completed Wisconsin H-Alpha Mapper¹ (WHAM) Northern Sky Survey is yielding an enormous amount of new information about the ionized nature of IVCs. Wakker (2001) has recently separated out the large ($\Delta l \sim 40^\circ$, $\Delta b \sim 40^\circ$) H I intermediate-velocity Complex K (previously classified with Complex C) centered near $l = 50^\circ$, $b = +50^\circ$, $v_{\text{LSR}} \approx -60$ to -80 km s^{-1} . Here we present the first map of the ionized component of Complex K.

2. OBSERVATIONS

The WHAM Northern Sky Survey provides the first velocity-resolved survey of $\text{H}\alpha$ emission from the Galaxy. Each of the 37,300 pointings in the northern survey captures a spectrum over $v_{\text{LSR}} \approx -100$ to 100 km s^{-1} from a 1° patch of sky. Since WHAM provides 12 km s^{-1} spectral resolution, we are able to cleanly remove the bright and variable geocoronal $\text{H}\alpha$ emission ($I \sim 2\text{--}13 \text{ R}$) and numerous fainter ($I \sim 0.1\text{--}0.3 \text{ R}$) atmospheric lines (N. R. Hausen et al. 2001, in preparation), allowing detections of faint Galactic emission below 0.1 R. The survey achieves nearly full coverage of the sky with beam spacings of $\Delta b = 0^\circ 85$ and $\Delta l = 0^\circ 98 / \cos b$ above $\delta > -30^\circ$. More information about the instrument and survey strategy can be found in Tuftte (1997), Haffner (1999), and L. M. Haffner et al. (2001, in preparation).

3. RESULTS

Figure 1 shows an image of the $\text{H}\alpha$ emission from WHAM and contours of 21 cm emission from the Leiden-Dwingeloo H I survey (Hartmann & Burton 1997) toward Complex K. Note that the image and contours reflect a strict integration limit between -95 and -50 km s^{-1} . As a result, the color bar legend underestimates the total $\text{H}\alpha$ line intensity by about 20% (e.g., Fig. 2; see below). Since the distance to Complex K is still relatively uncertain, we have not applied an extinction correction to the data presented here. However, since the total $N_{\text{H I}}(-100 < v_{\text{LSR}} < +100)$ over the face of the cloud only varies from about 1 to $4 \times 10^{20} \text{ cm}^{-2}$, such a correction to the observed $\text{H}\alpha$ flux would be at most about 25% if all the neutral material is between us and Complex K.

The ionized emission is distributed diffusely over the neutral

¹ More information about WHAM can be found at <http://www.astro.wisc.edu/wham>.

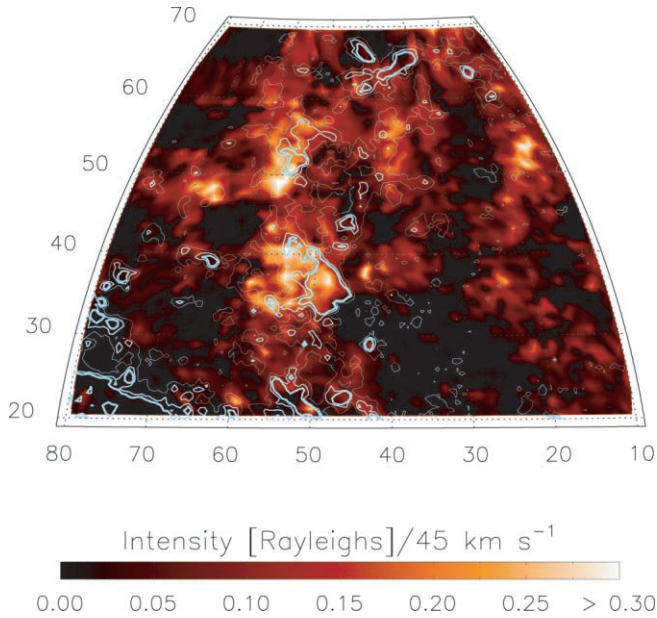


FIG. 1.—Ionized and neutral components of Complex K. Integrated $H\alpha$ emission from $v_{\text{LSR}} = -95$ to -50 km s^{-1} is presented as the color image. $H\text{ I}$ column densities (integrated over the same velocity range) of 7, 14, and $21 \times 10^{18} \text{ cm}^{-2}$ from Hartmann & Burton (1997) are displayed as light blue contours.

extent of the complex; it does not appear to arise from numerous point sources within the complex. The integrated $H\alpha$ intensity in the region displayed in Figure 1 ranges from 0.5 R down to a conservative detection limit of 0.1 R or an emission measure of $\sim 1.1\text{--}0.2 \text{ cm}^{-6} \text{ pc}$ ($1 \text{ R} \approx 2.25 \text{ cm}^{-6} \text{ pc}$ for $T = 8000 \text{ K}$). The extent of the $H\alpha$ emission in the main part of the complex ($l = 30^\circ\text{--}65^\circ$, $b = +30^\circ$ to $+70^\circ$) matches the $N_{\text{H}} = 7 \times 10^{18} \text{ cm}^{-2}$ contour quite closely; however, the peaks in each emission component do not correspond as well. A detailed quantitative analysis of the $H\alpha$ and $H\text{ I}$ intensities within each 1° WHAM pointing reveals that there is little correlation between the integrated intensities of the IVC components. The linear correlation coefficient for pointings within the main part of the complex is 0.4. Although the spatial distribution and velocity profiles correspond extremely well, a simple relationship relating the $H\alpha$ intensity to the $H\text{ I}$ column does not exist. In fact, for many of the largest concentrations of $H\text{ I}$ emission (e.g., $l = 48^\circ$, $b = +36^\circ$; $l = 54^\circ$, $b = +52^\circ$; $l = 45^\circ$, $b = +44^\circ$), the brighter $H\alpha$ emission is consistently at higher longitudes than the regions of brightest 21 cm emission. We created $H\alpha$ and $H\text{ I}$ latitude profiles from the images to quantify the extent of this offset. By examining the two latitude profiles simultaneously and by computing correlation coefficients between the profiles in their natural and offset positions, we find that the $H\alpha$ emission is consistently shifted or extended to higher Galactic longitudes in nearly all latitude slices by $2^\circ\text{--}4^\circ$.

Figures 2 and 3 present representative $H\alpha$ spectra (*top panels*) from Complex K with the 1° WHAM beam centered at $l = 57^\circ 02$, $b = +49^\circ 22$ and $l = 48^\circ 03$, $b = +36^\circ 49$, respectively. Corresponding $H\text{ I}$ 21 cm spectra centered at $l = 57^\circ 0$, $b = +49^\circ 0$ and $l = 48^\circ 0$, $b = +36^\circ 5$ from the Leiden-Dwingeloo $H\text{ I}$ survey are displayed in the bottom panel of each figure. These two sight lines sample some of the brighter emission from Complex K. The dashed vertical lines denote the integration range used to construct the $H\alpha$ image and

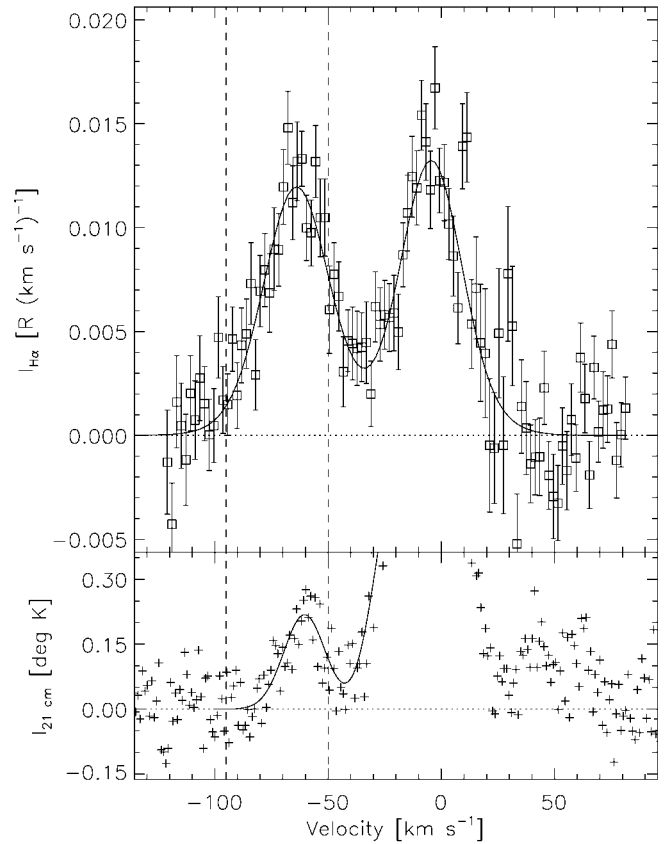


FIG. 2.—*Top*: WHAM $H\alpha$ spectrum of the 1° portion of the sky centered at $l = 57^\circ 02$, $b = +49^\circ 22$. WHAM data is plotted as squares with 1σ error bars. A 3.7 R geocoronal line centered near $v_{\text{LSR}} = +30 \text{ km s}^{-1}$ has been removed from the spectrum. A simple two-component fit to the Galactic emission is shown as the solid line (see text). *Bottom*: $H\text{ I}$ 21 cm emission spectrum toward $l = 57^\circ 0$, $b = +49^\circ 0$ from the Leiden-Dwingeloo $H\text{ I}$ survey. The local emission peaks off the displayed scale near 8.2 K. The solid line denotes the IVC portion of a multicomponent fit (see text). In both panels, the dashed lines denote the integration range used for the image in Fig. 1.

21 cm contours in Figure 1. Since hydrogen has a thermal width of $\sim 22 \text{ km s}^{-1}$ at $T = 10^4 \text{ K}$, we have chosen a restricted integration range to avoid contamination in the image from the local emission component centered near $v_{\text{LSR}} = 0 \text{ km s}^{-1}$. As noted above, the values in the color legend of Figure 1 should be increased by about 20% to estimate the total intensity of a typical Complex K emission line.

The solid lines in the top panels of Figures 2 and 3 represent a Gaussian component fit convolved with the WHAM instrument profile (approximately 12 km s^{-1} FWHM). We also performed a multicomponent fit on the $H\text{ I}$ spectrum. Only the IVC component is shown clearly in the bottom panels of Figures 2 and 3 since little effort was spent trying to accurately model the bright, local 21 cm emission. Figure 3 clearly shows at least two components in the intermediate-velocity neutral gas. A single-Gaussian fit to the $H\alpha$ emission in this direction results in a large ($> 40 \text{ km s}^{-1}$) width, atypical of diffuse gas; a free-fit two-Gaussian profile is not well defined due to the intrinsic ionized gas line widths. Instead, we have chosen to fix the mean velocity of the two components in the $H\alpha$ fit to be the same as those clearly defined in the $H\text{ I}$ profile. The best parameters for our fits are given in Table 1. Channel maps and profile analyses show some variation in the mean velocity of the $H\alpha$ and $H\text{ I}$ emission, with values that fall roughly

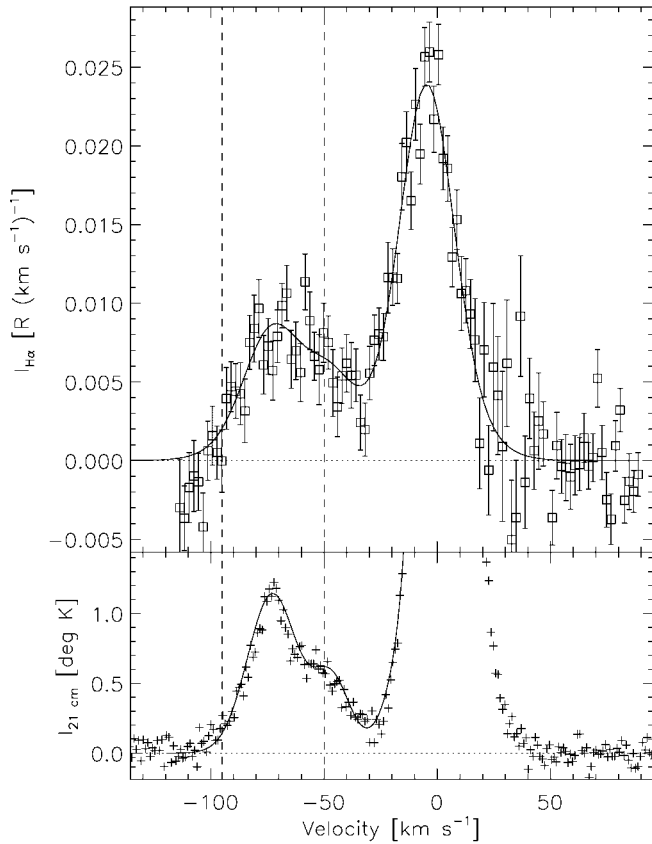


Fig. 3.—Same as Fig. 2, except toward $l = 48^{\circ}03$, $b = +36^{\circ}49$ for $H\alpha$ (top) and $l = 48^{\circ}0$, $b = +36^{\circ}5$ for $H\text{ I}$ (bottom). The local $H\text{ I}$ emission peaks off the displayed scale near 15.8 K .

between -50 and -75 km s^{-1} . There appears to be no systematic velocity gradients in the complex, although the higher velocity $H\text{ I}$ component at -75 km s^{-1} is limited to the two regions of the complex centered at $l = 48^{\circ}$, $b = +37^{\circ}$ and $l = 38^{\circ}$, $b = +62^{\circ}$.

4. DISCUSSION

As reviewed by Wakker (2001), little absorption-line data directly toward Complex K exists at this time, and thus we have little information about its distance, only that it lies between about 0.3 and 7.7 kpc . There is a firm upper limit since the cloud has been seen in absorption (de Boer & Savage 1983; Bates et al. 1995; Shaw et al. 1996) toward M13 ($l = 59^{\circ}$, $b = +41^{\circ}$). Carretta et al. (2000) have recently calculated the distance modulus of M13 to be 14.44 mag , which sets an upper

limit of 7.7 kpc on the distance to that portion of Complex K toward M13. A lower limit to the distance comes from the work of Bates et al. (1995), who included three local stars in their absorption-line study of stars in M13. Two of their targets, HD 151749 and HD 150462, have reliably measured parallaxes (*Hipparcos*; Perryman et al. 1997), which place them at 150 and 175 pc , respectively. Their third target, HD 149802, has an estimated distance of about 270 pc given that it and HD 150462 have both been classified as A0 but differ in V brightnesses by 0.9 mag . They did not detect Complex K absorption in either Ca II or Na I toward any of these stars.

If the entire complex is at a common distance, then its angular extent, from $b = +30^{\circ}$ to $b = +70^{\circ}$, corresponds to a length of $0.68d\text{ kpc}$ and a maximum vertical extent above the midplane of $0.94d\text{ kpc}$, where d is the distance to the complex in units of 1 kpc . If instead the complex is a column of gas perpendicular to the Galactic plane at a constant *radial* distance (distance along the Galactic plane) from the Sun, its length is $2.2r\text{ kpc}$, where r is the radial distance of the complex from the Sun in units of 1 kpc . Gas participating in Galactic rotation toward the center of the complex near $l = 55^{\circ}$, $b = +45^{\circ}$ would be expected to have a radial velocity of $v_{\text{LSR}} = +10\text{ km s}^{-1}$ at 1 kpc up to a maximum (at the tangent point) of $v_{\text{LSR}} = +30\text{ km s}^{-1}$ at 6.5 kpc (Clemens 1985). As a result, the deviation velocity (Wakker 1991) for Complex K is approximately -100 km s^{-1} from that expected by circular rotation.

With few observations of the ionized component of IVCs and HVCs, it is difficult to discriminate among possible candidates for the source of ionization. Since the clouds are moving at anomalous velocities, processes such as ram pressure heating (Weiner & Williams 1996) and radiation produced by a cloud-halo shocked interface have been explored (Tufté et al. 1998) in addition to photoionization by an ambient Lyman continuum flux (Tufté et al. 1998). In the case of Complex K, the relatively diffuse $H\alpha$ emission over the extent of the neutral gas suggests the latter ionization mechanism. However, at its lower distance limit (300 pc), the vertical extent of the complex is only $z = 150\text{ pc}$ to $z = 300\text{ pc}$, fully within the warm ionized medium layer, and its anomalous velocity would likely cause an interaction with the ambient medium. But unless Complex K is falling nearly directly toward us, we find little evidence for an $H\alpha$ enhancement in the morphology due to cloud motion. In support of photoionization by an external or ambient flux, note that while the total $H\text{ I}$ column densities presented in Table 1 for the IVC components vary by a factor of 8, the $H\alpha$ intensities are relatively constant. For the cloud as a whole, we find that the neutral gas displays much higher intensity contrast than the ionized gas in Complex K (see also Figs. 2 and 3). Furthermore, as noted above in § 3, the point-to-point corre-

TABLE 1
SPECTRAL FIT PARAMETERS

Direction (l, b) (deg)	Component	Mean (km s^{-1})	FWHM (km s^{-1})	Intensity
(57.02, +49.22)	$H\alpha$ local	-4.1 ± 0.8	27.0 ± 2.5	$0.50 \pm 0.03\text{ R}$
(57.02, +49.22)	$H\alpha$ IVC	-64.0 ± 0.8	29.0 ± 2.3	$0.48 \pm 0.02\text{ R}$
(57.00, +49.00)	$H\text{ I}$ IVC	-60.4 ± 1.0	22.0 ± 2.5	$(8.9 \pm 0.9) \times 10^{18}\text{ cm}^{-2}$
(48.03, +36.49)	$H\alpha$ local	-4.5 ± 0.5	23.9 ± 1.4	$0.78 \pm 0.02\text{ R}$
(48.03, +36.49)	$H\alpha$ IVC	-47^a	22.2 ± 10.0	$0.15 \pm 0.03\text{ R}$
(48.03, +36.49)	$H\alpha$ IVC	-73^a	24.7 ± 4.6	$0.27 \pm 0.03\text{ R}$
(48.00, +36.50)	$H\text{ I}$ IVC	-46.8 ± 1.1	19.1 ± 2.2	$(1.9 \pm 0.3) \times 10^{19}\text{ cm}^{-2}$
(48.00, +36.50)	$H\text{ I}$ IVC	-72.8 ± 0.6	25.7 ± 1.1	$(5.3 \pm 0.3) \times 10^{19}\text{ cm}^{-2}$

^a For the fit in this direction, the mean velocities of the ionized IVC components have been fixed to be the same as those derived from the fit to the neutral gas. See § 3 for full details.

spondence of the total IVC intensity of the two emission lines is poor. These observations are consistent with photoionizing the skin of a neutral cloud. In this case, the cloud becomes self-shielding from ionizing radiation and N_{H} is independent from the $\text{H}\alpha$ intensity, which becomes mostly a function of incident Lyman continuum flux and geometry.

If a cloud is ionized by an external photoionizing source, the incident Lyman continuum flux on the cloud surface can be estimated (see Tufte et al. 1998). Ignoring the complexity of geometry but applying the maximum possible extinction correction (25%; see § 3) to the sample ionized IVC component in Table 1, we find the incident flux of ionizing photons is $\phi \approx 1.2 \times 10^6$ photons $\text{cm}^{-2} \text{s}^{-1}$ for the brightest $\text{H}\alpha$ regions in Complex K. With the small lower limit on its distance, there is some chance that Complex K is a relatively local feature that could be ionized by nearby sources. A search within 16° of $l = 55^\circ$, $b = +45^\circ$ (the rough center of the brightest regions of the complex) reveals no early spectral type objects with sufficient luminosity to ionize the region, even at its minimum distance of ≈ 300 pc. As noted above, the ionized regions with higher $\text{H}\alpha$ intensities appear to be offset a few degrees from the larger column density neutral regions. To test whether the ionization of the complex could be sustained by a brighter, more distant halo source, we have explored a large region at higher Galactic longitudes than Complex K ($80^\circ < l < 180^\circ$; $+30^\circ < b < +80^\circ$) for possible ionizing sources. In this case, the only potential source appears to be the O9.5 V star HD 93521 ($l = 183^\circ$, $b = +62^\circ$, $d = 1.7$ kpc; Irvine 1989). Given the direction and range of distances possible for Complex K, it is closest to the star when placed about 700 pc away ($z \approx 500$ pc); here they are separated by about 1.5 kpc. Using a value of $\log Q_0 = 48.38$, where Q_0 is the number of hydrogen ionizing photons per second emitted from an O9.5 V star (Vacca, Garmany, & Shull 1996) and taking into account *only* the geometrical dilution of the radiation (i.e., no intervening gas or dust absorption), we find that the ionizing flux at Complex K from HD 93521 is $\phi \approx 8.4 \times 10^3$ photons $\text{cm}^{-2} \text{s}^{-1}$, far short of that needed to maintain the ionization of the complex.

More likely, a scenario similar to those used to explain the

ionization of the warm ionized medium (Miller & Cox 1993; Dove & Shull 1994; Dove, Shull, & Ferrara 2000; Slavin, McKee, & Hollenbach 2000) is also providing the ionizing flux for Complex K. Dove et al. (2000) cite upward halo ionizing fluxes for their various models of the propagation of OB association radiation through the surrounding superbubbles. Their range of calculated values, $\phi \sim 1\text{--}2 \times 10^6$ photons $\text{cm}^{-2} \text{s}^{-1}$, agree well with what is required to maintain the ionization of Complex K. Bland-Hawthorn & Maloney (1999) have produced a model of the propagation of the ionizing flux in the Galactic halo and the resulting $\text{H}\alpha$ emission from halo clouds. We find that our observed $\text{H}\alpha$ intensity is consistent with that expected from their model in the direction of Complex K for distances less than 8 kpc from the Sun (0.15–0.30 R; J. Bland-Hawthorn 2000, private communication). Cooling hot gas generated in supernova remnants has also been shown by Slavin et al. (2000) to provide a mean value of $\phi = 5.4 \times 10^5$ photons $\text{cm}^{-2} \text{s}^{-1}$ to the halo ionizing flux, nearly half that required for the brightest emitting regions in the complex and sufficient alone to sustain the faintest.

With WHAM, we have finally begun to explore the structure of the ionized component of IVCs and HVCs with the $\text{H}\alpha$ line in the same manner as has been done for the neutral gas with the 21 cm line. Furthermore, maps in other optical emission lines such as [S II] and [N II] will provide additional information about the temperature, ionization, and metallicity of the ionized gas (Haffner, Reynolds, & Tufte 1999; Wakker et al. 1999). These future observations have the potential to provide insight not only about the nature of these high-latitude structures but also about the ambient Galactic halo gas and radiation field.

We would like to thank Bart Wakker for the first H I– $\text{H}\alpha$ comparisons in this region, Joss Bland-Hawthorn for providing model results along the Complex K sight line, and Bob Benjamin for continuing halo consultation and Galactic rotation code. Source searches were conducted through the SIMBAD database operated at CDS, Strasbourg, France. WHAM is supported by the National Science Foundation through grant AST 96-19424.

REFERENCES

- Bates, B., Shaw, C. R., Kemp, S. N., Keenan, F. P., & Davies, R. D. 1995, *ApJ*, 444, 672
 Bland-Hawthorn, J., & Maloney, P. R. 1999, *ApJ*, 510, L33
 Bland-Hawthorn, J., Veilleux, S., Cecil, G. N., Putman, M. E., Gibson, B. K., & Maloney, P. R. 1998, *MNRAS*, 299, 611
 Carretta, E., Gratton, R. G., Clementini, G., & Fusi Pecci, F. 2000, *ApJ*, 533, 215
 Clemens, D. P. 1985, *ApJ*, 295, 422
 de Boer, K. S., & Savage, B. D. 1983, *ApJ*, 265, 210
 Dove, J. B., & Shull, J. M. 1994, *ApJ*, 430, 222
 Dove, J. B., Shull, J. M., & Ferrara, A. 2000, *ApJ*, 531, 846
 Haffner, L. M. 1999, Ph.D. thesis, Univ. Wisconsin, Madison
 Haffner, L. M., Reynolds, R. J., & Tufte, S. L. 1999, *ApJ*, 523, 223
 Hartmann, D., & Burton, W. B. 1997, *Atlas of Galactic Neutral Hydrogen* (Cambridge: Cambridge Univ. Press)
 Irvine, N. J. 1989, *ApJ*, 337, L33
 Miller, W. W., III, & Cox, D. P. 1993, *ApJ*, 417, 579
 Perryman, M. A. C., et al. 1997, *A&A*, 323, L49
 Shaw, C. R., Bates, B., Kemp, S. N., Keenan, F. P., Davies, R. D., & Roger, R. S. 1996, *ApJ*, 473, 849
 Slavin, J. D., McKee, C. F., & Hollenbach, D. J. 2000, *ApJ*, 541, 218
 Tufte, S. L. 1997, Ph.D. thesis, Univ. Wisconsin, Madison
 Tufte, S. L., Reynolds, R. J., & Haffner, L. M. 1998, *ApJ*, 504, 773
 Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, *ApJ*, 460, 914
 Wakker, B. P. 1991, *A&A*, 250, 499
 ———. 2001, *ApJS*, in press
 Wakker, B. P., et al. 1999, *Nature*, 402, 388
 Weiner, B. J., & Williams, T. B. 1996, *AJ*, 111, 1156