MOLECULAR CLOUD DENSITIES FROM OBSERVATIONS OF CARBON MONOSULFIDE

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We have made carefully calibrated measurements of the J=1→0 and J=2→1 transitions of CS in 32 molecular sources in order to obtain density and fractional abundance information from the excitation of this molecule. The antennas used provided beams of nearly equal size. The line intensities, which fall between 1 and 5K, have typically been determined with a (1σ) uncertainty of ∿10%. The two transitions show nearly equal intensities and linewidths which are, respectively, about one tenth and one half of the corresponding quantities for CO. Our observations are seen to be in good agreement with the results of excitation calculations involving either a velocity gradient model or a purely micro-turbulent model since in both cases optical depths are small (0.3 to 3.0). Values obtained for $n(H_2)$ *and* $X(CS)/dv/dr$ *from the velocity gradient model fall in the range* $2x10^4$ *to* $2x10^5$ cm^{-3} *and* $3x10^{-11}$ *to* $3x10^{-10}$ $(km\ s^{-1}pc^{-1})^{-1}$ *respectively.*

The accurately calibrated measurement of a number of transitions of a single molecular species provides our only generally applicable method of determining molecular hydrogen densities within molecular clouds. Since carbon monosulfide is a widely observed molecular cloud constituent which has a number of transitions conveniently accessible to millimeter astronomy, we have undertaken a comprehensive study of CS excitation in 32 sources,including both giant molecular clouds and dark clouds. Previous studies of CS (Turner et al 1973; Liszt and Linke 1975; Martin and Barrett 1975) suffered from a number of instrumental limitations and were restricted to a small number of sources.

The data for the CS J=1→0 line at 48991.0 MHz were obtained using a cooled 6mm mixer receiver on the 11m antenna of the National Radio Astronomy Observatory at Kitt Peak with a half power beamwidth of 2.6 arc minutes. The CS (J=2→1) data at 97981.0 MHz were taken at the Bell Laboratories' 7m Antenna in Holmdel, New Jersey with a FWHP beamwidth of 2.1 arc minutes. The receiver used was a cryogenic 60-90 GHz receiver described by Linke, Schneider and Cho (1978). The highest velocity resolution available was 0.2 Kms^{-1} for both

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transitions. Thus filter dilution, a potential problem only for the narrowest lines, was equal for both transitions. The data are summarized in Table 1. For considerably more detail, including source coordinates, linewidths, velocities and errors as well as line profiles, see Linke and Goldsmith (1980).

TABLE 1 CS CORRECTED ANTENNA TEMPERATURES (K)

SOURCE NAME	J=1→0	J=2→1	SOURCE NAME	J=1→0	J=2→1
W3	0.92	1.41	L134N	1.61	0.82
W3(OH)	2.38	2.71	ρ Oph	2.25	1.65
IC1848	0.56	0.38	G350	2.04	2.27
o PER	1.06	0.66	NGC6334	7.86	8.18
TMC	2.59	1.56	Sgr A	3.47	3.49
"(0,2)	2.47	2.29	Sgr B2	2.92	2.45
Heiles Cl 2	1.70	1.31	W33	5.35	5.32
"(-6,8)	2.52	2.08	M17L	5.56	7.74
Ori A	4.23	7.95	M17A	4.01	4.97
OMC2	2.01	4.24	W43	1.08	0.87
Ori B	4.03	5.53	W49	1.50	1.64
L1622	1.25	0.91	W51	2.51	3.80
B227	0.86	0.67	B335	1.22	0.61
Mon R2	3.34	5.06	DR21	3.24	3.16
S255	2.21	2.87	DR21(OH)	4.41	4.25
NGC2264	4.41	4.24	B361	0.66	0.27
L134	1.04	0.40	NGC7538	3.30	3.96

As demonstrated by Liszt and Linke (1975), the CS sources are significantly beam diluted by a 2.5' beam. In order to determine the sizes of some of our sources we obtained a limited number of maps with a resolution of one arc minute at CS(J=2→1) using the 14m antenna of the Five College Radio Astronomy Observatory. In addition, several of the sources were observed with the 10m antenna of the Owens Valley Radio Observatory at CS(J=4→3) with a 0.6 arc minute beam.

The data presented above include various types of molecular clouds, so we do not expect a single radiative transfer model to accurately describe all of them. Rather, we deal with the problem of radiative transfer only sufficiently accurately to derive characteristic conditions in the regions producing the CS emission. For the small optical depths encountered in CS, line intensities predicted by a microturbulent model (Liszt and Leung 1977) are not very different from results which we obtain from a 10 level large velocity gradient (LVG) model. In view of this fact, as well as the relative computational simplicity of the LVG radiative transfer calculations, we have applied the LVG model to all of our CS data to obtain the results summarized in Figure 1.

The most prominent feature of our results is the relatively narrow range of molecular hydrogen densities which characterize the molecular

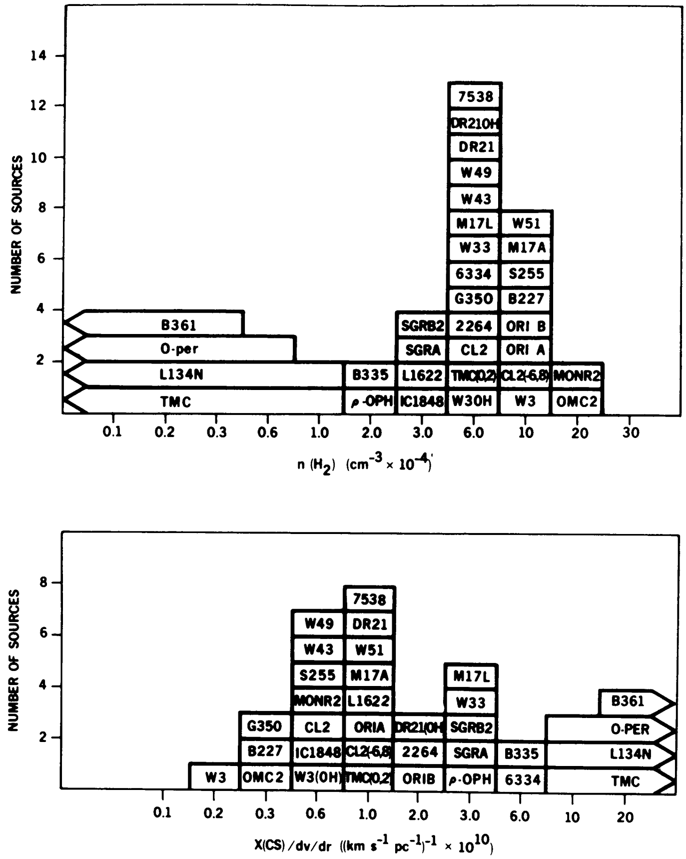

Figure 1 Distribution of molecular hydrogen densities and CS fractional abundances per unit velocity gradient. Arrows indicate no unique solution.

clouds. Our CS observations indicate that there is a density $n(H_2) \simeq 7 \times 10^4$ cm^{-3} characteristic of the central few square arc minutes of the clouds we have studied. The densities derived from CS are about 20 times those derived for a number of sources from ^{13}CO observations (Goldsmith, Plambeck and Chiao 1975; Phillips and Huggins 1977; Plambeck and Williams 1979). Our densities are generally consistent with those derived from observations of methanol (Gottlieb et al 1979) and SO (Gottlieb et al 1978) and about one tenth of those derived from H_2CO observations (Wootten et al 1978). In those cases where the data are available, there is an inverse correlation between the spatial extent of the emission from a particular molecule and the H_2 density derived from the observed line intensities. This is suggestive of systematic radial density gradients.

The CS abundance per unit velocity gradient shows considerable source to source variation with most sources having X(CS)/dv/dr between 3×10^{-11} and 6×10^{-10} (km s^{-1} pc^{-1})$^{-1}$. We can estimate the velocity gradient and therefore the fractional abundance itself for those sources for which we have cloud dimensions. These results are listed in Table 2 together with the total mass implied by the observations. Half intensity source sizes for Ori-B, M17L and W51 are from Liszt and Linke (1975).

TABLE 2 CS SOURCE PARAMETERS

NAME	SIZE (arc min)	MEAN RADIUS (pc)	X(CS)	H_2 DENSITY (cm^{-3})	TOTAL MASS ($m_\odot$)
W3(OH)	1.0x1.6	1.3	1.8×10^{-10}	6×10^4	2.5×10^4
Orion A	1.1x4.4	.35	5.0	10	8.2×10^2
Orion B	2x5	.30	9.2	10	5.1×10^2
Mon R2	2.5x2.5	.31	4.0	20	1.1×10^3
M17L	3x3	1.0	7.5	6	1.2×10^4
W51	4x3	4.4	1.8	10	1.6×10^6
DR21(OH)	1.5x2.4	1.2	8.0	6	2.0×10^4
NGC7538	1.6x2.2	2.7	1.7	6	2.2×10^5

We have examined the velocity dependence of the derived quantities for several sources and find that $n(H_2)$ remains constant while X(CS)/dv/dr falls off in the line wings. Thus our data are consistent with either a microtrubulent model or a uniform density LVG model. In view of the density gradients implied by other observations the former model may be more appropriate for the CS emission regions.

REFERENCES

Goldsmith, P.F., Plambeck, R.L., and Chiao, R.Y.: 1975, Astrophys. J. (Letters) 196, L39.

Gottlieb, C.A., Gottlieb, E.W., Litvak, M.M., Ball, J.A., and Penfield, H.: 1978, Astrophys. J. 219, 77.

Gottlieb, C.A., Ball, J.A., Gottlieb, E.W., and Dickinson, D.F.: 1979, Astrophys. J. 227, 422.

Linke, R.A., and Goldsmith, P.F.: 1980, Astrophys. J. 235.

Linke, R.A., Schneider, M.V., and Cho, A.Y.: 1978, IEEE, MTT 26, 935.

Liszt, H.S., and Linke, R.A.: 1975, Astrophys. J. 196, 709.

Liszt, H.S., and Leung, C.M.: 1977, Astrophys. J. 218, 396.

Martin, R.N., and Barrett, A.H.: 1975, Astrophys. J. (Letters) 202, L83.

Phillips, T.G., and Huggins, P.J.: 1977, Astrophys. J. 211, 798.

Plambeck, R.L., and Williams, D.R.W.: 1979, Astrophys. J. (Letters) 227, L43.

Turner, B.E., Zuckerman, B., Palmer, P., and Morris, M.: 1973, Astrophys. J. 186, 123.

Wootten, H.A., Evans, N.J. II, Snell, R., and Vanden Bout, P.: 1978, Astrophys. J. (Letters) 225, L143.

DISCUSSION FOLLOWING LINKE

T. Wilson: The H_2 density obtained from H_2CO observations of clouds common to the CS survey is $\sim 10^5 cm^{-3}$, only slightly larger than the CS density. Could it be that the CS and H_2CO are preferentially formed at densities of $\sim 10^4$ to $10^5 cm^{-3}$?

Linke: That is very possibly the correct interpretation of the observations. However we must keep in mind that, as Evans pointed out, excitation of CS requires a relatively high density of H_2, so in regions of low density we cannot be sure whether CS is under-abundant, or simply emits at a level below the limit to our sensitivity.

Mouschovias: Finally! I am pleased to make a comment which does not concern magnetic fields. Is not the choice between uniform and non-uniform density models a non-existent problem, in that a non-uniform density distribution is an inevitable consequence of self-gravity? Unless you artificially contrive forces to support the self-gravitating clouds with which you are concerned, a uniform density will violate Newton's Second Law.

Linke: One solution describing the gravitational collapse of a cold spherical cloud of uniform density maintains a uniform density distribution (albeit one that increases with time) and a velocity field of the form $v(r) \propto r$ (c.f. Spitzer, 1968, p. 226). Nevertheless, we conclude that such a model is not appropriate to the clouds we have studied.

Bok: Star counts show that the density of B361 has a steeply negative gradient. A uniform density model is inappropriate.

Glassgold: It was not clear from your description of the observations whether you mapped the clouds or simply made observations at a single position.

Linke: The densities obtained were for the central position (typically the intensity peak) of each cloud. We are currently mapping in the two transitions to obtain the spatial dependence of the derived quantities.

White: Did you assume a constant abundance of CS? One explanation of the apparent conflict could be that (CS/H_2) *decreases* into the cloud as n_{H_2} rises, since the excitation varies approximately as $n_{H_2}^2[CS/H_2]$.

Linke: In the sense that each velocity element is independent of the others in the LVG model, we did not assume any form for the CS abundance. We conclude, however, that X(CS) probably decreases with increasing radius.

Avery: I am concerned about the application of the LVG radiative transfer approximation in some of the very quiescent dark clouds you have considered. Why is this approximation valid for such sources?

Linke: The densities derived from our data using a microturbulent model are not very different from those which we quote. Of course, neither model takes proper account of the foreground absorption which may be present.