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PROBABLE DETECTION OF Hα EMISSION FROM A VERY HIGH VELOCITY CLOUD IN CETUS

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ABSTRACT

A high-sensitivity search for Hα emission from a -300 km s^{-1} H I cloud was carried out with the Wisconsin large-aperture Fabry-Perot spectrometer. Weak emission features were found in the Hα spectra at radial velocities coinciding with the 21 cm emission. The features have a total level of significance of 4.3 σ and, therefore, appear to represent the first detection of emission from a high-velocity cloud at a wavelength other than 21 cm. The derived Hα surface brightness of the cloud is $2.0 \pm 0.5 \times 10^{-8}$ ergs cm^{-2} s^{-1} sr^{-1} ($8.1 \pm 1.9 \times 10^{-2}$ R). The source of the excitation is not known; however, the low Hα surface brightness (i.e., less than 0.1 R) appears to place important constraints on the ambient radiation field and gas density. Specifically, the upper limit on the flux of Lyman-continuum photons in the vicinity of the cloud is $F_{\rm LC} \leq 2 \times 10^5$ cm^{-2} s^{-1}, which is almost a factor of 10 lower than the flux estimated to be present within the Galactic halo and is comparable to some estimates for the intergalactic EUV radiation field. Shock models indicate that the ambient gas density is less than 6×10^{-3} cm^{-3}, if the temperature of the ambient medium $T \lesssim 10^6$ K.

Subject headings: galaxies: The Galaxy — interstellar: matter

I. INTRODUCTION

Although high-velocity clouds (HVCs) have been studied in 21 cm for many years, their origin and distance are still not known. If HVCs are located within the Galactic disk or halo as some observations suggest (Cohen 1981, 1982; Sougaila *et al.* 1985; Münch and Zirin 1961; Hulsbosch 1975), then their interaction with the ambient gas and radiation field should produce emission at other wavelengths. However, until now the highest sensitivity searches for emission in the visible (Reynolds 1987) and infrared (Wakker and Boulanger 1986) have been negative. The first probable detection of Hα emission from an HVC is reported below.

II. OBSERVATIONS

The HVC that we observed is a large, relatively isolated cloud in the constellation Cetus, which has been investigated in detail at 21 cm by Cohen (1982). The cloud has a diameter of about 12°, is centered at $l = 165°$, $b = -45°$, and has H I velocities that range from -360 km s^{-1} to -190 km s^{-1} with respect to the local standard of rest (LSR). Cohen has suggested that a steep decrease in H I column densities toward the edges of the cloud may be due to confinement by an external medium. Lower velocity (approximately -110 km s^{-1} and -10 km s^{-1}) H I clouds in the vicinity of this -300 km s^{-1} cloud also have been interpreted as evidence for an interaction between the very high velocity gas and ambient material in the Galactic disk or halo (Cohen 1981, 1982). A subsequent search for weak Hα emission from the lower velocity clouds produced a negative result (Reynolds 1987). This possible interaction, the cloud's very high velocity, and an earlier report of a possible detection of weak Hβ emission from the region by Kutyrev (1985) make this cloud an interesting object for high-sensitivity Hα observations.

The observations were made with the Wisconsin 15 cm, dual etalon Fabry-Perot spectrometer located near Madison. The spectrometer has a circular field of view on the sky $0\overset{\circ}{.}8$ in diameter and a spectral resolving power of 25,000 (12 km s^{-1}). We obtained scans of Hα for two fields within the cloud: field 1 at $\alpha = 2^{\rm h}38\overset{\rm m}{.}0$, $\delta = +10\overset{\circ}{.}5$ and field 2 at $\alpha = 2^{\rm h}47\overset{\rm m}{.}0$, $\delta = +8\overset{\circ}{.}0$ (1950). Within field 1, the 21 cm line has a radial velocity of -337 km s^{-1} (LSR) and a width (FWHM) of 32 km s^{-1}, and within field 2, the 21 cm line has a velocity of -286 km s^{-1} and a width of 40 km s^{-1} (Cohen 1982). The velocities with respect to the Galactic standard of rest (GSR) are -280 km s^{-1} and -243 km s^{-1}, respectively. Each Hα scan sampled the radial velocity interval -412 km s^{-1} to -237 km s^{-1} (LSR). Thus field 2 serves as an "off-source" comparison direction for field 1 and vice versa. This type of observation makes it possible to search for an Hα emission line from the cloud that is comparable to or weaker than diffuse terrestrial or Galactic emission that may be present (e.g., Reynolds *et al.* 1986). A total of 15 scans were obtained for each field on the nights of 1988 December 6–7, 1988 December 10–11, and 1988 December 11–12. Scans of field 1 and field 2 were obtained alternately to eliminate possible systematic effects due to changing air masses and other atmospheric conditions. The mean zenith angle of the observations was 43°, and the total integration time for each field was 6.85 hr. The atmospheric OH emission line at 6553.6 Å and a laboratory thorium line source provided wavelength (radial velocity) calibrations that were accurate to ± 0.05 Å (± 2 km s^{-1}).

The two spectra that result from the sum of the scans in each field are shown in Figures 1*a* and 1*b*. The spectra consist of the accumulated photomultiplier counts in 4.1 km s^{-1} velocity bins plotted versus radial velocity with respect to the LSR.

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Approximately 70% of the counts are detected photons from the sky and 30% are due to thermionic emission from the photocathode. The vertical bars on each data point represent ±1 standard deviation from Poisson statistics; an inspection of the statistical fluctuations of the counts in the original scans has shown that the fluctuations are consistent with Poisson statistics. The radial velocity and full width at half-maximum of the 21 cm emission line in each field is indicated by the horizontal bar. A number of spectral features are apparent in Figures 1*a* and 1*b*. The sharp increase in counts at the red edge of the spectra appears to be due primarily to the sum of the ± first-order Fabry-Perot ghosts associated with the OH λ6553.6 line and the geocoronal Hα line (6562.8 Å). The other features are unidentified, the two narrow and extremely faint (0.06–0.08 R) emission lines at -377 km s^{-1} (6555.1 Å) and -341 km s^{-1} (6555.9 Å), for example. However, the narrowness of these lines (FWHM < 12 km s^{-1}) and the fact that they are similar in the two fields suggest that they are not associated with the HVC.

There do appear to be differences between the spectra in Figures 1*a* and 1*b* that can be interpreted as a slight enhancement in the signal near -330 km s^{-1} in field 1 relative to the signal at that velocity in field 2 and an enhancement in the signal near -280 km s^{-1} in field 2 relative to that in field 1. These differences may be seen more clearly in Figure 1*c*, which is the difference spectrum obtained by subtracting the spectrum in field 2 from the spectrum in field 1. In the difference spectrum, any Galactic and terrestrial spectral features common to both fields should be absent, while any Hα emission from the cloud should appear as an enhancement near -337 km s^{-1} (the field 1 H I velocity) and a depression near -286 km s^{-1} (the field 2 H I velocity). Such a pattern in fact does appear to be present in Figure 1*c*. We have fitted these features with two Gaussians in order to estimate the statistical significance of this pattern and to derive best-fit intensities and radial velocities. Because of the weakness of the features, their widths could not be determined well and, therefore, for the Gaussian fitting were fixed at the widths of the corresponding 21 cm lines, 32 km s^{-1} and 40 km s^{-1} for fields 1 and 2, respectively. The resulting least-squares fit, represented by the solid curve in Figure 1*c*, gives $I_1 = 7.3 \pm 2.5 \times 10^{-2}$ R, $v_1 = -333 \pm 6$ km s^{-1}, and $I_2 = 8.9 \pm 2.8 \times 10^{-2}$ R, $v_2 = -286 \pm 7$ km s^{-1}, for fields 1 and 2, respectively. Within the uncertainties of the fit the radial velocities of the Hα features coincide with the velocities of the 21 cm lines. The absolute surface brightness is based on calibrations that use bright emission nebulae and standard stars (Scherb 1981) and is estimated to have a systematic error that is less than 15%. Because of the cloud's high Galactic latitude, interstellar extinction has been neglected. The best-fit "baseline" (*dotted horizontal line*) indicates that the background continuum in field 1 is approximately 6% higher than that in field 2. This appears to be due primarily to a difference in the number and brightness of stars within the two fields. These Hα results plus the 21 cm data from Cohen (1982) are summarized in Table 1.

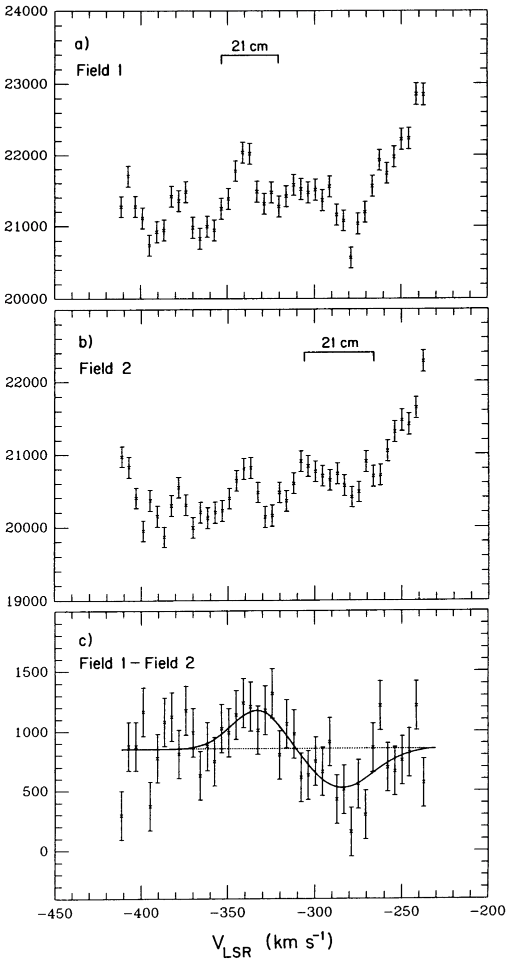

FIG. 1.—The Hα spectra of the high-velocity H I cloud for field 1 (*a*) and field 2 (*b*). Each spectrum is the sum of 15 individual scans obtained on three nights. The spectra consist of the total photomultiplier counts accumulated in 4.1 km s^{-1} velocity bins plotted against radial velocity with respect to the LSR. The radial velocity and full width at half-maximum of the 21 cm emission line in each field is denoted by a horizontal bar. The field 1 spectrum minus the field 2 spectrum (*c*) is shown with an expanded vertical scale. The solid curve drawn through this difference spectrum is a least-squares, two-Gaussian fit to the data (see text). The dotted horizontal line is the best-fit "baseline." The vertical bars on each data point represent ±1 standard deviation from Poisson statistics.

The Gaussian fitting routine indicated that each of the two features in Figure 1*c* has about a 3 σ level of significance providing a total significance of 4.3 σ. The level of significance of the Hα emission signature in Figure 1*c* was estimated independently of this fit by examining the total number of counts within 23 km s^{-1} velocity intervals centered on the H I velo-

TABLE 1

Hα AND 21 CENTIMETER PARAMETERS OF THE CLOUD

			21 cm			Hα	
FIELD	α_{1950}	δ_{1950}	$N_{\rm H\,I}$ (10^{19} cm^{-2})	$V_{\rm LSR}$ (km s^{-1})	$\Delta V_{1/2}$ (km s^{-1})	I (R)	$V_{\rm LSR}$ (km s^{-1})
1.........	$2^{\rm h}38^{\rm m}.0$	+10°.5	7.4	−337	32	$7.3 \pm 2.5 \times 10^{-2}$	-333 ± 6
2.........	2 47.0	+8.0	7.6	−286	40	$8.9 \pm 2.8 \times 10^{-2}$	-286 ± 7

cities; this sampled the peaks of any associated Hα emission lines. The resulting difference between the counts in the two velocity intervals was about 2.5 σ for each of the three nights of observations and 4.3 σ for the sum of the three nights, which is in agreement with the Gaussian fitting routine.

III. DISCUSSION AND CONCLUSIONS

The Hα data presented above indicate that the Hα surface brightness of the -300 km s^{-1} H I cloud in Cetus is ≤ 0.1 R with a best-fit mean value of $8.1 \pm 1.9 \times 10^{-2}$ R ($2.0 \pm 0.5 \times 10^{-8}$ ergs cm^{-2} s^{-1} sr^{-1}). This surface brightness is approximately a factor of 2 below the lowest upper limit derived previously for the Hα surface brightness of other HVCs (Reynolds 1987) and is about a factor of 3 below the value associated with the tentative detection of Hα emission from the intergalactic H I cloud in Leo (Reynolds *et al.* 1986). It also is much less than would be expected (≈ 2 R) if the Hβ detection reported by Kutyrev (1985) were correct.

The source of excitation and the origin and location of this cloud (and of HVCs in general) are uncertain. Cohen (1982) has suggested that the Cetus cloud is debris produced by the tidal interaction between our Galaxy and the Magellanic Clouds, which would place the cloud at a distance $d \lesssim 10$ kpc from the Galactic disk. The very low Hα surface brightness implied by the observations presented above appears to place important, new constraints on the cloud's environment and thus its location. First, the observations provide an upper limit on the flux $F_{\rm LC}$ of ambient Lyman continuum (LC) photons. Since each hydrogen recombination produces on the average 0.46 Hα photons (Martin 1988; Pengelly 1964; case B, $T \sim 10^4$ K), the Hα surface brightness I_α of the cloud due to incident ionizing photons is given by

$$I_\alpha = 4.6 \times 10^{-7} F_{\rm LC}\ {\rm R}\ , \qquad (1)$$

where $F_{\rm LC}$ is in units of photons cm^{-2} s^{-1} and I_α is in rayleighs (R). Therefore, since $I_\alpha \leq 0.1$ R, $F_{\rm LC} < 2 \times 10^5$ photons cm^{-2} s^{-1}. This flux limit is consistent with existing estimates of the intergalactic (QSO) flux of ionizing radiation, which range from 10^4 photons cm^{-2} s^{-1} (Cowie and McKee 1976, and references therein) up to 2×10^5 photons cm^{-2} s^{-1} (Paresce and Jacobsen 1980). Since these estimates predict $0.005\ {\rm R} \lesssim I_\alpha \lesssim 0.1$ R for intergalactic H I clouds (eq. [1]), it is possible that the Cetus HVC is far from the Galactic plane and excited solely by the intergalactic radiation field. On the other hand, if the cloud is close ($d \lesssim 10$ kpc) to the plane, then escaping LC photons from OB stars and a shock formed by the interaction of the cloud with low-velocity gas in the disk or halo could be additional sources of excitation. Based on the standard picture of the Galactic disk Bregman and Harrington (1986) have estimated that the LC flux escaping into the halo is 1.8×10^6 photons cm^{-2} s^{-1} (or larger). This estimate is almost a factor of 10 larger than the upper limit set by the Hα observations, indicating that the Cetus cloud may be in a shadow, or that the interstellar medium is much less transparent to LC photons than Bregman and Harrington have assumed. Furthermore, if the cloud were located within the Galactic disk or halo, an interaction with the ambient gas should produce shock-excited optical emission provided that the cloud's velocity is supersonic (i.e., the ambient gas temperature is $\lesssim 10^6$ K). The intensity of this shock-excited Hα depends upon the density of the ambient gas and the velocity of the shock (HVC). Therefore, since the Hα observations limit the intensity of such a shock, an upper limit can be placed on the density of the ambient gas. To estimate the Hα surface brightness of the shock as a function of ambient density we used the plane-shock model by Hartigan, Raymond, and Hartmann (1987), which can be extrapolated to low ambient densities (J. Raymond, private communication). For a shock velocity of -310 km s^{-1} (mean LSR velocity of the two fields) or -260 km s^{-1} (mean GSR velocity) consistency with the Hα data requires an ambient gas density $n \leq (4\text{–}6) \times 10^{-3}$ cm^{-3}, respectively. A model of the distribution of the mean gas density with distance z from the plane (Reynolds 1989), which is based upon observations of the dispersion measures of pulsars, suggests that such densities are reached at $|z| \geq 2\text{–}3$ kpc. Finally, if the Hα emission is due to H-recombination within the HVC, then the cloud's emission measure ${\rm EM} = 0.22 \pm 0.05 T_4^{0.9}$ cm^{-6} pc (Martin 1988), and its rms electron density $\langle n_e^2 \rangle^{1/2} \approx 1.0 \times 10^{-2} T_4^{0.45} d_{10}^{-0.5}$ cm^{-3}, where T_4 is the temperature in units of 10^4 K and d_{10} is the distance in units of 10 kpc. Since the corresponding mean density of neutral hydrogen $\langle n_{\rm H\,I} \rangle \approx 1 \times 10^{-2} d_{10}^{-1}$ cm^{-3}, the Hα data suggest that a significant fraction ($\approx$30%–50% for $d_{10} = 2$ kpc to 10 kpc and $T_4 = 1$) of the gas in the HVC may be H$^+$. The recombination time, $\tau = 1/\alpha_{\rm H} n_e \approx 1 \times 10^7 T_4^{0.36} d_{10}^{0.5}$ yr, therefore, limits the time since any transient ionization of the cloud may have occurred.

In summary, a high-sensitivity search for Hα emission from a -300 km s^{-1} H I cloud has shown that the Hα surface brightness of the cloud is ≤ 0.1 R. The data indicate a mean Hα surface brightness of about 8×10^{-2} R at the 4.3 σ level of significance. The source of this excitation is unknown; however, the observations place significant limits on the ambient radiation field and gas density, which provide some new constraints on the nature and location of the cloud. Further optical emission line observations of this cloud and other HVCs, particularly with higher sensitivity techniques, would seem to be very desirable.

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