THE $^{12}C/^{13}C$ RATIO IN INTERSTELLAR DARK CLOUDS

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Since ^{13}C is believed to be produced by non-equilibrium CNO processing in stellar evolution (Truran 1977), measurements of the carbon ratio $R_C \equiv [^{12}C]/[^{13}C]$ in the interstellar medium may provide important information on nucleo-synthesis. Commonly, the ratio $(N_{13}/N_{18})_{LTE} \equiv [^{13}CO/C^{18}O]_{LTE}$ is measured and from this $R_{LTE} \equiv [^{12}CO/^{13}CO]_{LTE}$ is deduced and these values are often identified with R_C. However, this line of reasoning can be misleading for two reasons (Dickman et al. 1979):

(1) The difficulty of determining accurate column densities, $[^{13}C^{16}O]$ and $[^{12}C^{18}O]$, because of the complexity of the radiative transfer problem;

(2) The possible role of fractionation, whereby $R_{CO} \equiv [^{12}CO]/[^{13}CO]$ does not necessarily reflect the initial atomic abundance ratio R_C (Watson et al. 1976, Langer 1977, Liszt 1978).

Mahoney et al. (1976) and Dickman et al. (1977) presented measurements of $(N_{13}/N_{18})_{LTE}$ in the dark cloud L134 which suggested that fractionation was occurring. An analysis by Dickman et al. (1979) showed that $(N_{13}/N_{18})_{LTE}$ in L134 did in fact represent the local abundance ratio $[^{13}CO]/[C^{18}O]$ in which case R_{CO}, obtained by using a terrestrial oxygen isotope ratio, was found to vary systematically with visual extinction A_V. This result was attributed to isotopic fractionation of ^{13}CO. The values of R_{CO} found in regions where $A_V \gtrsim 4$ mag. are close to the terrestrial value and this was interpreted as evidence for a terrestrial value for R_C. These results are in contrast to those of Wannier et al. (1976) who measured $(N_{13}/N_{18})_{LTE}$ in 14 HII regions and deduced R_C to be about 40. Other recent measurements supporting a terrestrial value of R_C have been made by Langer et al. (1978), Guélin and Thaddeus (1979) and Tucker et al. (1979).

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Here we present further observations of CO, ^{13}CO and $C^{18}O$ in four additional dark clouds. Data were obtained using the 4.6 m telescope at the Aerospace Corporation with a 2.6 arcmin beam width and a 0.65 km s^{-1} velocity resolution at 115.3 GHz. Table 1 lists the positions observed.

TABLE 1

Position ($\Delta\alpha,\Delta\delta$)	T_{12}^{*}(K)[a]	T_{13}^{*}(K)	T_{18}^{*}(K)	$\frac{^{13}C^{16}O}{^{12}C^{18}O}$[b]	Av(mag)
L183 α_o (1950) = $15^h51^m18^s$, δ_o (1950) = $-3^\circ 00'00''$					
s '					
0.0, 8.0	9.0	3.8	$\leq$0.9	$\geq$6.1	2.4
0.0, 16.0	8.3	4.1	1.4	5.3(+2.2,-1.4)	$\geq$5.7
0.0, 20.0	20.0	3.2	$\leq$0.6	$\geq$4.4	$\geq$5.7
15.0, 8.0	8.6	4.1	0.6	5.5(+4.4,-2.1)	$\geq$8.2
L1524 α_o (1950) = $04^h25^m00^2$, δ_o (1950) = $24^\circ 30'00''$					
s '					
0.0, 8.0	6.6	3.8	0.7	5.9(+2.7,-1.6)	1.8
-20.0, 0.0	6.9	4.5	0.9	9.8(+3.1,-2.4)	2.7
20.0, 0.0	7.5	4.3	0.8	6.6(+4.2,-2.2)	3.8
0.0, 4.0	7.6	4.8	1.1	5.9(+2.4,-1.6)	3.8
-20.0, 4.0	(7.6)	5.1	1.1	8.0(+2.6,-1.8)	4.0
20.0, 4.0	(7.6)	4.3	0.8	5.3(+2.8,-1.6)	2.9
L204 α_o (1950) = $16^h45^m00^s$, δ_o (1950) = $-12^\circ 00'00''$					
s '					
0.0, 0.0	9.0	5.1	1.1	6.9(+1.4,-1.1)	$\geq$9.2
0.0, 5.0	9.6	5.7	1.2	6.6(+2.3,-1.1)	$\geq$9.2
0.0, 10.0	6.2	5.1	1.2	5.5(+3.4,-1.7)	$\geq$9.2
-20.0, 5.0	12.5	5.2	0.6	14.8(+8.6,-4.9)	1.5
30.0, 60.0	11.0	5.6	0.9	12.5(+3.3,-2.5)	$\sim$3 (c)
30.0, 75.0	10.4	5.1	0.4	10.8(+6.6,-3.7)	0.6
IC5146 α_o (1950) = $21^h51^m37^s$, δ_o (1950) = $47^\circ 02'07''$					
-61.'2,14.'5	(5.7)	2.3	0.5	6.6(+2.9,-1.9)	$\gtrsim$7.0 (d)

NOTES TO TABLE 1

(a) Values in brackets are assumed values.

(b) Values in brackets are the errors in the double ratio obtained from the 1σ errors in each column density.

(c) Very sharp gradient in A_v at this position; value uncertain.

(d) Stars at this location assumed to be foreground stars and hence were ignored in computing extinction

$(N_{13}/N_{18})_{LTE}$ is tabulated in Table 1 for 17 of the 22 positions observed (five other positions observed in IC5146 will be discussed later). R_{LTE} was obtained by assuming a terrestrial oxygen isotope ratio, an assumption commonly made in the absence of conflicting evidence, particularly for dark nebulae, and values range from approximately terrestrial, 89, down to $\sim$33. Based on the results of Dickman et al. (1979), we assume that the ratios R_{LTE} adequately reflect the values R_{CO} in regions of moderate density and low kinetic temperature and evaluate these results in the framework of fractionation chemistry.

In regions of a low temperature cloud where the extinction is low (and the interstellar UV flux high) [^{13}CO] may be enhanced by large factors (Langer 1977, Liszt 1978). In regions of high extinction $R_{CO} \rightarrow R_C$ after sufficiently long times. In order to evaluate our results extinction was determined at each position from star counts in a reseau size of 2.6 arcmin, taking into account the probability of foreground stars. Fig. 1 shows R_{LTE} plotted against A_V for the four clouds in Table 1.

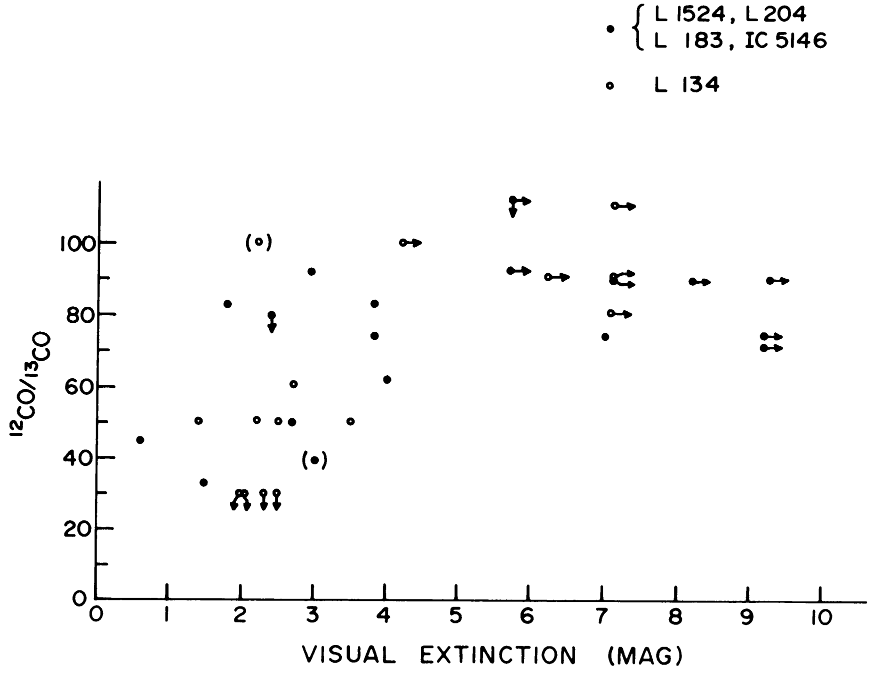

Fig. 1 Ratio of inferred CO column densities vs. visual extinction in magnitudes for the 4 clouds in Table 1 and for L134. For the 4 clouds in this study, the ordinate is R_{LTE}. For L134, the ordinate is R_{CO} and the values are from Fig. 3 of Dickman, McCutcheon and Shuter (1979). R_{LTE} has been derived from the double ratio $[^{13}CO/C^{18}O]$ at each position by assuming $[^{16}O]/[^{18}O]$ is terrestrial. Vertical arrows indicate upper limits to R_{LTE} and R_{CO} because of undetected $C^{18}O$ emission. Uncertainties in R_{LTE} are obtained from the maximum and minimum values of the double ratio in Table 1. Uncertainties in R_{CO} are similar. Horizontal arrows denote lower limits to extinction. The brackets indicate that the extinction for that position is uncertain because a sharp extinction gradient exists over a region comparable to the beam size.

R_{LTE} is generally in agreement with the terrestrial value 89 at positions where $A_V \gtrsim 4$ mag., but at lower extinctions significantly lower values occur. These results are qualitatively consistent with the expected behaviour of carbon monoxide isotope ratios in regions of varying A_V where fractionation is expected to be important. This

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conclusion is based on the assumption that the ratios R_{LTE} reasonably indicate the values R_{CO} in the dark clouds studied. Considerable confidence is given to this assumption by the close agreement of our R_{LTE} vs. A_V plot with the variation of non-LTE values of R_{CO} vs. A_V for L134 also shown in Fig. 1.

LTE isotope ratios were obtained at six positions in the vicinity of IC5146, a young stellar cluster embedded in the eastern edge of an elongated complex of dark clouds. Fig. 2 shows the values of R_{LTE} placed on a photograph reproduced from the Palomar Sky Survey Print.

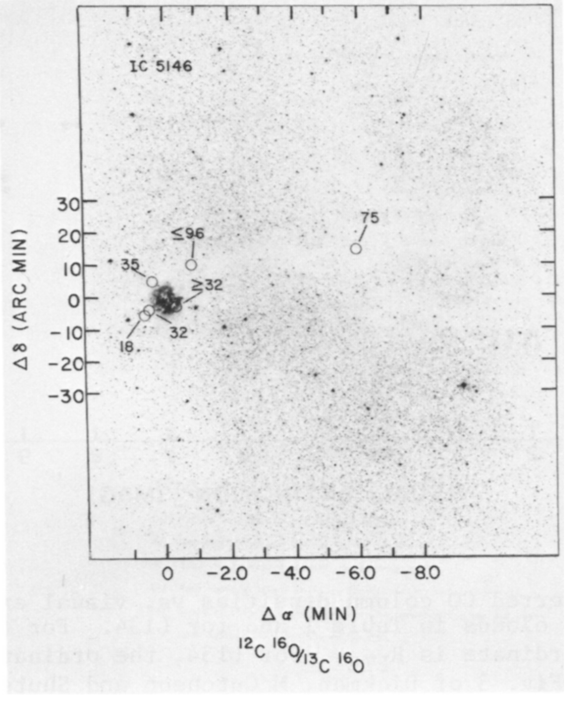

Fig. 2 Positions observed in IC5146 are indicated on a reproduction from the Palomar Sky Survey Prints. The circles represent the beam size and are centered on the observed positions. The numbers are the values of R_{LTE}.

Because of the increased flux of ionizing radiation close to the nebula, these results would appear to be further evidence for fractionation. However, there are two reasons why this effect cannot be interpreted unambiguously. First, the use of LTE may not apply to the warmer and probably denser areas near the ionized nebula and second, at the three positions where R_{LTE} is lowest the kinetic temperature is well in excess of 20 K, and fractionation should be inhibited (Langer 1977, Liszt 1978). However, the trends embodied in Fig. 1 of this paper and

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Fig. 3 of Dickman et al. (1979) do not agree in detail with theory and it may be that theoretical models must be modified.

In summary, the average value for R_{LTE} from twelve data points in Fig. 1 where $A_V > 4$ is 88 ± 3, with the quoted error being the standard error of the mean. We conclude that R_{CO} is statistically consistent with the terrestrial value 89 in the clouds studied here where $A_V > 4$ mag. These results imply a terrestrial value for R_C in dark clouds.

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DISCUSSION FOLLOWING McCUTCHEON

Penzias: Since a quite similar result could be obtained from a partial saturation of the central ^{13}CO lines, one needs to take possible saturation into account. The excitation of CO in the diffuse exterior should be greater than the excitation in the core, where the ^{13}CO line originates. This excitation difference will lead to an underestimate of the saturation of the ^{13}CO line, a possibility which could be checked by observing the J=2-J=1 transitions.

McCutcheon: The non-LTE analysis using an LVG model has taken account of possible ^{13}CO saturation, and the answer still remains the same. A uniform kinetic temperature (12K) was used in the calculations, and a reasonable variation of this parameter had no sizeable effect upon the results. However, this parameter was not varied across the cloud.

Langer: When Dickman, Langer, McCutcheon, and Shuter (1977) suggested that fractionation explained the CO data in L134, the data were criticized as being under-resolved or filter-diluted because of the velocity resolution of 0.65 km s^{-1}. Could you comment on this?

McCutcheon: The LTE results were obtained by integrating the line optical depths and are not affected by resolution. The non-LTE analysis, however, uses peak temperatures and the results can be affected by filter dilution. In fact, depending upon the intrinsic isotopic line-shapes, dilution by 0.65 km s^{-1} filters can skew the resultant ratios either up or down in a non-linear fashion which depends upon where in the cloud emergent model spectra are computed. In general, though, the trend indicating fractionation was preserved, although the absolute values of the ratios could change by up to 30%.

It is encouraging that Myers, Buxton, and Ho (this conference) have CO results from three dark clouds using a velocity resolution of 0.08 km s^{-1} that agree closely with our results.

Glassgold: In Langer's explicit calculation of Watson's fractionation theory, he finds that the fractionation depends on depth into the cloud as well as on temperature. The fractionation first increases and then decreases on a scale of about A_V=1. Do you have sufficient angular resolution to observe this variation?

McCutcheon: In some cases, perhaps. However, variation in extinction is often not uniform. In the centres of many dark clouds, there are large opaque areas where lower limits only may be placed on the visual extinction. These regions may be several of our (2.6 arcmin) beamwidths in diameter. Towards the edges of the clouds, there are sometimes very steep gradients in extinction, over dimensions much smaller than our beamwidth. In other instances, the variation in extinction is more gradual and unit changes of A_V occur over angular extents which we can resolve. Our plot of ratio vs A_V (Fig. 1) does not agree in detail with Langer's theory.

Wannier: Your quoted $^{12}C/^{13}C$ ratio, which you call "consistent with the terrestrial value" is also consistent with the value given earlier by Penzias to within 30% or so. What is the correction that you calculate using the non-LTE calculations? It surprises me that such a correction for the ^{13}CO line intensity at the cold cloud centers could produce ratios accurate to within 30%.

McCutcheon: The non-LTE calculation shows ^{13}CO optical depths to be typically 1.5, which is somewhat higher than found from an LTE calculation. An individual ratio is not claimed to be accurate to 30%. The value quoted, 88±3, is an average of 12 values.

Scoville: One important implication of ^{13}CO fractionation in low extinction dark clouds is that many estimates of giant cloud masses (based upon Dickman's measurements of $^{13}CO/A_V$) must be revised upward. This is because the inferred $^{13}CO/H_2$ ratio obtained for the low A_V regions is anomalously high compared to that for the bulk of giant molecular clouds which have $A_V \gtrsim 10$ mag. If the fractionation in Dickman's original data is a factor 2, then the mass estimates of the giant clouds increase by a factor 2.

McCutcheon: Dickman found $[^{13}CO]/A_V$ to be linear with A_V to $A_V \sim 5$ mag. where fractionation is no longer effective. Thus, Dickman's empirical result applies to regions where fractionation is present and where it is not, i.e. his result is independent of fractionation; so it is not obvious that the masses of giant clouds must be multiplied by a factor to account for fractionation. The question, perhaps, is whether Dickman's result is applicable to the hotter, more massive giant molecular clouds.