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# DETECTION OF $^{13}C^{17}O$ AND OBSERVATIONS OF RARE CO ISOTOPOMERS TOWARD THE $\rho$ OPHIUCHI MOLECULAR CLOUD[1]

F. BENSCH,[2,3] I. PAK,[2,4] J. G. A. WOUTERLOOT,[5,6] G. KLAPPER,[2] AND G. WINNEWISSER[2]
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## ABSTRACT

We report the detection of $^{13}C^{17}O$ and present observations of three additional rare CO isotopomers made toward core C of the $\rho$ Ophiuchi molecular cloud. The data encompass single-pointed observations of the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ rotational transitions for $C^{18}O$, $C^{17}O$, $^{13}C^{17}O$, and the $J = 1 \rightarrow 0$ transition for $^{13}C^{18}O$. Emission is detected for all isotopes and transitions observed. For the two $^{17}O$-containing species, the interstellar spectra display a partially resolved hyperfine spectrum due to the $I = 5/2$ spin of the $^{17}O$ nucleus. The isotope abundance ratios derived from these measurements are $[^{12}C]/[^{13}C] = 65.0 \pm 6.3(\text{stat}) \pm 9.2(\text{syst})$ and $[^{18}O]/[^{17}O] = 4.15 \pm 0.52(\text{stat}) \pm 0.59(\text{syst})$, consistent with recent measurements for nearby molecular clouds. Thus, our measurements support the idea that both ratios are smaller in the local interstellar medium (ISM) than their terrestrial values of 89 and 5.5.

*Subject headings:* ISM: abundances — ISM: evolution — ISM: individual ($\rho$ Ophiuchi) — ISM: molecules — nuclear reactions, nucleosynthesis, abundances

## 1. INTRODUCTION

Observations of carbon monoxide (CO) rotational transitions are widely used to probe the structure, dynamics, and chemistry of the cold and dense interstellar medium (ISM). CO is one of the most abundant molecular species after molecular hydrogen. But unlike molecular hydrogen, the low rotational transitions of CO are easily excited at the physical conditions prevailing in molecular clouds, and they can be observed with relative ease by ground-based radio telescopes. This makes the CO rotational transitions important tracers of the molecular gas in the ISM. Its high abundance, however, leads to serious optical depth effects, which can be partly eliminated by observing the rarer isotopomers. For instance, observations of $^{13}CO$ and $C^{18}O$ transitions are used to deduce the gas column densities of molecular clouds.

The large CO abundance gives a detectable signal for even more rare isotopomers, such as $C^{17}O$ and $^{13}C^{18}O$. Among other tracers, these isotopomers are used to study the abundance ratio of carbon and oxygen isotopes (see Wilson & Rood 1994 for a review). They provide important constraints for models of the Galactic chemical evolution which predict isotopic abundance ratio as a function of stellar nucleosynthesis, star formation history, and the degree of mixing of the gas in the ISM (Prantzos, Aubert, & Audouze 1996; Wilson & Matteucci 1992; Wilson & Rood 1994, and references therein). The $^{12}C$ isotope abundance, for example, is enhanced during the early Galactic evolution by metal-poor stars, while in second-generation stars, subsequent processing by the CNO cycle depletes $^{12}C$ and enhances $^{13}C$. Thus, the $[^{12}C]/[^{13}C]$ ratio can be used to determine the primary/secondary nuclear processing ratio. Similarly, the abundance ratio of the stable oxygen isotopes $^{16}O$, $^{17}O$, and $^{18}O$ are modified by the CNO cycle and other processes, such as nonequilibrium H burning in novae.

The $C^{18}O$, $C^{17}O$, and $^{13}C^{18}O$ emission are often assumed to be optically thin, introducing an error of typically not more than a few percent for the deduced column density and thus the isotopic abundance ratios. For some molecular cloud cores, however, even the $C^{18}O$ lines are noted to suffer from significant saturation effects (cf. Frerking, Langer, & Wilson 1982). This limits the accuracy to which the abundance ratios can be determined, in particular, for cold clouds with high gas column densities. In this case, observations of $C^{17}O$ and $^{13}C^{17}O$ transitions would provide a more reliable estimate of the $[^{12}C]/[^{13}C]$ ratio than is possible with the corresponding $C^{18}O$ transitions. In addition, the $[^{17}O]/[^{18}O]$ ratio can be determined using observations of two doubly rare isotopomers, providing a cross-check on the results derived from the $C^{18}O$ to $C^{17}O$ intensity ratio.

Here, we present the first observation of interstellar $^{13}C^{17}O$, the most rare of the stable CO isotopomers. The rest frequencies of $^{13}C^{17}O$ and $C^{17}O$ rotational transitions have recently been measured with Doppler and sub-Doppler resolution by the KOSMA group at the University of Cologne.

Based on these laboratory measurements, we conducted a search for this rare species in the ISM. In § 2, we summarize the laboratory measurements for $C^{17}O$ and $^{13}C^{17}O$. The observations made toward core C of the $\rho$ Oph molecular cloud are presented in § 3, and the isotopic abundance ratios derived from these measurements are given in § 4, together with a discussion of the results.

## 2. LABORATORY SPECTROSCOPY OF CO ISOTOPOMERS

The lowest rotational transition of $C^{17}O$ and $^{13}C^{17}O$ was detected at the University of Cologne using a highly sensitive OROTRON intercavity jet spectrometer (Surin et al. 2001). The absorption measurements were made using CO gas with $C^{17}O$ and $^{13}C^{17}O$ in its natural abundance. For the first time, we fully resolved the hyperfine (hf) structure of the $C^{17}O$ $J = 1 \rightarrow 0$ spectrum. The splitting of the rotational transition in three components is determined essentially by the electric quadrupole interaction with the $I = 5/2$ nuclear spin of $^{17}O$. The peak positions of the observed lines are consistent with

[1] Based on observations collected at the European Southern Observatory, Chile (ESO 66.C-0143).

[2] Physikalisches Institut der Universität zu Köln, Zülpicher Strasse 77, 50937 Cologne, Germany.

[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.

[4] Institute of Spectroscopy, Russian Academy of Sciences, 142190 Troitsk, Russia.

[5] Radioastronomisches Institut, Universität Bonn, Auf dem Hügel 71, 53121 Bonn, Germany.

[6] Joint Astronomy Centres, 660 North A'ohoku Place, University Park, Hilo, HI 96720.

TABLE 1
OBSERVATIONS OF CO ISOTOPOMERS TOWARD $\rho$ OPH C

| Isotopomer and Transition | Frequency[a] (MHz) | $t_{on}$ (minutes) | Typical $T_{sys}$ (K) | Baseline rms[b] $\Delta T_A^*$ (mK) | Peak Intensity[c] $T_{A,max}^*$ (K) | $I \pm \Delta I_{stat} \pm \Delta I_{syst}$ $I = \int_{v_1}^{v_2} T_A^* \, dv$ (K km s$^{-1}$) |
|---|---|---|---|---|---|---|
| $C^{18}O$ $J = 1 \rightarrow 0$ ..... | 109782.173 | 19.0 | 200–300 | 24.9 | 5.82 | 8.96 ± 0.03 ± 0.90 |
| $C^{18}O$ $J = 2 \rightarrow 1$ ..... | 219560.357 | 19.0 | 275–450 | 35.0 | 4.01 | 7.33 ± 0.04 ± 0.73 |
| $^{13}C^{18}O$ $J = 1 \rightarrow 0$ ..... | 104711.404 | 67.0 | 240–330 | 17.0 | 0.24 | 0.25 ± 0.02 ± 0.03 |
| $C^{17}O$ $J = 1 \rightarrow 0$ ..... | 112358.983 | 44.5 | 200–300 | 15.0 | 1.97 | 4.26 ± 0.02 ± 0.43 |
| $C^{17}O$ $J = 2 \rightarrow 1$ ..... | 224714.284 | 42.5 | 300–400 | 23.0 | 2.37 | 4.07 ± 0.03 ± 0.41 |
| $^{13}C^{17}O$ $J = 1 \rightarrow 0$ ..... | 107288.681 | 425.6 | 170–270 | 4.6 | 0.029 | 0.062 ± 0.006 ± 0.006 |
| $^{13}C^{17}O$ $J = 2 \rightarrow 1$ ..... | 214573.940 | 475.0 | 190–350 | 5.1 | 0.055 | 0.071 ± 0.006 ± 0.007 |

NOTE.—The observations were made with the SEST 15 m telescope on La Silla, Chile. The main-beam efficiency/full width half-maximum of SEST at 105 GHz (220 GHz) is 0.72/50″ (0.52/26″). The on-source position is R.A. = $16^h26^m55\overset{s}{.}7$, decl. = −24°34′27″ (J2000.0); the position of the emission-free reference is R.A. = $16^h27^m00\overset{s}{.}0$, decl. = −25°26′42″ (J2000.0)

[a] Rest frequency of the transition. For transitions with hf splitting, the frequency of the strongest component is given.

[b] Baseline rms per velocity channel ($\Delta v = 0.2$ km s$^{-1}$).

[c] Line peak intensity; for transitions with hf splitting, the peak temperature of the strongest component is given.

the astrophysically determined rest frequencies (Frerking & Langer 1981). For the doubly rare isotopomer, the spin rotational interaction of the $^{13}C$ nuclear spin ($I = 1/2$) results in additional line splitting. However, this splitting is smaller than 50 kHz and cannot be resolved in our measurements, whereas the much larger splitting due to the $^{17}O$ spin is partly resolved. Thus, at Doppler limited resolution, the $^{13}C^{17}O$ spectrum looks similar to the $C^{17}O$ spectrum.

The $J = 2 \leftarrow 1$ transition of $C^{17}O$ and $^{13}C^{17}O$ was detected at Doppler limited resolution using the Cologne Terahertz Spectrometer (Winnewisser 1995). Here, the hf splitting due to the quadrupole interaction of the $^{17}O$ atom is only partly resolved.

Further details of the laboratory measurements and the analysis of the spectra are given by G. Klapper et al. (2002, in preparation). The frequency of the strongest hf component is listed in Table 1. A more detailed list of the rotational spectrum up to THz frequencies can be found in the Cologne Database for Molecular Spectroscopy.[7]

## 3. OBSERVATIONS

We made single-pointed observations of the rotational transitions for the four rare carbon monoxide isotopomers $C^{18}O$, $^{13}C^{18}O$, $C^{17}O$, and $^{13}C^{17}O$ (Table 1). The observations were made in 2001 January using the Swedish-ESO Submillimetre Telescope (SEST) at La Silla, Chile. We choose the $\rho$ Oph molecular cloud as the target for our study because high column densities are needed to detect the faint emission of the doubly rare isotopes. In addition, the low source intrinsic line width ($\lesssim$1.5 km s$^{-1}$ for $C^{18}O$ toward $\rho$ Oph C) allows us to (partly) resolve the hf splitting for the $C^{17}O$ and $^{13}C^{17}O$ transitions. The observation of the characteristic hf pattern will ease the assignment of a possible detection for the doubly rare $^{13}C^{17}O$. The observations were made in position-switching mode, with the on-source position being centered on the not very well defined peak of the $C^{18}O$ $J = 1 \rightarrow 0$ map made by J. G. A. Wouterloot, J. Brand, & C. Henkel (2002, in preparation) toward $\rho$ Oph C. The $C^{18}O$ map shows a relatively flat maximum with only a little variation of the integrated intensity and line peak temperature on angular scales smaller than ~1′.5. This is in contrast to $\rho$ Oph A and B, which have higher column densities but exhibit steep intensity gradients offset from the peak position. Thus, by choosing $\rho$ Oph C for this study, we minimize the influence of pointing errors in the observed intensity and the deduced line ratios.

[7] Accessible on-line via http://www.cdms.de (see Müller et al. 2001).

Simultaneous observations were made for both lower rotational transitions of all rare CO isotopomers, except for $^{13}C^{18}O$ $J = 2 \rightarrow 1$, which lies outside the tuning range of the 115/230 GHz receiver at SEST. We used the high-resolution acousto-optical spectrometer (HRS) as back end, with a channel spacing of 43 kHz.

The resolution bandwidth of the HRS is 80 kHz, which corresponds to a velocity resolution of 0.2 km s$^{-1}$ at 115 GHz and 0.1 km s$^{-1}$ at 230 GHz. All observations were resampled to a channel spacing of $\Delta v = 0.2$ km s$^{-1}$ for the further data reduction, and a second-order polynomial baseline was subtracted from the co-added spectra.

We detected emission for all four isotopomers and transitions observed, including $^{13}C^{18}O$ and $^{13}C^{17}O$ (Fig. 1). For the $J = 1 \rightarrow 0$ transition of $^{13}C^{17}O$, the hf components are detected at a level of 4 $\sigma$ and 5 $\sigma$, respectively, where $\sigma$ is the baseline rms per 0.2 km s$^{-1}$ velocity channel. The $J = 2 \rightarrow 1$ transition of $^{13}C^{17}O$ is detected at an 11-$\sigma$ level. For both transitions, the line profile is very similar to the corresponding $C^{17}O$ profile, with the characteristic substructure due to the partially resolved hf splitting. The image sideband rejection ratio of the receiver is 0.01. We checked the $^{13}C^{17}O$ $J = 2 \rightarrow 1$ spectrum for emission from the image sideband of the receiver by shifting the central $v_{lsr}$ (here, an integration time of ~1 hr is sufficient for a detection of the line). These tests confirm the identification of the observed emission with the rotational transition of $^{13}C^{17}O$. To our knowledge, this is the first detection of $^{13}C^{17}O$ in the interstellar medium.

A summary of the observations is given in Table 1, together with the velocity-integrated intensities. The statistical error ($\Delta I_{stat}$) is derived from the rms noise of the signal-free channels. An estimate of the systematic error is provided with a comparison of the integrated line intensities to those given by J. G. A. Wouterloot, J. Brand, & C. Henkel (2002, in preparation) toward their position 1. The integrated intensities agree to better than 10%, and we adopt a (conservative) systematic error of 10% for the intensity calibration of our observations ($\Delta I_{syst}$). The error introduced by the pointing accuracy is negligible. Both receivers are co-aligned within 3″ and the radio pointing was checked in intervals of 2 hr with typical being smaller than 5″.

## 4. RESULTS AND DISCUSSION

The line-integrated intensities are given in the last column of Table 1. Using these intensities, we deduce a $C^{17}O$ to $^{13}C^{17}O$ line ratio of 68.7 ± 6.7 and 57.3 ± 4.9 for the $J = 1 \rightarrow 0$ and

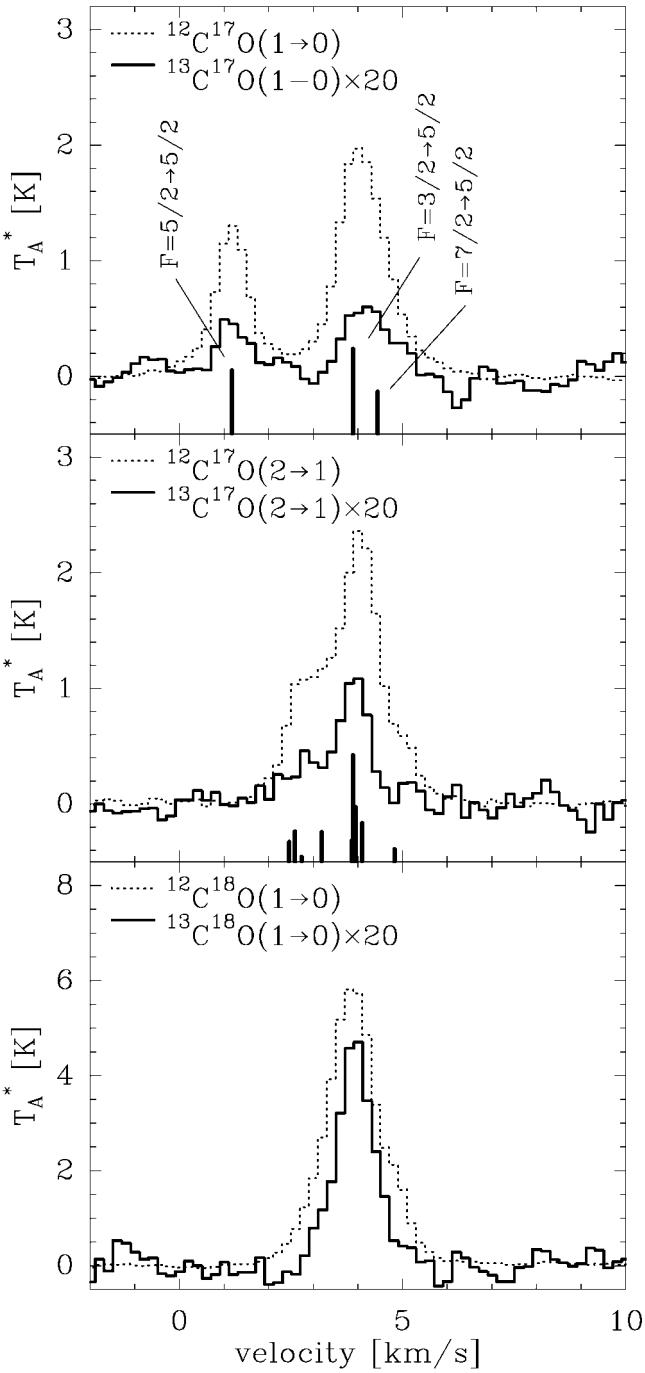



FIG. 1.—$J = 1 \rightarrow 0$ (*top panel*) and $J = 2 \rightarrow 1$ (*second panel*) spectrum of $C^{17}O$ and $^{13}C^{17}O$, observed toward core C of $\rho$ Oph. $C^{18}O$ and $^{13}C^{18}O$ $J = 1 \rightarrow 0$ spectrum is shown in the bottom panel. Note that the intensity scale is multiplied by a factor of 20 for the doubly rare isotopomers. Position and relative strengths of the $C^{17}O$ hf transitions are indicated. Line splitting for the $C^{17}O$ and $^{13}C^{17}O$ transitions are both dominated by the electric quadrupole interaction with the $I = 5/2$ spin of the $^{17}O$ nucleus. Thus, the $^{13}C^{17}O$ spectrum looks similar to the $C^{17}O$ spectrum at the velocity resolution of the spectrometer.

$J = 2 \rightarrow 1$ transitions, respectively. The $C^{18}O$ to $^{13}C^{18}O$, $J = 1 \rightarrow 0$, line ratio is $36.6 \pm 2.8$, and the ratio for both doubly rare isotopomers, $^{13}C^{18}O$ to $^{13}C^{17}O$, $J = 1 \rightarrow 0$, is $3.95 \pm 0.50$. Here, the quoted accuracy reflects the statistical errors, whereas the systematic error due to the limited accuracy of the intensity calibration is 14%.

The significantly lower ratio deduced for the $C^{18}O/^{13}C^{18}O$ pair can be understood in terms of line saturation. We applied the escape probability model by Stutzki & Winnewisser (1985) to estimate the optical depth for both $C^{18}O$ transitions assuming a density of $10^5$ cm$^{-3}$ for the emitting material. This is slightly lower than the density of $(1.1–1.9) \times 10^5$ cm$^{-3}$ derived by Motte, André, & Neri (1998); however, the results are not very sensitive to the density in this regime. Comparing the model results to the observed $C^{18}O$ line peak temperatures scaled to $T_{mb}$, we arrive at an excitation temperature of 13.5 K, and a CO column density per velocity interval of $dN/dv = 8.9 \times 10^{18}$ cm$^{-2}$ km s$^{-1}$. This gives line center optical depths of 3.4 and 7.5 for the $C^{18}O$ $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions, respectively.

However, large errors have to be attributed to the optical depth estimates, as small variations in the line peak intensities result in large variations of the deduced line opacities. Nevertheless, the model results demonstrate that line saturation effects can be significant for $C^{18}O$. The corresponding correction for the $C^{18}O$ to $^{13}C^{18}O$ line ratio is therefore large, and the results corrected this way are uncertain. The influence from significant line saturation effects is also evident from the line ratios derived for individual velocity channels, showing a systematic variation across the line profile. The ratio is as small as 25 for the center channels close to $v = 4.0$ km s$^{-1}$, but exceeds 45 for the more optically thin line wing emission.

In contrast to the $C^{18}O$ case, the optical depths of the $C^{17}O$ lines are small. Only for the $J = 2 \rightarrow 1$ transition are the effects of optical depth noticeable. This is suggested by the $^{13}C^{17}O$ to $C^{17}O$ $J = 2 \rightarrow 1$ intensity ratio, which is slightly smaller than for the $J = 1 \rightarrow 0$ transition, and the systematic variation of this ratio as a function of velocity. Ratios close to 40 are found for the line core channels ($3.6$ km s$^{-1} \le v \le 4.0$ km s$^{-1}$), whereas those in the line wings are systematically larger. A fit to the observed line profiles using the known splitting and relative strength of the hf transitions yield a peak optical depth of 0.10 and 0.94 for the strongest hf component of the $C^{17}O$ $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transition, respectively. This implies that optical depth effects are noticeable even for the $C^{17}O$ $J = 2 \rightarrow 1$ line.

The $C^{17}O$ to $^{13}C^{17}O$ abundance ratio can be deduced from the observed line ratios if we assume that the emission for both isotopomers arises from the same volume of space. We use the line-integrated intensity observed for the $J = 1 \rightarrow 0$ transition, because the optical depth correction (4%) is smaller for the lower rotational transition. An additional (subtractive) correction of 9% is applied to account for the slightly different rest frequencies of the transitions (Linke et al. 1977). This gives a $C^{17}O$ to $^{13}C^{17}O$ abundance ratio of $65.0 \pm 6.3$(stat) $\pm 9.2$(syst).

Similar corrections are applied to the integrated intensity ratio of both doubly rare isotopomers, giving $[^{13}C^{18}O]/[^{13}C^{17}O] = 4.15 \pm 0.52$(stat) $\pm 0.59$(syst). The statistical and systematic error assigned to each ratio is dominated by the finite signal-to-noise ratio in the spectra, and the accuracy of the intensity calibration, respectively. The uncertainty resulting from the correction of the optical depth effects and the excitation temperature (in the correction for the difference in the frequency of the transitions) are estimated to be each smaller than 2%.

In order to determine the true isotopic abundance ratios, we have to consider the possible influence of isotope-selective photodissociation and chemical fractionation. Both effects can result in a relative abundance ratio of the CO isotopomers which are different from the underlying isotopic abundance ratios. Selective photodissociation is due to the dissociation process of CO by far-ultraviolet (FUV) photons determined by line

absorption. With its relatively high abundance, mutual and self-shielding of the CO isotopomers are important, as well as shielding by H and $H_2$ transitions. Compared to $^{12}CO$, larger dissociation rates apply to the rarer isotopomers $^{13}CO$, $C^{18}O$, and $^{13}C^{18}O$ (van Dishoeck & Black 1988), resulting in a relative underabundance of these isotopomers predominantly in translucent clouds, molecular cloud surfaces, and clouds embedded in strong FUV fields (see Bally & Langer 1982; van Dishoeck & Black 1986; Sheffer et al. 1992). This is because of the smaller self-shielding column density of the rarer isotopomers and the small frequency shift which is introduced by isotopic substitution and which put some of the FUV transitions outside the $H_2$ and $^{12}CO$ absorption lines (bands). Unfortunately, the photodestruction of the $^{17}O$-bearing isotopomers is less well studied, and it is not entirely clear to which extent they suffer from selective photodissociation. Chemical fractionation results from isotopic exchange reactions, such as $^{13}C^+ + ^{12}CO \rightarrow ^{13}CO + ^{12}C^+ + \Delta E$, where $\Delta E/k = 35$ K (see Watson, Anicich, & Huntress 1976; Smith & Adams 1980). This causes an overabundance of $^{13}CO$ with respect to $^{12}CO$ for regions with low temperatures and an appreciable abundance of ionized carbon. While $C^{17}O$ and $C^{18}O$ are much less affected by fractionation (see Langer et al. 1984), exchange reactions similar to the one above increase the relative abundance of their $^{13}C$ substitutes. Thus, the $[^{13}C^{17}O]/[C^{17}O]$ and $[^{13}C^{18}O]/[C^{18}O]$ ratios potentially underestimate the true $[^{12}C]/[^{13}C]$ ratio.

We assess the influence of isotope-selective photodissociation and chemical fractionation to be negligible for our observations. Both effects are significant only for clouds emerged in strong FUV fields and in surface layers of molecular clouds where photochemistry plays an important role and the abundance of ionized carbon is large. In contrast, the ambient FUV field of the $\rho$ Oph molecular cloud is relatively weak (see Liseau et al. 1999) with an enhancement of $\chi \sim 25$ relative to the Draine (1978) field at the location of $\rho$ Oph C. The influence by the FUV radiation is further reduced by the fact that the emission observed for the rare CO isotopomers originates from well-shielded regions. Thus, the CO ratios should reflect the isotopic abundance ratios, giving $[^{12}C]/[^{13}C] = 65.0 \pm 6.3(\text{stat}) \pm 9.2(\text{syst})$ and $[^{17}O]/[^{18}O] = 4.15 \pm 0.52(\text{stat}) \pm 0.59(\text{syst})$.

The $[^{12}C]/[^{13}C]$ ratio determined for $\rho$ Oph C is in good agreement with the ratios recently determined for clouds in the solar neighborhood using observations at FUV, UV, and radio wavelengths. Savage & Sembach (1996) arrive at the ratio of $[^{12}C]/[^{13}C] = 66$ using UV absorption measurements of $CH^+$ and $^{13}CH^+$ lines made with the *Hubble Space Telescope* for the diffuse cloud in front of $\zeta$ Oph. This ratio also agrees with the results from recent ground-based observations of these lines for the $\zeta$ Oph diffuse cloud ($67.6 \pm 4.5$: Crane, Hegyi, & Lambert 1991; $71 \pm 3$: Stahl & Wilson 1992; and $63 \pm 8$: Hawkins, Craig, & Meyer 1993) and from measurement of CO and $^{13}CO$ FUV absorption lines, giving $[^{12}CO]/[^{13}CO] = 55 \pm 11$ for $\zeta$ Oph (Wannier, Penzias, & Jenkins 1982).

More recent radio observations of the $C^{18}O$ and $^{13}C^{18}O$ rotational transitions toward nearby dark clouds give carbon isotopic ratios of $75 \pm 8$ (Wilson, Langer, & Goldsmith 1981) and $62 \pm 4$ (Langer & Penzias 1993). Langer & Penzias (1990) find a ratio of 57 for the solar neighborhood using a fit to the $^{12}C/^{13}C$ isotopic ratio measured for clouds across the Galaxy. Studies of formaldehyde isotopomers suggest a larger ratio for the interstellar medium near the Sun, closer to the terrestrial value of ~89 (see Gardner & Whiteoak 1979; Henkel, Wilson, & Bieging 1982). However, the accuracy of these results is limited by the relatively low signal-to-noise ratio of the observations. Our result for $\rho$ Oph C supports a ratio which is below the terrestrial value and suggests that the local interstellar medium has undergone some processing since the formation of the solar system 4.5 Gyr ago.

The result for the oxygen isotopes is at the upper end of the range published in the literature. While a $[^{18}O]/[^{17}O]$ ratio close to 4 is found for giant molecular clouds (Wannier et al. 1976; Penzias 1981) and more recently for $\rho$ Oph (Wouterloot, Brand, & Henkel, in preparation), a lower ratio of $2.8 \pm 0.2$ is deduced by Wilson, Langer, & Goldsmith (1981) for nearby dark clouds. Our result of $4.15 \pm 0.52(\text{stat}) \pm 0.59(\text{syst})$ supports the larger ratio; however, it still is smaller than the terrestrial value of 5.5.

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REFERENCES

Bally, J., & Langer, W. D. 1982, ApJ, 255, 143
Crane, P., Hegyi, D. J., & Lambert, D. L. 1991, ApJ, 378, 181
Draine, B. T. 1978, ApJS, 36, 595
Frerking, M. A., & Langer, W. D. 1981, J. Chem. Phys., 74, 6990
Frerking, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590
Gardner, F. F., & Whiteoak, J. B. 1979, MNRAS, 188, 331
Hawkins, I., Craig, N., & Meyer, D. M. 1993, ApJ, 407, 185
Henkel, C., Wilson, T. L., & Bieging, J. 1982, A&A, 109, 344
Langer, W. D., Graedel, T. E., Frerking, M. A., & Armentrout, P. B. 1984, ApJ, 277, 581
Langer, W. D., & Penzias, A. A. 1990, ApJ, 357, 477
———. 1993, ApJ, 408, 539
Linke, R. A., et al. 1977, ApJ, 214, 50
Liseau, R., et al. 1999, A&A, 344, 342
Motte, F., André, P., & Neri, R. 1998, A&A, 336, 150
Müller, H. S. P., Thorwirth, S., Roth, D. A., & Winnewisser, G. 2001, A&A, 370, L49
Penzias, A. A. 1981, ApJ, 249, 518
Prantzos, N., Aubert, O., & Audouze, J. 1996, A&A, 309, 760
Savage, B. D., & Sembach, K. R. 1996, ARA&A, 34, 279
Sheffer, Y., Federman, S. R., Lambert, D. L., & Cardelli, J. A. 1992, ApJ, 397, 482
Smith, D., & Adams, N. G. 1980, ApJ, 242, 424
Stahl, O., & Wilson, T. L. 1992, A&A, 254, 327
Stutzki, J., & Winnewisser, G. 1985, A&A, 144, 13
Surin, L. A., et al. 2001, Rev. Sci. Instrum., 72, 2535
van Dishoeck, E. F., & Black, J. H. 1986, ApJS, 62, 109
———. 1988, ApJ, 334, 771
Wannier P. G., et al. 1976, ApJ, 205, L169
Wannier, P. G., Penzias, A. A., & Jenkins, E. B. 1982, ApJ, 254, 100
Watson, W. D., Anicich, V. G., & Huntress, Jr., W. T. 1976, ApJ, 205, L165
Wilson, R. W., Langer, W. D., & Goldsmith, P. F. 1981, ApJ, 243, L47
Wilson, T. L., & Matteucci, F. 1992, A&A Rev., 4, 1
Wilson, T. L., & Rood, R. T. 1994, ARA&A, 32, 191
Winnewisser, G. 1995, Vibr. Spectrosc., 8, 241