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A REASSESSMENT OF THE DOUBLE ISOTOPE RATIO [^{13}CO]/[C^{18}O] IN MOLECULAR CLOUDS

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ABSTRACT

We have reexamined the double isotope ratio [^{13}CO]/[C^{18}O] in molecular clouds using previously published and new millimeter-wave carbon monoxide isotopic data. Our study reveals that ground-state column density ratios in giant molecular clouds (GMCs) show a markedly higher value, by a factor of 2–4, than do dark clouds. When measured at positions of high extinction, the latter objects tend to have values near the terrestrial value of 5.5.

Large increases in the ^{13}CO to C^{18}O column density ratio at low extinctions are seen in all the data and can be attributed to isotopic fractionation and isotope-selective photodissociation. However, these processes, as well as non–LTE effects, are found to be *unable* to account for the GMC–dark cloud distinction. We suggest that unresolved local density fluctuations ("clumps") may be responsible for the observed enhancement in the ^{13}CO to C^{18}O column density ratios in GMCs.

If this hypothesis proves to be correct, the true double isotope ratio will be most accurately determined in dark molecular clouds and along lines of sight of extremely high extinction in GMCs. Also, the combination of a terrestrial double isotope ratio with the carbon isotope ratio value of Hawkins and Jura, [^{12}C]/[^{13}C] $\approx$ 43, implies that both the oxygen and carbon isotopic abundances have evolved substantially since the formation of the solar system. In any case, interstellar isotopic and chemical abundances—especially those derived from studies of GMCs—must be critically reexamined.

Subject headings: interstellar: molecules—nebulae: abundances

I. INTRODUCTION

Accurately determined carbon and oxygen isotopic abundances are essential to a complete understanding of the chemical composition of the interstellar medium (ISM), past and present. Because the isotopes serve as tracers of various stages of stellar processing, knowledge of their abundances is important in modeling chemical evolution and material transport in the ISM throughout the Galaxy. Equally important, the abundances of the primary isotopes of carbon monoxide, ^{13}CO and C^{18}O, are frequently used as tracers of H$_2$ in molecular clouds, in radiative transfer calculations, and other atrophysical applications.

Over the past dozen years many studies of isotope ratios have been carried out, sometimes with conflicting results. (For a review of the prevalent viewpoints in this field prior to 1980, see Penzias 1980 and Wannier 1980.) By observing the $J = 1 \rightarrow 0$ transition of ^{13}CO and C^{18}O in numerous giant molecular clouds (GMCs), Wannier *et al.* (1976), determined that $R \equiv [^{13}\mathrm{CO}]/[\mathrm{C}^{18}\mathrm{O}] \approx 14$, a value 2.5 times larger than the terrestrial value $R_\oplus = 5.5$. This result was attributed to an increase in the interstellar [^{13}C]/[^{12}C] ratio since the formation of the solar system. Subsequent work (Dickman, McCutcheon, and Shuter 1979; Langer *et al.* 1980; McCutcheon *et al.* 1980) found $R \approx$ 5–6 in the central regions of dark clouds, but enhanced in the outer regions. This result was attributed to fractionation of the ^{13}CO isotopic species and, as pointed out by McCutcheon *et al.* (1980), appeared to be consistent with a terrestrial carbon isotope ratio. Subsequent observations of the feeble $J = 1 \rightarrow 0$ emission line of the doubly substituted species ^{13}C^{18}O suggested [^{12}C]/[^{13}C] $\approx$ 75 in dark clouds (Wilson, Langer, and Goldsmith 1981), a result close to the terrestrial value of 89, with no clear evidence for a nonterrestrial [^{16}O]/[^{18}O] ratio. However, Penzias (1981) showed that the [^{16}O]/[^{18}O] ratio appears to exceed the terrestrial value of 500 in the Galactic center, but is *lower* than the terrestrial value in the Galactic plane near the Sun. Penzias (1983) also found that $R \approx 2R_\oplus$ in the GMCs NGC 2264 and W3(OH).

Formaldehyde (H$_2$CO) observations by Gardner and Whiteoak (1979, 1982) suggested the presence of a gradient in the [H$_2$CO]/[H$_2$ ^{13}CO] ratio across the inner Galaxy with the lowest values of 20–30 seen in the Galactic center. This gradient and low Galactic center value was also seen by others (Henkel, Walmsley, and Wilson 1980; Henkel, Wilson, and Bieging 1982; Güsten and Henkel 1983). A value of 5 ± 1 for the double ratio [H$_2$ ^{13}CO]/[H$_2$C^{18}O] was found in four GMCs, consistent with the terrestrial double ratio $R_\oplus$.

Finally, recent observations of the optical absorption lines of ^{12}CH$^+$ and ^{13}CH$^+$ toward several early-type stars in the solar neighborhood suggest that the ^{12}C/^{13}C isotope ratio is 43 (Hawkins and Jura 1987). This implies that the carbon isotopes, at least, have evolved chemically in the last 4.5 billion yr in the vicinity of the solar neighborhood.

Clearly, a reliably determined and self-consistent set of isotopic abundances are yet to be found. However, one may hope that from such a large body of work distinct trends can be discerned. In this paper we report the discovery of a marked systematic distinction between measurements of the double isotope ratio R in dark molecular clouds and giant molecular clouds: the GMC data, in general, have values of R which are systematically larger by a factor of 2–4 than the dark cloud values. In § II we describe these data, which have been taken from the literature and combined with results from extensive observations of the $J = 1 \rightarrow 0$ transitions of CO, ^{13}CO, and C^{18}O in the dark cloud L134N (also known as L183) and the

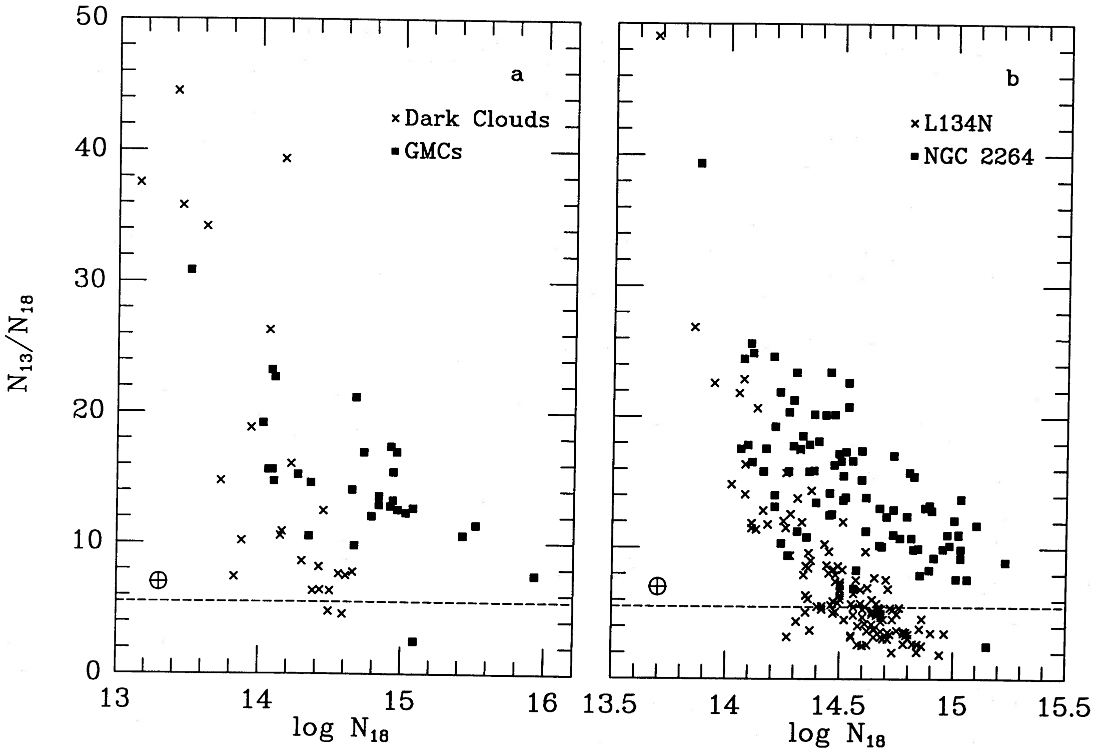

FIG. 1.—Ratio of ^{13}CO to C^{18}O ground-state column densities (N_{13}/N_{18}) as a function of the log of the C^{18}O column density (N_{18}) for (*a*) the sample of dark and giant molecular clouds taken from the literature and (*b*) from observations of the dark ckoud L134N and the GMC NGC 2264. The C^{18}O column density is used as a measure of extinction along the line of sight through the cloud. The dashed line is the terrestrial value of 5.5.

GMC associated with NGC 2264. In § III we show, using a "core-envelope" GMC model, that non-LTE effects, isotopic fractionation, and isotope-selective photodissociation are inadequate to explain the enhancements observed in the GMC data. In § IV we point out that unresolved gas clumps driven by turbulence in GMCs may influence the observed line temperatures of the CO isotopes in such a way as to produce the discrepancy between the double ratio in the two classes of objects. We discuss the implications of this conclusion.

II. THE DATA

a) *Published Data*

The published data consist of observations of the three most abundant CO isotopic species in both dark clouds and GMCs. The dark clouds include the Taurus and ρ Oph molecular clouds (Frerking, Langer, and Wilson 1982); L183, L204, and L1524 (McCutcheon *et al.* 1980); B5, B335, and L1262 (Wilson, Langer, and Goldsmith 1981); and a Bok globule (Dickman and Clemens 1983). The GMC data include observations of NGC 2264 and W3(OH) (Penzias 1983) and Sgr B2, M8, M17A, W51, DR21, NGC 7538, NGC 2024, and NGC 6334 (Wannier *et al.* 1976). The above-mentioned data sets were chosen both for their high-quality spectra and because the ^{12}CO, ^{13}CO, and C^{18}O observations in a given cloud were done at identical spatial positions and with the same instrument.

b) *Further Observations*

The L134N data consist of 131 coincident observations of ^{12}CO, ^{13}CO, and C^{18}O taken from a larger grid of observations spaced at 1′ intervals about the center position $\alpha = 15^{\mathrm{h}}51^{\mathrm{m}}30^{\mathrm{s}}$, $\delta = -2°43'31''$ (1950.0). The data were obtained with the 14 m antenna of the Five College Radio Astronomy Observatory by D. Swade (1987), and we are grateful to him for permitting their use in this work. At a wavelength of 2.6 mm, the 14 m antenna provides a HPBW of 45″. The CO and ^{13}CO spectra were obtained with a spectral resolution of 0.26 km s^{-1}, while the C^{18}O data have a resolution of 0.14 km s^{-1}.

The observations of NGC 2264 were made by the authors using the FCRAO antenna. From a grid of 320 positions spaced by 1$'$.5, with a center position of $l = 203°.3158$, $b = 2°.0553$, 106 coincident observations of the three CO isotopes were taken. All spectra utilized a 256 × 250 kHz spectrometer giving a velocity resolution of 0.68 km s^{-1}.

Both data sets used a cooled mixer receiver and were calibrated using the standard chopper wheel method (Penzias and Burrus 1973). All antenna temperatures were corrected to radiation temperature values T_R^* as suggested by Kutner and Ulich (1981), by dividing by a forward spill-over and scattering efficiency, $\eta_{\mathrm{fss}} = 0.70$ (Snell and Schloerb 1983).

III. DISCUSSION

a) *The* ^{13}CO/C^{18} *Ratio*

In Figure 1*a* we show the ground state column density ratio of ^{13}CO to C^{18}O (hereafter denoted N_{13}/N_{18}) plotted against N_{18} for the dark cloud and GMC data taken from the literature. The column densities are calculated using the assumptions of local thermodynamic equilibrium (LTE) (Dickman 1978). We shall interpret C^{18}O column density as a tracer of visual extinction (Frerking, Langer, and Wilson 1982; Wilking and Lada 1983) rather than ^{13}CO (Dickman 1978), in order to avoid fractionation-related ambiguities. However, the Figure would be qualitatively unaltered if ^{13}CO column density were used as an abscissa.

Three features are readily apparent in Figure 1*a*. First, in the region $14 \leq \log N_{18} \leq 15$, the GMC data, in general, lie above the dark cloud data by a factor of $\sim$2–4. Although the scatter in the data does produce some overlap between the dark cloud and GMC data sets, the distinction between them is definite. Much of the scatter may be due to errors in determining LTE values. A straightforward error analysis of the column densities suggest that errors may be as large as 30%, assuming a 10% minimum uncertainty in the observed line temperatures, line widths, and derived excitation temperatures (Taylor 1989). Second, in the dark cloud data set R approaches the terrestrial double isotope ratio $R_{\oplus}$ as long N_{18} increases, suggesting that this apparently asymptotic value may be representative of the true value of R. The GMC data appear to show this same asymptotic trend, but it is difficult to tell whether R approaches the terrestrial value or remains a factor of 2 higher. Third, an increase in N_{13}/N_{18} at lower values of $\log N_{18}$ is seen in both data sets, although it is more pronounced in dark clouds.

It should be borne in mind that in interpreting the trends in Figure 1*a*, we shall assume that the true double isotope ratio, [^{13}C][^{16}O]/[^{12}C][^{18}O], does not vary significantly from cloud to cloud. This may not always be true, especially when considering such unique and distant clouds as Sgr B2. For this reason, we also obtained extensive observations of one dark cloud (L134N) and one GMC (NGC 2264), each taken to be typical representatives of that type of cloud. All the trends described above are also seen in this data set (Fig. 1*b*). Figure 2 shows the distribution of the column density ratios for the two clouds. Clearly, the majority of the values from NGC 2264 are enhanced over those of L134N which are peaked near the terrestrial value of 5.5, but which drop below it at the highest N_{18} values (see below).

A potential source of systematic error in the column density ratios is the possibility of non–LTE conditions in the clouds, most importantly subthermal excitation conditions in either the ^{13}CO or C^{18}O line, or both. If subthermal excitation conditions are present, the LTE column densities will be underestimated. For a homogeneous cloud, this will be the dominant manifestation of non–LTE conditions. However, even under the extreme conditions $T_X(\mathrm{C^{18}O}) = 0.5T_X$ and $T_X(\mathrm{^{13}CO}) = 0.75T_X$ (Frerking, Langer, and Wilson 1982), with T_X being derived in the usual manner from the ^{12}CO line temperature, the net change in the column density *ratio* is minimal. A second related source of systematic error in LTE-derived column densities occurs when the observed emission line becomes optically thick, i.e., $\tau \approx 1$. When excitation is subthermal, LTE opacities will tend to underestimate the true line-center optical depths. In the context of this work, the concern is that ^{13}CO will become saturated before C^{18}O, and that the inferred opacity ratio, $(\tau_{13}/\tau_{18})_{\mathrm{LTE}}$, will thus be less than the true abundance ratio.

To estimate the magnitude of these non–LTE effects, we generated $J = 1 \rightarrow 0$ line temperatures for the three CO isotopes using a radiative transfer model employing the Sobolev approximation (e.g., Goldsmith, Young, and Langer 1983). These three line temperatures were then treated as observed quantities in an LTE calculation. The quantity $(\tau_{13}/\tau_{18})_{\mathrm{LTE}}$ was then compared directly to the model fractional abundance ratio, $x(\mathrm{^{13}CO})/x(\mathrm{C^{18}O})$. Over a wide range of kinetic temperature, hydrogen densities, and values of $x(\mathrm{^{13}CO})$ and $x(\mathrm{C^{18}O})$, we find that for $\tau_{13} < 1$, the LTE opacity ratio gives the correct abundance ratio to within 15%. However, under typical dark cloud conditions, $T_k = 10$ K and $n(\mathrm{H_2}) = 10^3$, and when $\tau_{18} \approx 0.5$ and $\tau_{13} \geq 1$, $(\tau_{13}/\tau_{18})_{\mathrm{LTE}} \approx 0.7[x(\mathrm{^{13}CO})/x(\mathrm{C^{18}O})]$. This easily explains the large number of

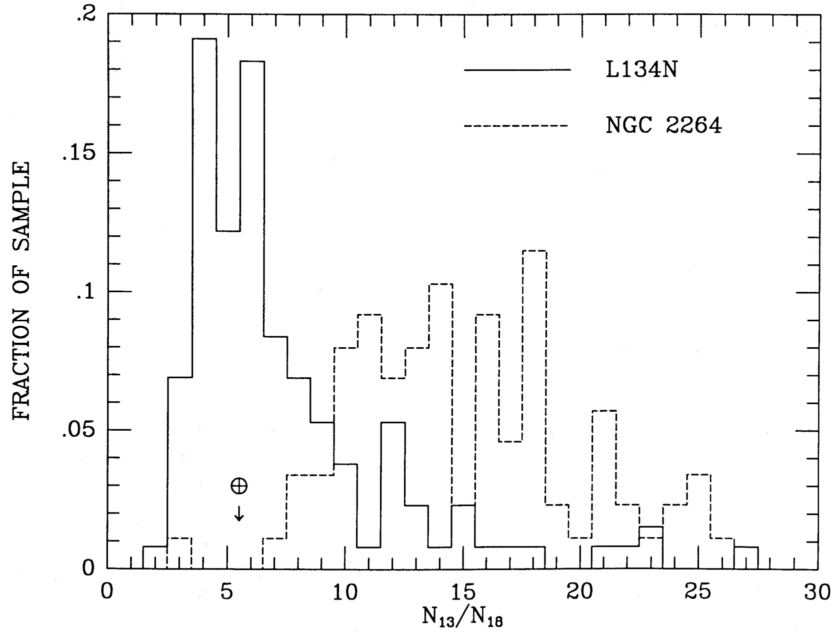

FIG. 2.—Distribution of LTE–derived column density ratios in L134N and GMC NGC 2264. The values determined in L134N are peaked near the terrestrial value of 5.5, while those determined in NGC 2264 show an enhancement by a factor of 2–4 over the terrestrial value.

data points in Figure 1*b* at high values of N_{18} lying below the terrestrial value of 5.5.

Two other processes may be much more important in explaining the increase in N_{13}/N_{18} at low log N_{18} values in all four data sets of Figure 1: fractionation (Watson, Ancich, and Huntress 1976) and isotope-selective photodissociation (Glassgold, Huggins, and Langer 1985). In the low density [$n(H_2) \approx 300$ cm^{-3}] outer regions of molecular clouds, both processes act in concert to enhance the ^{13}CO/C^{18}O column density ratio. Fractionation will tend to overproduce ^{13}CO relative to ^{12}CO and isotope-selective photodissociation will tend to suppress the abundance of C^{18}O relative to the two other isotopes. However, in order for these coupled mechanisms to reconcile the GMC–dark cloud *disparity* shown in Figure 1, they must operate far more extensively in GMCs than in dark clouds. We consider this issue next.

b) Cloud Model

As a first step in determining the magnitude of these effects, we construct a simple "core-envelope" model of a GMC. This two component model consists of a low density [$n(H_2) \approx 300$ cm^{-3}], chemically homogeneous envelope symmetrically surrounding a high-density [$n(H_2) \geq 10^3$ cm^{-3}] core. Isothermality is assumed for simplicity. Along any line of sight and independent of cloud geometry, the observed visual extinction, A_v, can always be written

$$A_v = 2A^e + A^c , \tag{1}$$

where A^e is the extinction from the cloud edge through the envelope and A^c is the extinction in the core. The factor of 2 comes from the fact that equal amounts of envelope material are present both on the near and far side of the core. The ^{13}CO and C^{18}O column densities may be written in a similar way: $N_{13} = 2N^e_{13} + N^c_{13}$ and $N_{18} = 2N^e_{18} + N^c_{18}$, respectively. The observed column density ratio is then

$$\frac{N_{13}}{N_{18}} = \frac{2N^e_{13} + N^c_{13}}{2N^e_{18} + N^c_{18}} . \tag{2}$$

We can now relate the carbon monoxide column densities to the molecular hydrogen column density by $N_x = f_x N(H_2)$, where f_x is the fractional abundance of the species in question. But $N(H_2)$ is directly proportional to the visual extinction via the relation $N(H_2) \approx 5 \times 10^{20} A_v$ (Bohlin, Savage, and Drake 1978). This gives for equation (2)

$$\frac{N_{13}}{N_{18}} = \frac{2f^e_{13} A^e + f^c_{13} A^c}{2f^e_{18} A^e + f^c_{18} A^c} . \tag{3}$$

By factoring f^c_{18} from equation (3) and defining the quantities $R_\infty \equiv f^c_{13}/f^c_{18}$ and $\beta \equiv (f^e_{13}/f^e_{18})/R_\infty$, we obtain

$$\frac{N_{13}}{N_{18}} = \frac{2q_{18}\beta R_\infty A^e + R_\infty A^c}{2q_{18} A^e + A^c} , \tag{4}$$

where $q_{18} = f^e_{18}/f^c_{18}$, the C^{18}O abundance ratio of the envelope to the core and R_∞ is the abundance ratio of ^{13}CO to C^{18}O in the core and in this model represents the true double isotope ratio. The quantity β is the enhancement factor of R_∞ in the envelope.

To determine A^e, we note that all chemical model calculations show that isotopic enhancements seen in cloud envelopes should be suppressed when a value of $A_v \approx 1.5$ is reached (Chu and Watson 1983; Glassgold, Huggins, and Langer 1985). Since the envelope in our model is, by definition, the region experiencing these enhancements, we set $A^e = 1.5$. For A^c, we notice that the largest values of N_{18} seen in the NGC 2264 data set are $\sim 10^{15}$ cm^2. This implies a peak observed extinction of $A_v \approx 10$ mag (Frerking, Langer, and Wilson 1982; Wilking and Lada 1983). Therefore, $A^c \approx 10 - 2A^e \approx 7$ mag. Substituting these values into equation (4) gives

$$\frac{N_{13}}{N_{18}} = \frac{3q_{18}\beta R_\infty + 7R_\infty}{3q_{18} + 7} . \tag{5}$$

For q_{18}, we adopt the reasonable value $q_{18} = 10^{-9}/4 \times 10^{-7} = 2.5 \times 10^{-3}$ (Glassgold, Huggins, and Langer 1985). Equation (5) then becomes

$$\frac{N_{13}}{N_{18}} = \frac{7.5 \times 10^{-3}\beta R_\infty + 7R_\infty}{7.5 \times 10^{-3} + 7} , \tag{6}$$

or

$$\frac{N_{13}}{N_{18}} \approx R_\infty(1.07 \times 10^{-3}\beta + 1) . \tag{7}$$

From equation (7) it is clear that any ^{13}CO/C^{18}O enhancement in the envelope has a negligible effect on the observed column density ratio. Even a value of $\beta = 30$, an exceptionally high value and present only under very restrictive conditions ($T_k = 10$ K, $A_v = 0.6$ [Glassgold, Huggins, and Langer 1985]), produces an observed column density ratio that is increased by only 3% over R_∞. It might be argued that the envelope abundance of 10^{-9} used to estimate q_{18}—a value representative of f^e_{18} near $A_v \approx 0.8$—is too low, and that the value of f^e_{18} should reflect a more interior region of the envelope, a region more likely to contribute to the observed emission. However, a worst case fractional abundance near 10^{-8}, the value of f^e_{18} at $A_v \approx 1.0$, would cause the 3% enhancement in R_∞ to grow as large as 30%. It is apparent that even this enhancement still falls far short of explaining the GMC-dark cloud distinction.

The model described here is obviously oversimplified, and any realistic GMC model must contain a more sophisticated density and temperature structure. However, this core-envelope model represents a worst-case scenario when attempting to determine the impact of fractionation and isotope-selective photodissociation on *measured* double isotope ratios, since by fixing the density of the entire envelope to the low value $n(H_2) = 300$ cm^{-3}, rather than providing a density gradient from cloud edge to center, we have allowed the maximum isotopic enhancement to occur. We conclude, therefore, that neither fractionation nor isotope-selective photodissociation appears capable of explaining the *systematic* differences between dark clouds and GMCs.

c) Clumped Structure in GMCs

Due to the apparent failure of the line formation and chemical processes mentioned above to cause observable distinctions between dark clouds and GMCs, we have been led to consider the role which gas clumping driven by turbulence might play in the line formation process for the rarer CO isotopes. Unresolved clumps (i.e., local density fluctuations) are in fact observed to be present in GMCs (Matsakis *et al.* 1981; Blitz 1987), but not in dark clouds (Brown and Padman 1988). Clumps are also routinely invoked to explain a number of observational results, such as the low volume filling factor seen in GMCs and the absence of self-reversed CO line profiles toward hot regions (Kwan and Sanders 1987). The existence of pronounced density fluctuations in GMCs but not dark clouds is expected on general hydrodynamic grounds, in view of the highly turbulent character of the former objects. Indeed, for subsonic motions characterized by Mach number m, the rms density fluctuation amplitude $\langle \delta\rho^2 \rangle^{1/2}/\langle \rho \rangle \sim m^2$ (Jones 1976), with even steeper behavior expected above the sound speed.

Ascribing a dynamical origin to the density fluctuations in GMCs which are demanded on both observational and theoretical grounds avoids the issue of whether the "clumps" are equilibrium structures (Penzias 1975; Dickman 1985). Clearly, they need not be stable onjects. However, self-gravity may greatly prolong the lifetime of clumps in a favored size range (Taylor 1989), and this means that these objects may even acquire a reasonably regular internal density structure, analogous to miniscule Bok globules. In any case, the strong local density contrasts which must inevitably accompany turbulent motions within GMCs implies that the CO isotopes within these clouds will, in general, possess different emission filling factors, arising naturally from radiative trapping considerations. As a result, one expects progressively larger emission surfaces in any line of sight as one observes C^{18}O, ^{13}CO, and CO. The collective emission of a group of clumps along a particular line of sight, which depends upon the total area of emitting material filling the antenna beam, therefore also depends upon the isotopic species in question. Hence, naive column density estimates (and ratios constructed from them) in highly turbulent clouds will be subject to potentially large systematic errors and will tend to yield erroneously high ^{13}CO/C^{18}O intensity and column density ratios along all but the highest column density sightlines.

The presence of clumps also provides unimpeded lines of sight through GMCs. The low volume filling factor of these objects then allows their interior regions to be affected by fractionation and isotope-selective photodissociation, thereby further enhancing the true value of [^{13}CO]/[C^{18}O] throughout the cloud.

The above-mentioned effects will be strongly suppressed in dark clouds, and there is little or no evidence that strong density fluctuations exist in these objects (Dickman *et al.* 1988; Brown and Padman 1988). We therefore conclude that the value of R at large values of N_{18} in dark clouds seen in Figures 1*a* and 1*b* represents the value least affected by error. Therefore, $R \approx 4$–6, a value very nearly terrestrial, is representative of the *double isotope ratio* [^{13}CO]/[C^{18}O] in the local ISM. It is interesting to note that this value is consistent with the results of Hawkins and Jura (1987) only if the [^{16}O]/[^{18}O] ratio is ~ 250, implying that the chemical evolution of the Galaxy which has led to a [^{13}C] enhancement has also led to an [^{18}O] enhancement relative to [^{16}O]. This is precisely the sense of the change found by Penzias (1983) and is of about the right magnitude as well. We shall discuss the implications of this result elsewhere (Taylor 1989).

It should be emphasized that the effects described here arise not through the use of fundamentally new concepts, but rather through an application of *known* GMC structural features. In subsequent work, contraints on clumping in GMCs, as implied by our data, will be explored through the use of more sophisticated and self-consistent dynamical models of GMCs. A primary goal is the revaluation of not only isotopic abundances but all molecular abundances in GMCs and elsewhere in the ISM.

IV. CONCLUSIONS

The main conclusions of this paper are as follows.

1. In general, GMCs show an enhanced value of the double isotope ratio $R \equiv [^{13}\mathrm{CO}]/[\mathrm{C}^{18}\mathrm{O}]$ relative to dark clouds at the same value of C^{18}O column density.

2. Non-LTE effects, while almost certainly present in the regions of minimum extinction, cannot explain the difference in R between dark clouds and GMCs.

3. A "core-envelope" model of GMCs, in which the envelope allows for a substantial enhancement in the ^{13}CO abundances due to isotope-selective photodissociation and fractionation is shown to be inadequate in reconciling the GMC–dark cloud distinction, especially at large values of N_{18} (high extinction).

4. By incorporating a *known* structural feature of GMCs—unresolved clumps—we can qualitatively reconcile the GMC—dark cloud distinction, by assuming ^{13}CO has a larger area filling factor in the cloud than does C^{18}O. We argue that this is expected on simple dynamical and line formation grounds.

5. The value of the double ratio R in dark clouds along lines of sight of high extinction is very near the terrestrial value and is probably representative of the true value in the local ISM. This double ratio can only be reconciled with the carbon isotope results of Hawkins and Jura (1987) if oxygen isotope abundances in the Solar neighborhood have also been altered since the formation of the Solar System.

6. All molecular abundances determined in GMCs must be reexamined through the use of self-consistent clumped models of GMCs.

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