Distance Constraints for High Velocity Clouds from Optical Emission Lines

Benjamin J. Weiner
Carnegie Observatories, 813 Santa Barbara St., Pasadena, CA 91101

Stuart N. Vogel
Department of Astronomy, University of Maryland, College Park, MD 20742

T.B. Williams
Department of Physics & Astronomy, Rutgers University, 136 Frelinghuysen Rd., Piscataway, NJ 08854

Abstract. We report results from a survey of high velocity clouds and the Magellanic Stream for faint, diffuse optical recombination emission lines. We detect Hα emission with surface brightness from 41 to 1680 mR from HVCs, and from < 40 to 1360 mR in the MS. A simple model for the photoionizing radiation emergent from the Galaxy, normalized to the HVCs A and M with known distances, predicts distances from a few to 40 kpc, placing the faintest HVCs in the Galactic halo, too far away for a Galactic fountain. This model cannot explain the bright and spatially varying Hα in the Magellanic Stream, which requires another source of ionization. However, we do not find any HVCs super-faint in Hα; even with another ionization source, we conclude that the detected HVCs are not more than 2–4 times the distance of the MS (100-200 kpc).

1. Introduction

High velocity clouds are detected primarily in H i; no resolved optical counterparts such as stars have been detected in HVCs, and the only distance upper limits are for two HVCs seen in absorption against background halo stars. The lack of distance constraints makes the nature of and models for HVCs extremely uncertain; see the review of Wakker & van Woerden (1997). Currently favored models include recycling of disk gas through a fountain (e.g. Bregman 1980); stripping from Galactic satellites; and infall of possibly primordial gas (e.g. the Local Group model of Blitz et al. 1999). These models place HVCs at from < 10 kpc to ~ 1 Mpc respectively, a range of 100 in distance and 10^4 in gas mass.

Faint, diffuse optical recombination emission lines are observed from some HVCs. Hα emission must be caused by ionization on the cloud, either from photo-ionization by Lyman continuum radiation, or another process such as collisional ionization. Measurements of Hα flux can constrain HVC distances, given models for the ionization processes.
2. Observations

Observing diffuse emission lines from HVCs is difficult because the emission is faint, night sky emission lines are strong and fluctuating, and HVCs are degrees across, larger than the field of view of most optical telescopes. Fabry-Perot observations of diffuse emission provide large collecting solid angle with moderate to high spectral resolution, needed to separate HVC emission from sky lines. FPs have previously been used to detect Hα emission from four HVCs and the Magellanic Stream (Weiner & Williams 1996, Tufte et al. 1998, Bland-Hawthorn et al. 1998). Chopping by several degrees between object and sky fields is necessary to obtain decent sky subtraction.

Figure 1 shows example spectra from the Wide Field Camera F-P at the Las Campanas 2.5-m, with a field of view of 25′ and etalon FWHM 1.2 Å \( (R = 5500) \). The top panel is a extracted spectrum of a 900 sec exposure of HVC 343+32–140, one of the HVCs brightest in Hα, before subtraction of a sky-field spectrum. The second panel is after a two-step sky subtraction: sky lines in the object-
field and sky-field spectra are fit and subtracted, then the sky-field continuum is subtracted from the object-field continuum. The Hα flux is strong, 1060 milli-Rayleighs (mR), as is [N ii] 6583, with [N ii]/Hα = 1.1. (1 Rayleigh = 10^6 photons cm^{-2} s^{-1} into 4π.) The lower two panels show two HVCs very faint in Hα, HVC 165–43–280 (41 mR) and HVC 230+61+165 (48 mR). The Hα detections agree well with the H i velocities. No [N ii] is detected. Note the tremendous difference in strength of HVC Hα and night-sky lines.

Figure 2 compiles our results from the LCO FP and the Rutgers FP at the CTIO 1.5-m, and HVC Hα detections from Tuft et al. (1998) and Bland-Hawthorn et al. (1998). There is a wide range of HVC Hα intensity, but clouds in the same complex tend to have similar intensities, which suggests that the variations between complexes are due to HVC properties (e.g. distances) rather than extrinsic variations (e.g. spatial variations in the ionizing field escaping from the Galaxy). On the other hand, the Magellanic Stream points vary widely: some points have strong emission while others have weak or no Hα despite a high H i column density. Strong emission in the MS is often located near cloud edges.
A fundamental result of our \( \text{H} \alpha \) survey is that we have not found any cloud near or below our photon-limited noise (generally 10–20 mR at 2\( \sigma \)). The faintest \( \text{H} \alpha \) detections, at 41–50 mR, are well above our noise limit. We always either detect \( \text{H} \alpha \) (15 of 20 HVCs), or are clobbered by residuals from sky-subtraction when HVCs are not well separated from sky lines, raising the detection limit.

3. Models for the source of the emission

If \( \text{H} \alpha \) emission from HVCs is due to photo-ionization by flux from the Galaxy, we can infer distances to the HVCs. We use the HVCs A and M with known distance brackets (4–10 kpc and < 5 kpc; van Woerden et al. 1999, Danly et al. 1993) and \( \text{H} \alpha \) fluxes (Tuft et al. 1998) to normalize a model for the ionizing flux escaping from the Galaxy. Figure 3 shows contours of the ionizing photon flux \( F_{\text{LC}} \) in the model; it has a total ionizing luminosity of \( L_{\text{LC}} = 2.7 \times 10^{53} \) photons s\(^{-1} \), distributed in an exponential disk, and models the Galactic absorbing layer with a one-sided face-on optical depth to ionizing photons of \( \tau = 2.5 \), yielding an overall, angle-averaged escape fraction \( < f_{\text{esc}} > = 2\% \). (See also Bland-Hawthorn & Maloney 1999 and Bland-Hawthorn, these proceedings.)

The inferred distances of HVCs are indicated; the error bars are for systematic variations by a factor 1.5 up or down in \( \text{H} \alpha / L_{\text{C}} \) ratio (statistical errors on the fluxes are much smaller). The brightest clouds are within a few kpc of the Galactic plane but fainter clouds are well away from the plane. These clouds at \( |z| > 10 \) kpc are inconsistent with a Galactic fountain origin, especially given their high velocities.

However, the observed \( \text{H} \alpha \) in the Magellanic Stream cannot be explained by this model; MS II and MS IV are much too bright compared to HVCs A and M. In fact, at a distance of \( D \sim 50 \) kpc, the MS \( \text{H} \alpha \) emission cannot be explained by a reasonable model of photoionization from the Galaxy. The \( \text{H} \alpha \) photon flux is \( F(\text{H} \alpha) = 0.46 \times F_{\text{LC}} \simeq 0.46 \times L_{\text{LC}} / (4\pi D^2) \times e^{-\tau \csc b} \), so that \( \text{H} \alpha \) of 300–600 mR at MS II requires \( \tau = 0.3 - 0 \) and \( < f_{\text{esc}} > = 60 - 100\% \). The required escape fraction is unrealistically large (even if \( L_{\text{LC}} \) were increased by \( \times 2 \)) since most ionizing radiation must be absorbed in the Galaxy to power \( \text{H} \text{II} \) regions. (In agreement with the authors, we find that Bland-Hawthorn & Maloney 1999 overestimated the ionizing flux incident on the MS.) Furthermore, there are strong spatial variations in the MS \( \text{H} \alpha \), shown by the large dispersion of points in Figure 2. Photoionization from the Galaxy should produce roughly the same \( \text{H} \alpha \) flux on any \( \text{H} \text{I} \) surface optically thick to ionizing radiation, since the ionizing photons travel nearly along our line of sight to the MS. Factors of 2–3 variation between different points are tolerable either from variations in the incident field or geometry of the absorbing surface, but factors of 30 are not.

A second source of ionization in the Galactic halo is needed to explain the MS \( \text{H} \alpha \). Simply put, why are some points in the Magellanic Stream brighter than Complexes A and M, despite being much further away? The only likely source is collisional ionization, probably from interaction with hot halo gas through ram pressure and turbulent mixing/thermal conduction (Weiner & Williams 1996).

The MS radial velocities are large and the space velocities with respect to halo gas are probably above 200 km s\(^{-1} \); energy input from ram pressure goes as \( v^3 \), so it may explain the brightness of the MS with respect to HVCs A and M, but
it is barely adequate for reasonable halo gas densities (Weiner & Williams 1996); perhaps the Magellanic Stream clouds are colliding with each other. Collisional ionization is required, but the brightest MS points remain a puzzle.

Recent FUSE detections of O vi absorption in the Magellanic Stream and in a few HVCs provide further evidence for collisional ionization in HVCs (Sembach et al. 2000). O vi can be produced collisionally in hot gas at $T \sim 10^{5.5}$ K, which could arise from the interaction of an H i cloud with hot halo gas, but O vi cannot realistically be produced in HVCs by photoionization from O stars.

4. Conclusions

Given the existence of a second source of ionization in the Galactic halo, simple photoionization models may not yield reliable distances. However, robust predictions can still be made for a relation of Hα flux to distance.

HVCs which are bright in Hα (as HVCs go) are likely only a few kpc from the Galactic plane. The brightest HVCs plotted in Figure 2 (L, GCP, CR) have inferred distances which give them low “deviation velocities” (Wakker & van
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Woerden 1991), so they are not too far from Galactic differential rotation, despite having high $V_{LSR}$; these HVCs could well be recycled disk gas. High $[\text{N} \text{II}]/\text{H}\alpha$ ratios suggest high-metallicity gas photoionized by a hardened radiation field, as in the extraplanar diffuse ionized gas of NGC 891 (Rand 1998).

Conversely, if an HVC is very far from the Galaxy, the only source of ionization is the metagalactic UV background. Then the HVC should be very faint in H$\alpha$, approaching the upper limits on H$\alpha$ emission from isolated extragalactic H I clouds: $<20$ mR at 2$\sigma$ from the Giovanelli-Haynes cloud (Vogel et al. 1995) and $<30$ mR at 2$\sigma$ from the Leo Ring (Donahue et al. 1995).

We do not find any HVCs that are very faint, even though our photon-limited noise is generally 10–20 mR (2$\sigma$): we either detect H$\alpha$, or are limited by sky subtraction residuals. The faintest HVCs we find are 165–43–280, 47–52–129, 227–34+114, and 230+61+165, with H$\alpha$ emission at 41–48 mR. In the photoionization model of Figure 3 their distances are $D = 15, 40, 11, \text{and } 26$ kpc from the Sun. We can push the distances to the limit by considering solely collisional ionization: the HVC H$\alpha$ fluxes are some 5-15 times smaller than the fluxes typical of the Magellanic Stream. If we attribute the H$\alpha$ to interaction with hot halo gas, and assume that the hot gas density falls off as $r^{-2}$ to $r^{-3}$, the HVCs can be at most 2 to 4 times farther than the MS, or 100-200 kpc.

At distances of somewhere between 20 and at most 200 kpc, the H$\alpha$-faint HVCs are not Local Group objects as defined by the Blitz et al. (1999) model. However, their low $[\text{N} \text{II}]/\text{H}\alpha$ ratios suggest low metallicity, and they are not easily produced by a Galactic fountain: for example, HVC 165–43–280, with $V_{GSR} = -240$ km s$^{-1}$, has faint H$\alpha$, is at least 10 kpc away (20 kpc Galactocentric radius), and has a large mass and kinetic energy; perhaps it is infalling tidal debris. The best explanation for these H$\alpha$-faint HVCs is still likely to be gas, of uncertain origin, accreting onto the Galaxy.

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