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TWO POPULATIONS OF DIFFUSE MOLECULAR CLOUDS

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ABSTRACT

We observed 16 diffuse clouds and eight high-latitude molecular clouds in the $J = 2$–1 transition of CO and ^{13}CO and compared their properties. Results suggest that the diffuse clouds are not a homogeneous population of molecular clouds but can be divided into two groups depending on the column density of CO. The two groups have very different CO abundances. One group consists of "CO-poor" clouds with $N(\mathrm{CO}) < 4 \times 10^{14}$ cm^{-2} and $N(\mathrm{CO})/N(\mathrm{H}) < 10^{-6}$. The other consists of "CO-rich" clouds with mean $N(\mathrm{CO}) = 4.2 \times 10^{16}$ cm^{-2} and $N(\mathrm{CO})/N(\mathrm{H}) \approx 1.7 \times 10^{-5}$. Comparing the mean CO properties of the objects studied, such as $T_R{}^*$, Δv, $T_R{}^*(\mathrm{CO})/T_R{}^*(^{13}\mathrm{CO})$, $N(\mathrm{CO})$, and $N(\mathrm{CO})/N(\mathrm{H})$, we find that the high-latitude clouds resemble the CO-rich diffuse clouds. The transition from the CO-poor to the CO-rich clouds occurs over a range of $E(B-V)$, indicating that the transition is not determined by extinction alone. This is consistent with models of CO self-shielding, and we suggest that the transition from one group to the other is the result of different UV radiation fields, cloud densities, carbon abundances, cloud ages, or a combination of these effects.

Subject headings: interstellar: abundances — interstellar: molecules

I. INTRODUCTION

The recently discovered high-latitude molecular clouds (HLCs) (Blitz, Magnani, and Mundy 1984) have introduced a vexing problem for understanding interstellar clouds. The mean extinction, A_v, averaged over regions of detectable CO emission is measured to be 0.6 mag (Magnani and de Vries 1986), similar to measurements of diffuse molecular clouds. Yet CO abundance measurements (Magnani, Blitz, and Wouterloot 1988) find a mean value for $N(\mathrm{CO})/N(\mathrm{H_2})$ to be 5×10^{-5}, typical of the value for dark clouds having much higher extinctions, and two orders of magnitude greater than typical diffuse cloud values of $\leq 10^{-6}$. Why then do the HLCs have optical properties similar to diffuse clouds, but CO abundances like those of dark clouds?

To answer this question, we have made sensitive CO and ^{13}CO measurements toward a number of diffuse clouds and HLCs. The results suggest that the diffuse clouds are an inhomogeneous class of objects which can be separated according to their CO column density. The diffuse clouds with high CO column densities appear to be indistinguishable from the HLCs.

II. OBSERVATIONS

We observed 16 diffuse clouds along stellar lines of sight in the $J = 2$–1 rotational transition of CO. Diffuse molecular clouds are generally considered to be objects with $A_v \leq$ 1–2 mag of extinction; they are relatively transparent and stars are readily visible through them in both the optical and ultraviolet portions of the spectrum. In the present sample, all but two stars have $E(B-V) < 0.9$ mag, and the clouds in front of all of them have been previously classified as "diffuse." The clouds have been studied using optical absorption lines (Adams 1949; Cohen 1973; Hobbs 1973), and many have been studied by ultraviolet absorption of CO (Federman *et al.* 1980). A number of the sources have also been detected in the $J = 1$–0 transition of CO, but none have been detected in ^{13}CO except for ζ Oph (Dickman *et al.* 1983; Knapp and Jura 1976; Langer, Glassgold, and Wilson 1987). For comparison, eight high-latitude molecular clouds from the Magnani, Blitz, and Mundy (1985) survey were observed in CO ($J = 2$–1). For every line of sight along which CO was detected with $T_A{}^* > 1$ K, ^{13}CO ($J = 2$–1) or ^{13}CO ($J = 1$–0) was sought, with the exception of HD 154368.

The observations were carried out using the 4.9 m telescope of the Millimeter Wave Observatory[2] near Fort Davis, Texas, during 1986 January, February, and March. The observations of the diffuse clouds were frequency-switched by 3 MHz and the observations of the high-latitude clouds were position-switched, using emission-free reference positions determined from the maps of Magnani, Blitz, and Mundy (1985). Signals were simultaneously processed using the 62.5 kHz (0.08 km s^{-1}) and 250 kHz (0.33 km s^{-1}) resolution filterbanks. Integration times were chosen to produce a signal-to-noise ratio of approximately 10 for the CO detections, of at least 5 for the ^{13}CO detections and a noise level ≤ 0.3 K (rms) for the nondetections.

Standard chopper wheel calibrations were performed before every scan. Antenna temperatures were corrected for forward scattering and spillover. The resulting temperatures are presented as $T_R{}^*$ (Kutner and Ulich 1981). The value for η_{fss} was taken to be 0.90 ± 0.03. The globule B5 was monitored daily as a calibration source and was measured to have average antenna temperatures, $T_A{}^* = 8.8$ K in CO and $T_A{}^* = 3.8$ K in ^{13}CO.

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Two sources were also observed in the $J = 1$–0 transition of CO and ^{13}CO. HD 26571 was observed at MWO in 1986 June and HD 21389 was observed using the SIS receiver at the 12 m NRAO[3] telescope in 1986 June.

III. RESULTS

Of the 16 diffuse clouds observed, CO was detected in seven. CO was sought but not detected at an rms level of <0.3 K toward the remaining nine lines of sight. ^{13}CO was sought along six lines and sight and was detected in five clouds. In only one case, X Per, was CO detected with $T_A^* > 1$ K and ^{13}CO not detected. Eight high-latitude clouds were observed and detected in CO, and five of these clouds were observed and detected in ^{13}CO.

[3] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

Table 1 summarizes the results of the observations of the diffuse clouds and the high-latitude clouds. The velocity, v, is given with respect to the local standard of rest, and Δv is the full width at half-maximum. In order to ensure that the radio detections correspond to the optically identified diffuse clouds, only the lines with velocities which correspond to the optical interstellar line velocities were analyzed. Line parameters were determined from Gaussian fits to the spectra. Also presented are $E(B-V)$, N(CO) and N(CO)/N(H) for the sources studied. Upper limits to the CO column densities were calculated for sources that were not detected in CO by assuming the CO emission is optically thin and the CO antenna temperature is 3 times the rms noise. These upper limits are consistent with UV measurements of CO listed in Table 1B (Federman *et al.* 1980).

For sources where both CO and ^{13}CO were unambiguously detected, $N(^{13}$CO) was determined by assuming the ^{13}CO emission is optically thin. N(CO) was then estimated by

TABLE 1

RESULTS

A. DETECTIONS

Object	Position α(1950)	Position δ(1950)	$E(B-V)$	V (km s^{-1})	CO T_R^* (K)	CO ΔV (km s^{-1})	CO rms (K)	^{13}CO T_R^* (K)	^{13}CO ΔV (km s^{-1})	^{13}CO rms (K)	N(CO) (10^{16} cm^{-2})	N(CO)/N(H) (10^{-5})
					$J = 2$–1							
o Per	03h41m11s	32°07′54″	0.32	8.6	6.4	1.8	0.4	1.0	1.1	0.3	7.2[a]	3.8
HD 21389	03 25 54	58 42 26	0.54	−10.5	3.8	2.3	0.2	...[b]	...	...	3.6[c]	1.2
X Per	03 52 15	30 54 26	0.62	7.8	1.6	1.5	0.1	<0.27	...	0.09	<1.8[d]	<0.5
HD 26571	04 09 53	22 17 12	0.29	10.3	3.3	1.8	0.3	...[b]	...	...	6.63[e]	3.93
HD 154368	17 03 08	−35 23 05	0.87	5.5	3.1	1.4	0.2	...	...	...	...[f]	...
HD 169454	18 22 24	−14 00 25	1.13	5.9	3.5	1.4	0.3	0.7	0.6	0.2	2.8	0.4
HD 208501	21 53 12	56 22 26	0.76	−1.6	3.8	1.3	0.1	0.4	1.2	0.1	3.2	0.7
MBM 12	02 54 00	19 20 00	...	−5.4	6.0	1.8	0.2	1.0	1.6	0.1	10.0	...
MBM 25	08 01 12	46 00 00	0.42	−8.4	3.7	1.7	0.3	...	...	...	...	...
MBM 26	08 02 56	63 43 00	0.39	−0.5	3.9	0.7	0.3	0.4	0.4	0.1	10.0	...
MBM 40	16 08 24	21 57 00	...	3.4	3.8	1.1	0.2	0.6	0.6	0.1	2.4	...
MBM 41	16 48 18	60 05 00	0.45	−23.0	2.0	1.6	0.2	...	...	...	...	...
MBM 42	16 50 06	60 55 00	0.35	−19.75	0.57	4.44	0.09	...	...	...	...	...
MBM 51	21 51 12	12 40 00	0.26	8.5	5.0	0.9	0.4	0.8	0.6	0.2	3.2	...
MBM 55	23 05 54	14 49 00	1.55	−8.1	4.3	2.8	0.3	1.7	1.2	0.2	13.0	...
					$J = 1$–0							
HD 21389	...	...	...	−10.5	5.0	1.1	0.1	0.7	0.7	0.1	...	...
HD 26571	...	...	...	10.3	4.9	1.6	0.3	0.7	1.2	0.1	...	...

B. NONDETECTIONS

Object	α(1950)	δ(1950)	$E(B-V)$	T_R^* (K) (rms)	N(CO) (10^{14} cm^{-2})	N(CO)/N(H) (10^{-6})	N(CO)-uv (cm^{-2})
π Sco	15h55m49s	−25°58′18″	0.08	0.1	<2.1	<0.4	9.0×10^{11}
δ Sco	15 57 22	−22 28 51	0.16	0.1	<2.1	<2.2	6.4×10^{12}
w^1 Sco	16 03 53	−20 32 07	0.22	0.1	<2.1	<1.6	1.3×10^{12}
υ Sco	16 09 05	−19 19 56	0.27	0.1	<2.1	<1.4	5.4×10^{12}
σ Sco	16 18 09	−25 28 30	0.40	0.2	<4.2	<1.8	...
χ Oph	16 24 07	−18 20 42	0.52	0.2	<2.8	<0.9	...
μ Nor	16 30 31	−43 56 28	0.38	0.2	<4.2	<1.9	$>3.1 \times 10^{13}$
67 Oph	17 58 53	02 55 57	0.12	0.06	<1.27	<1.82	8.0×10^{12}
55 Cyg	20 47 14	45 55 42	0.55	0.1	<2.1	<6.5	...

[a] $N(\mathrm{CO})_{\mathrm{UV}} \approx 5 \times 10^{14}$ cm^{-2} (Snow 1975).

[b] Observed in the $J = 1$–0 transition of CO and ^{13}CO.

[c] $N(\mathrm{CO})_{\mathrm{UV}} < 10^{14}$ cm^{-2} (Dickman *et al.* 1983).

[d] An upper limit to the CO column density was also calculated for X Per, where ^{13}CO is below 3 σ detection. This upper limit was estimated by further assuming that the ^{13}CO antenna temperature is 3 times the rms noise and that $\Delta v(^{13}\mathrm{CO}) = 0.68\ \Delta v(\mathrm{CO})$, where 0.68 is the average ratio of the ^{13}CO to CO FWHM linewidths for all ^{13}CO detections.

[e] $N(\mathrm{CO})_{\mathrm{UV}} \geq 10^{16}$ cm^{-2} (Joseph *et al.* 1986).

[f] $N(\mathrm{CO})_{\mathrm{UV}} \approx 8.9 \times 10^{15}$ cm^{-2} (Dickman *et al.* 1983).

assuming a value for the $CO/^{13}CO$ abundance ratio, R. CO column densities were calculated for the terrestrial abundance, $R = 89$. Fractionation of ^{13}CO is not expected to be important in these low-extinction clouds since any enhanced formation of ^{13}CO may be balanced by the ^{13}CO photodissociation (van Dishoeck and Black 1986).

CO column densities were also calculated for these sources, using the LTE approximation. Using this method, we found the average optical depth for ^{13}CO, τ_{13}, to be approximately 0.16, indicating that the optically thin assumption of the first method is valid. Column densities determined using the LTE approximation are consistent with those determined using the optically thin assumption, agreeing within a factor of 2.

Column densities, determined for *o* Per, HD 21389, and HD 26571 from UV observations of CO are also included as a check to the radio determined values. The UV column densities toward both *o* Per (Snow 1975) and HD 21389 (Dickman *et al.* 1983) are on the order of 10^{14} cm^{-2}, differing from the results ($\sim 10^{16}$ cm^{-2}) of this study. The most likely explanation for this discrepancy is that the stars are at the front face of a dense cloud and most of the molecular material lies behind the stars. *IUE* observations of HD 26571 (Joseph *et al.* 1986) are consistent with our results [$N(CO) \approx 10^{16}$ cm^{-2}] and therefore indicate that most of the molecular material toward HD 26571 lies in front of this star.

In order to compare the CO abundances in these clouds to those in high-latitude and dark clouds, we determine N(H) from measured reddening of stars, using

$$N(\mathrm{H}) = N(\mathrm{H\ I}) + 2N(\mathrm{H_2}) = 5.8 \times 10^{21}\ E(B-V)\ \mathrm{mag^{-1}\ cm^{-2}}$$

(Savage and Mathis 1979).

IV. DISCUSSION

Earlier studies of CO emission from diffuse clouds by Knapp and Jura (1976) and Dickman *et al.* (1983) did not detect ^{13}CO, except toward *o* Per, and therefore the CO emission was assumed to be optically thin. Surprisingly, in the present study, ^{13}CO was detected everywhere that it was sought, with the exception of X Per. Furthermore, the mean ratio of $T_R^*(CO)/T_R^*(^{13}CO)$ is approximately 7. This indicates that the CO emission is *not optically thin.* The observations of Knapp and Jura (1976) and Dickman *et al.* (1983) were insufficiently sensitive to detect the weak ^{13}CO lines present in Table 1. Also a number of the CO lines detected in the Knapp and Jura study (1976) were actually detections of telluric CO (G. Knapp, private communication).

Figure 1 plots log N(CO) versus $E(B-V)$ for the diffuse clouds observed (UV column densities are plotted for both *o* Per, HD 21389, and HD 154368). The clouds are clearly separated into two groups; four have $N(CO) > 10^{16}$ cm^{-2}, and 11 have $N(CO) < 10^{15}$ cm^{-2}. This separation suggests that the diffuse clouds are not a homogeneous population of molecular clouds, but can be divided into two distinct groups depending on their CO column densities. Furthermore, since N(H) is proportional to $E(B-V)$, the two group are also separated according to CO abundance. The former groups are "CO-poor" clouds with $N(CO)/N(H) < 10^{-6}$ and the latter are "CO-rich" clouds with $N(CO)/N(H) \approx 1.7 \times 10^{-5}$.

Three high-latitude clouds are also plotted in Figure 1. Values for extinction were taken from Magnani, Blitz, and Mundy (1985) who calculated them from estimates of the total hydrogen column density for the lines of sight observed. From the figure, we see that the high-latitude molecular clouds fall into the regime of the CO-rich diffuse clouds. If we compare

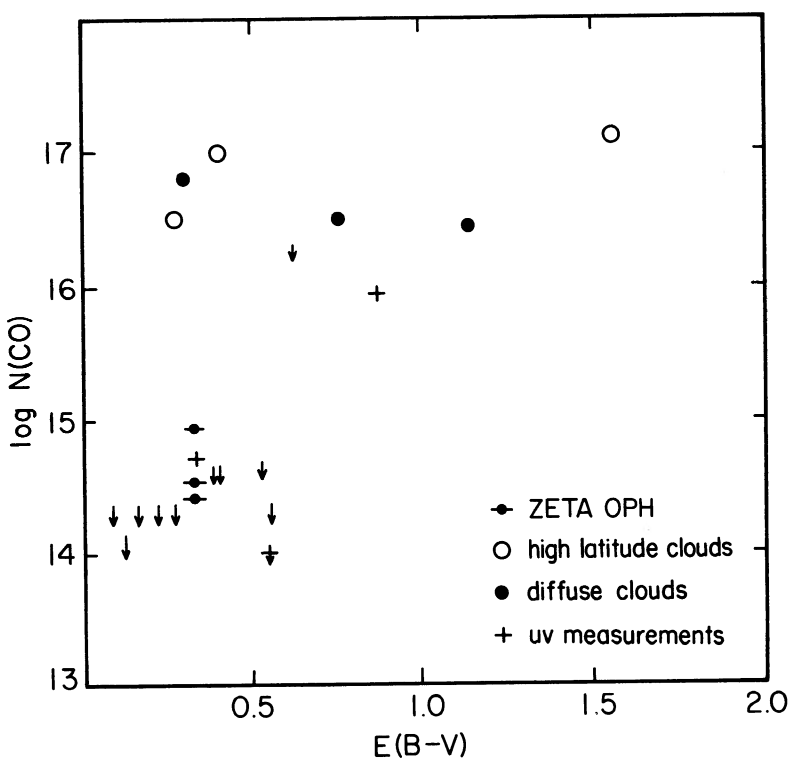

FIG. 1.—Log N(CO) vs. $E(B-V)$ for the column densities listed in Table 1. Column densities determined from UV measurements of CO are plotted for both *o* Per and HD 21389, since the radio-based determinations may be contaminated by background molecular clouds, and for HD 154368, since ^{13}CO measurements are not available for this source.

TABLE 2

MEAN CO PROPERTIES

Mean Property	CO-poor Clouds	CO-rich Clouds	High-latitude Clouds	Dark Clouds
T_R*(CO 2–1) (K)	<0.2 rms	3.3	3.7	...
FWHM(CO) (km s^{-1})	...	1.6	1.9	...
T_R*(CO)/T_R*(^{13}CO)	...	7.0	6.2	...
N(CO) (cm^{-2})	$<4.2 \times 10^{14}$	4.2×10^{16}	7.7×10^{16}	10^{17} [a]
N(CO)/N(H)	$<6.0 \times 10^{-7}$	1.7×10^{-5}	2.5×10^{-5} [b]	3.0×10^{-5} [a]

[a] Thaddeus 1977.
[b] Magnani, Blitz, and Wouterloot 1987.

the average CO properties of the two groups (see Table 2), we find that the HLCs are indistinguishable from the CO-rich clouds. In addition, one can see from Table 2 that the high-latitude molecular clouds and the CO-rich diffuse clouds resemble dark clouds in their CO abundance, in spite of their much lower extinctions.

For completeness, we also plot the position of Zeta Oph from the recent work of Langer, Glassgold, and Wilson (1987). Their work shows that there are three diffuse clouds along the line of sight to the star, and all are CO-poor.

To understand the reason for the two populations of diffuse clouds, we consider the effects of CO self-shielding. The amount of CO observed in molecular clouds is determined by the competition between the rates of CO formation and the rates of CO destruction. CO is formed by gas phase chemical reactions. In diffuse molecular clouds and near the edges of dense clouds, CO is primarily destroyed by photodissociation due to absorption of ultraviolet background radiation. Photodissociation of CO has been studied by Bally and Langer (1982), Glassgold, Huggins, and Langer (1985), and van Dishoeck and Black (1986, 1987), who find that CO is mainly dissociated by line absorption of UV radiation rather than continuous absorption. Line absorptions can be saturated and therefore at large enough column depths the molecules are self shielded from the UV radiation. For CO, model calculations predict that this occurs at a column density of approximately 10^{14} cm^{-2} (van Dishoeck and Black 1987). Once a molecular cloud reaches the threshold, $N(CO) \approx 10^{14}$ cm^{-2}, the CO becomes self-shielding, resulting in enhanced CO abundances. This is strikingly similar to what is observed. The CO poor clouds have CO column densities less than 4.2×10^{14} cm^{-2}. The CO-rich clouds have an average column density of 4.2×10^{16} cm^{-2}, at least two orders of magnitude greater than the column densities of the CO-poor diffuse clouds. Therefore the existence of these two populations of molecular clouds reflects the difference in the ability of the CO in the clouds to be self-shielded.

It is interesting to note that the transition from the CO-poor clouds to the CO-rich clouds does not occur at a single $E(B-V)$ but instead occurs over a range of $E(B-V) = 0.29$–0.55 mag (Fig. 1). The values of $E(B-V)$ were determined from observed colors and spectral types and therefore the errors in $E(B-V)$ are small, on the order of a few hundredths of a magnitude, and the overlap of the two populations is real. This indicates that the transition from one population to the other or the point at which a cloud becomes self-shielding is not solely dependent on extinction. Consequently, other physical effects that influence the formation and destruction rates of CO must be important in producing the transition.

The UV heating of the clouds in this sample, for example, is likely to be different from one cloud to another because the radiation field is inhomogeneous on scales smaller than the mean separation between O and B stars, the relevant scale for these observations. Therefore individual clouds probably suffer different rates of photodissociation, which could allow higher CO abundances to be produced in regions of relatively low UV radiation density. The overlap may also be a result of different mean densities or different carbon abundances in the two populations of clouds. Both of these factors will affect the formation rate of CO and hence influence the point at which the cloud will become self-shielding. Finally, the first population, the CO-poor diffuse clouds, may be interpreted as a younger population of molecular cloud that has not yet reached the threshold column density needed for CO self-shielding. The second population, the CO-rich clouds, may be thought of as an older population which has reached the CO self-shielding threshold and therefore has enhanced CO abundances.

It is quite possible that the two populations of diffuse clouds result from a combination of the effects mentioned above. Further studies are needed to determine which mechanism dominates.

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REFERENCES

Adams, W. S. 1949, *Ap. J.*, **109**, 354.
Bally, J., and Langer, W. D. 1982, *Ap. J.*, **255**, 143.
Blitz, L., Magnani, L., and Mundy, L. 1984, *Ap. J. (Letters)*, **282**, L9.
Cohen, J. G. 1973, *Ap. J.*, **186**, 149.
Dickman, R. L., Somerville, W. B., Whittet, D. C. B., Mcnally, D., and Blades, J. C. 1983, *Ap. J. Suppl.*, **53**, 55.
Federman, S. R., Glassgold, A. E., Jenkins, E. B., and Shaya, E. J. 1980, *Ap. J.*, **242**, 545.
Glassgold, A. E., Huggins, P. J., and Langer, W. D. 1985, *Ap. J.*, **296**, 615.
Hobbs, L. M. 1973, *Ap. J.*, **181**, 79.
Joseph, C. J., Snow, T. P., Seab, C. G., and Crutcher, R. M. 1986, *Ap. J.*, **309**, 771.
Knapp, G. R., and Jura, M. 1976, *Ap. J.*, **209**, 782.
Kutner, M. L., and Ulich, B. L. 1981, *Ap. J.*, **250**, 341.
Langer, W. D., Glassgold, A. E., and Wilson, R. W. 1987, *Ap. J.*, **322**, 450.
Magnani, L., Blitz, L., and Mundy, L. G. 1985, *Ap. J.*, **295**, 402.
Magnani, L., Blitz, L., and Wouterloot, J. G. A. 1988, *Ap. J.*, **326**, 909.
Magnani, L., and de Vries, C. P. 1986, *Astr. Ap.*, **168**, 271.

Savage, B. D., and Mathis, J. J. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Snow, T. P. 1975, *Ap. J.* (*Letters*), **201**, L21.
Thaddeus, P. 1977, in *IAU Symposium 75, Star Formation*, ed. T. de Jong and A. Maeden (Dordrecht: Reidel), p. 37.
van Dishoeck, E. F., and Black, J. H. 1986, *Ap. J. Suppl.*, **62**, 109.
———. 1987, in *Physical Processes in Interstellar Clouds*, ed. G. E. Morfill and M. Scholer (Dordrecht: Reidel), p. 241.

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