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THE CO $J = 2 \rightarrow 1$ EMISSION FROM THE INTERSTELLAR GAS TOWARD ZETA OPHIUCHI

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ABSTRACT

Measurements of the $J = 2 \rightarrow 1$ transition of ^{12}CO have been obtained with a high signal-to-noise ratio. Two distinct velocity components are seen—one at the velocity of the strongest optically observed atomic lines and a weaker, second component at the velocity of the CH^+ absorption line. This second component has a full width at half-intensity of ~ 0.4 km s^{-1}, considerably narrower than the CH^+ line. These new observations place severe constraints on the shock models used to reproduce the CH^+ abundance.

Subject headings: interstellar: abundances — interstellar: molecules

I. INTRODUCTION

In this *Letter* we present observations of ^{12}CO emission in the $J = 2 \rightarrow 1$ line arising from the cloud toward ζ Ophiuchi. The diffuse cloud toward ζ Oph is, in many ways, the prototypical cloud. Its rich absorption-line spectrum provides clues to the molecular chemistry of regions in the interstellar medium permeated by the ambient ultraviolet flux of the Galaxy. The observations at high spectral resolution of CH^+ and atomic species, such as Na I, made by Hobbs (1973) indicates the presence of a shift in the velocity at line center for CH^+ relative to other species. Radio observations of ^{12}CO and CH (Liszt 1979) show that the strongest emission arises from components at the velocity of the atomic lines, not that of the molecule CH^+. Elitzur and Watson (1978, 1980) incorporated this information into a model for the production of CH^+.

Under ambient, steady state conditions, ion-molecule chemical schemes (Black and Dalgarno 1973) are able to reproduce the abundance of CH, but predict CH^+ abundances that are two to three orders of magnitude below the observed ones. Elitzur and Watson (1978) suggested that the high temperature reaction,

$$C^+ + H_2 \rightarrow CH^+ + H - 0.4 \text{ eV},$$

can produce the observed amounts of CH^+ when, for instance, the gas is heated by a passing shock wave with a velocity of ~ 10 km s^{-1}. One manifestation of their model is that a shift in the CH^+ velocity relative to other species is expected. Thus, the diffuse cloud toward ζ Oph is considered to represent a strong case for the shock model (see also Pineau des Fôrets *et al.* 1986 and Draine 1986, who incorporate the effects of a magnetic field on the shock structure). One might expect CO in the postshock gas to have a thermal line width of ~ 2.5 km s^{-1}, in agreement with the observed CH^+ line width. Our CO data are inconsistent with this expectation.

II. OBSERVATIONS

The $J = 2 \rightarrow 1$ line of ^{12}CO was observed with a cooled Schottky-diode receiver on the 4.9 m telescope of the Millimeter Wave Observatory[1] at McDonald Observatory. The data were collected in two filterbanks of 128 channels each; the frequency resolutions of the two filterbanks were 62.5 kHz and 250 kHz. The measurements were acquired by position-switching at an offset (30′ N, 30′ E) to the direction of ζ Oph. The total integration time was 4.7 hr.

Figure 1 shows the $J = 2 \rightarrow 1$ spectra for both filter banks. Least-squares fits to the data with Gaussian profiles are displayed by the thicker curves in the figure. The results of the fitting routine are given in Table 1, where T_A^*, v_{LSR}, and Δv are listed for the two components. Both spectra indicate the presence of a weaker second velocity component at $v_{LSR} = +0.5$ to $+0.6$ km s^{-1}, the velocity of CH^+ absorption (Hobbs 1973). This second component is redshifted by ~ 1.4 km s^{-1} from the primary component seen in neutral atoms and molecules. (In the standard picture of CH^+ chemistry in a shock, the primary component corresponds to the cold postshock gas, while the second component corresponds to the hot postshock gas.) The major difference between the lines of CO and CH^+ in the second component is that the CO line is much narrower: $\Delta v(\text{CO}) \approx 0.4$ km s^{-1}, while $\Delta v(\text{CH}^+) \approx 3.9$ km s^{-1}.

III. DISCUSSION

Liszt (1979) displayed the spectra of CO and CH, showing that additional emission occurs at velocities similar to that for CH^+ absorption. In particular, a plateau of emission of weaker intensity appears at velocities redshifted from the

[1] The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory of the University of Texas at Austin, with support from the National Science Foundation and McDonald Observatory.

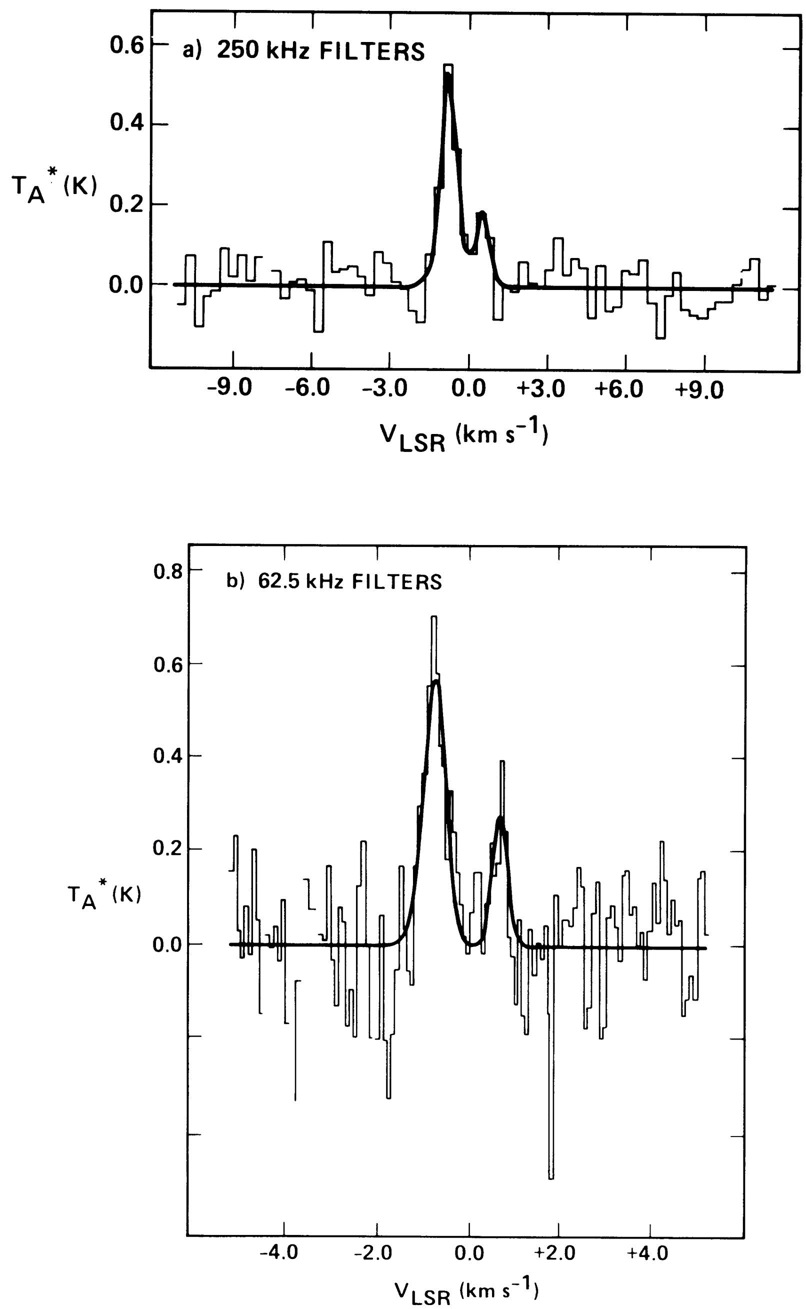

FIG. 1.—The $J = 2 \rightarrow 1$ spectrum of CO toward ζ Oph: (a) data from the 250 kHz filters, and (b) data from the 62.5 kHz filters

TABLE 1

PARAMETERS FOR THE ^{12}CO $J = 2 \rightarrow 1$ LINES

Filters	T_A^* (K)	v_{LSR} (km s^{-1})	Δv (km s^{-1})
250 kHz ...	0.54	−0.76	0.75
	0.20	+0.52	0.59
62.5 kHz ...	0.58	−0.80	0.58
	0.28	+0.63	0.38

main atomic and molecular component. Our data for the $J = 2 \rightarrow 1$ line of ^{12}CO resolves the plateau into a velocity component at +0.6 km s^{-1} (LSR), the velocity of the CH$^+$ line! The width of the second component is equivalent to a thermal broadening of only 100 K, much lower than the thermal broadening of the CH$^+$ line, which is 4000 K. Recently obtained $J = 1 \rightarrow 0$ emission from ^{12}CO also reveals the relatively narrow, second component (Langer, Glassgold, and Wilson 1987).

Another interesting fact emerges when our data are compared to the $J = 1 \rightarrow 0$ data of Liszt (1979) in terms of a Large Velocity Gradient (LVG) Model (cf. Goldsmith, Young, and Langer 1983). The radiation temperature T_R is obtained by dividing T_A^* by $\eta_{\rm fss}$ ($\eta_{\rm fss} = 0.85$ for our observations). The ratios of $T_R(J = 2 \rightarrow 1)$ to $T_R(J = 1 \rightarrow 0)$ are ~ 0.5 for the main component and ~ 0.7 for the component that corresponds to the CH^+ velocity. When a kinetic temperature of 30 K is assumed for the main component, the abundance of CO, x(CO), is 7.8×10^{-7} (for a velocity gradient of 1 km s^{-1} pc^{-1}) and a density of ~ 500 cm^{-3}; these values are in excellent agreement with ultraviolet observations and with the results of a chemical model for this cloud (van Dishoeck and Black 1986). The agreement between the results of the LVG analysis and the ultraviolet observations lends confidence to applying the LVG model also to the second component. The same kinetic temperature for the weaker component yields the inconsistent results of lower x(CO) but higher densities. If, instead, the ratio is taken to be 0.5, which is within the uncertainties of the measurements, the LVG analysis indicates that $x(\mathrm{CO}) \approx 2.3 \times 10^{-7}$ and $n \approx 500$ cm^{-3}. On the other hand, a slightly higher kinetic temperature (~ 100 K), corresponding to the thermal width of the line, may pertain to the weaker component; then the analysis shows that the appropriate values are, respectively, $1.4–3.7 \times 10^{-7}$ and 200–500 cm^{-3}.

These results are difficult to comprehend from the perspective of shock models for CH^+ production. Why do the weaker of the CO lines and the CH^+ line have velocities that differ by at most 0.1 km s^{-1}? The chemical models of Mitchell and Watt (1985), Pineau des Fôrets *et al.* (1986), and Draine and Katz (1986) do produce enhanced amounts of CO behind the shock with x(CO) attaining values as large as 4×10^{-6}, but then if the CO is forming in the shock, why is its linewidth so narrow? The LVG analysis suggests that both CO components have similar densities. Thus, the analysis of the radiative transfer leads to the possible conclusion that there are two comparable, cold clouds along the line of sight to ζ Oph.

One possible explanation of the narrower CO line involves chemical dynamics. When C^+ and H_2 react to form CH^+ at elevated energies, the heavy C^+ ion may "pick up" an H atom from the light H_2 molecule and retain a substantial fraction of the translational kinetic energy. On the other hand, the reactions leading to CO involve the production of CO^+ (C^+ with OH and CH^+ with O; Mitchell and Watt 1985) and are between a heavy ion and a heavy neutral. These reactions are likely to proceed through a more complex collision in which the translational energy is transmitted to the lighter H atom, leaving the CO^+ translationally cold. Since in magnetohydrodynamic shocks the temperature of the neutral species behind the shock ($T_n < 1000$ K) is less than that attained by the ions, the neutral molecule CO might be expected to track T_n and thus have a narrower thermal width than an ion. As mentioned above, however, CO is tied to the ions through its formation. Further clarification of these issues requires additional measurements and modeling.

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