DETECTION OF THE $^3P_2 \rightarrow ^3P_1$ SUBMILLIMETER TRANSITION OF $^{13}$C $^1$ IN THE INTERSTELLAR MEDIUM: IMPLICATION FOR CHEMICAL FRACTIONATION

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Received 1997 October 9; accepted 1997 December 2; published 1998 January 20

ABSTRACT

We report the first detection of the submillimeter emission from the $^{13}$C isotope of atomic carbon in the interstellar medium. The $F = 5/2-3/2$ component of the $^3P_2^1-^3P_1^0$ transition was observed with the Caltech Submillimeter Observatory in a region around S of Orion IRC2, near the western end of the Orion Bar. The $^{12}$C-$^{13}$C isotopic abundance ratio is $58 \pm 12$ corrected for opacity of the $^{12}$C $^1$ line and the fractional intensity of the $^{13}$C $^1$ hyperfine component (60%). This is in agreement with the value for the equivalent ratio in C$^+$. In comparison, our measurement of the C$^{18}$O-$^{13}$CO ratio from observations of 2$-$1 and 3$-$2 lines toward the same position gives a value of $75 \pm 15$. Photodissociation region models predict that the C$^{13}$C-$^{12}$C abundance ratio is particularly sensitive to chemical fractionation effects. If C$^+$ is preferentially incorporated into $^{13}$CO at cloud edges, there will be a dramatic reduction in the abundance of $^{13}$C. This is contrary to our observations, implying that the importance of chemical fractionation is small or is compensated for by isotopic-selective photodissociation of $^{13}$CO in this region with a large UV illumination.

Subject headings: ISM: abundances — ISM: atoms — ISM: individual (Orion Bar, Orion OMC) — ISM: molecules — radio lines: ISM

1. INTRODUCTION

The abundances and ratios of the CNO isotopes in the interstellar medium (ISM) are sensitive to details of stellar and Galactic chemical evolution. Many attempts have been made to measure the ratio of $^{12}$C to $^{13}$C throughout the Galaxy and in the local ISM, as well as in stars, to help guide the Galactic evolutionary models. Optical, UV, and IR absorption line techniques have been used for these measurements as well as radio emission line measurements (see the review by Wilson & Rood 1994).

One of the most successful attempts for ISM measurements has been made by Langer & Penzias (1990 and 1993, hereafter LP90 and LP93, respectively), who compared the weak emission lines of C$^{18}$O and $^{13}$CO. They found a Galactic gradient in the $^{12}$C-$^{13}$C ratio ranging from 0.6 near the Galactic center to about 0.7 near the Galactic center (R_c) of about 1 kpc. The value in the local ISM is 6.2 ± 4. For R > 16 kpc, Wouterloot & Brand (1996), using the same technique, found a value greater than 100. Ratios derived from observations of H$_2$CO show a similar Galactic gradient but are ∼50% higher (Wilson & Rood 1994). Unfortunately, ratios derived from both CO and H$_2$CO can be distorted by chemical fractionation and isotopic-selective photodissociation, two processes discussed further in § 4.

Centurión, Cássola, & Vladilo (1995) have reviewed the various determinations using optical absorption lines of CH$^-$ and concluded that the abundance ratio in the local ISM is 67 ± 3. Boreiko & Betz (1996) have measured the $^{12}$C$^-$-$^{13}$C$^-$ ratio for the average of several positions toward the Orion Nebula region. The value they found is 58 ± 6. It is thought that neither of these probes should suffer from chemical fractionation effects.

In this Letter, we describe measurements of the ratio with another fundamental probe, neutral atomic carbon. According to photodissociation region (PDR) models, the ratio of atomic $^{12}$C to $^{13}$C in the dense interstellar medium is particularly sensitive to the opposing effects of chemical fractionation and isotopic-selective photodissociation, which can also affect the isotopomeric ratios of many molecules, e.g., CO and H$_2$CO. In this Letter, we use the atomic carbon isotopic ratio to assess the relative importance of these effects in one astronomical source. We compare the isotopic ratio in atomic carbon with that in CO, through measurements of the weak lines of $^{12}$C$^{18}$O and C$^{18}$O that are similarly affected by chemical fractionation and isotopic-selective photodissociation as the more abundant species (Langer et al. 1984; van Dishoeck & Black 1988).

The $^3P_2^1-^3P_1^0$ transition of $^{12}$C $^1$ at 492 GHz has been available for high spectral resolution measurements in molecular clouds for many years. Unfortunately, the equivalent $^{13}$C $^1$ transition is insufficiently split from the $^{12}$C $^1$ line to allow its discrimination; the largest split is only 3.6 MHz (2.2 km s$^{-1}$; Yamamoto & Saito 1991). However, the splitting between the $^{13}$C $^1$ ($^3P_2^1$) and the strongest hyperfine component of the $^{13}$C $^1$ equivalent transition, both lying near 809 GHz, is 152 MHz (56 km s$^{-1}$; Klein et al. 1998), providing a better opportunity for detection of $^{13}$C $^1$.

2. OBSERVATIONS

The observations were made during two periods of good weather in 1996 December and 1997 February with the recently available 850 GHz receiver (Kooi et al. 1997) at the Caltech Submillimeter Observatory (CSO). The 225 GHz zenith opacity at the time was ∼0.03, corresponding to an 809 GHz opacity of ∼0.7. We observed $^{12}$C $^1$ and $^{13}$C $^1$ in the upper sideband in 1996 December and in the lower sideband in 1997 February. There was excellent agreement between the two observing runs. Using Mars (diameter 10%6), we measured the main-beam efficiency at 809 GHz to be 33% in 1997 February assuming the theoretical beam size of 9$''$. Our source is very extended, so the Moon efficiency would be more appropriate to use in correcting the measured intensities. We estimate it to be
60% ± 20%. In addition, we measured some of the lines of CO and its isotopomers in the 2–1 and 3–2 transitions.

We decided to observe the \( F = 5/2–3/2 \) component of the \( ^3P_2–^3P_1 \) transition of \(^{12}\text{C}\) 1 because it is the strongest of the three components, with 60% of the total line strength. We centered this component within the quietest part of our bandpass, which meant that the two weaker components were not observed.

We chose to observe a position in the clump at the base of the Orion Bar ionization front, \( \alpha(1950) = 5^h32^m47.7^s, \delta(1950) = -5^\circ28'30''\) (~4′ S of IRC2), because it is known to have bright 492 GHz C 1 lines (Tauber et al. 1995). Unlike the Bar itself, the clump does not appear to have a strong edge-on geometry. It also has a simple molecular spectrum, thus avoiding line confusion such as occurs near Orion IRC2.

The fine-structure energy level intervals of the \(^{12}\text{C}\) and \(^{13}\text{C}\) atoms have been measured with high precision in the laboratory by Saykally & Evenson (1980), Cooksy et al. (1986), Yamamoto & Saito (1991), and most recently by Klein et al. (1998).

3. RESULTS

The observed spectra of \(^{13}\text{C} 1\) and \(^{12}\text{C} 1\) and the comparison isotopomeric lines of CO are shown in Figure 1. This is the first detection of submillimeter emission from \(^{13}\text{C}\) in the ISM. We measured the frequencies of the \(^{13}\text{C} 1\) and \(^{12}\text{C} 1\) lines by comparing them with the \(^{13}\text{CO}\) (2–1) line (not shown), which has a shape nearly identical to that of the \(^{12}\text{C} 1\) line. The frequency we measure for the \(^3P_2–^3P_1\) transition of \(^{12}\text{C} 1\) is 809342.3 ± 0.4 MHz, and the frequency of the \( F = 5/2–3/2 \) component of the \(^3P_2–^3P_1\) transition of \(^{13}\text{C} 1\) is 809492.8 ± 1.1 MHz. These agree well with the new laboratory measurements by Klein et al. (1998).

To compare the atomic isotopic ratio to the molecular isotopomeric ratio, we need to derive the ratio of column densities from the ratio of line intensities for both sets of data.

3.1. Atomic Carbon Isotopic Ratio

The column density ratio is derived from the line intensity ratio as follows:

\[
\frac{N(^{13}\text{C})}{N(^{12}\text{C})} = \frac{S(^{13}\text{C}) I(^{13}\text{C})}{S(^{12}\text{C}) I(^{12}\text{C})},
\]

where \( N \) indicates column density, \( I \) is the measured integrated line intensity (in units of K km s\(^{-1}\)), \( S \) is the fractional strength of the \( F = 5/2–3/2 \) component of the \(^3P_2–^3P_1\) transition of \(^{13}\text{C} 1\), and \( \beta = (1 – e^{-τ}) / τ \) is the escape probability of the \(^{13}\text{C} 1\) line photons, which compensates for the finite optical depth, \( τ \), in the \(^{13}\text{C} 1\) line.

Because of the low signal-to-noise ratio (S/N) of the weak \(^{13}\text{C} 1\) line, we use three methods of measuring line intensity ratios. First, we integrate the line intensities over the interval 5–14 km s\(^{-1}\). This method has the disadvantage of including excess noise outside the line core. Next, we integrate over the \(^{13}\text{C} 1\) and \(^{12}\text{C} 1\) line profiles weighted by the \(^{12}\text{C} 1\) line profile, a method used by LP90 for CO isotopomers to lessen the contribution of noise outside the line core. Finally, we fit Gaussians to the \(^{12}\text{C} 1\) line and use the same width and central velocities for the \(^{13}\text{C} 1\) line. The dispersion in these determinations is low (4%), and we adopt the mean value, 80. The S/N in the line integral measurement for the \(^{13}\text{C} 1\) line estimated from the noise in the baseline is ~6.5, so we assign a 15% uncertainty to the ratio. Thus, the measured line intensity ratio is 80 ± 12. Because the \(^{13}\text{C} 1\) and \(^{12}\text{C} 1\) lines were measured simultaneously in the same receiver sideband, there is no significant calibration uncertainty in the line intensity ratio.

The \(^{13}\text{C} 1\) transition has three hyperfine components. We assume that the excitation is thermal so that the hyperfine line intensities are proportional to the quantum mechanical line strengths and \( S(^{13}\text{C}) = 0.6 \).

The most difficult factor to estimate is the correction for the finite optical depth of the \(^{13}\text{C} 1\) line. We assume that the C 1 excitation temperature is 104 K, as we measured for the \(^{12}\text{CO}\) (2–1) line, and that the telescope beam efficiency for
large sources is $60\% \pm 20\%$. The uncorrected line intensity of 17 K then corresponds to a true line intensity of $28.3 \pm 14$ K and an opacity $\tau = 0.40 ^{+0.12}_{-0.08}$, with line escape probability $\beta = 0.83 ^{+0.04}_{-0.01}$.

The resulting ratio of the $^{12}$C to $^{13}$C column densities is $58 \pm 12$, where we have added the uncertainty in the escape probability in quadrature with that of the line intensity ratio.

### 3.2. CO Isotopomeric Ratios

The CO isotopomeric column density ratio is derived from the line intensity ratio as follows:

$$\frac{N(C^{18}O)}{N(C^{15}O)} = \frac{F}{\beta(C^{18}O)} \frac{I(C^{18}O)}{I(C^{15}O)},$$

where $F$ is a small correction due to the difference in the molecular excitation and the transition probabilities caused by the difference in frequency between the two lines.

We use the same three methods described in § 3.1 for determining line intensity ratios and adopt the mean values of these determinations: 81 for the 2–1 lines and 67 for 3–2. Because the $^{13}$CO lines are very weak, the uncertainties in the line ratios are substantial. One measure of the uncertainties is the ranges in the ratios determined by the three different methods. These are $\sim 7\%$ for the 2–1 ratio and $\sim 12\%$ for 3–2. The uncertainties in the integrated line intensities for the $^{13}$CO (2–1) and (3–2) lines, as estimated from the noise in the baselines, are $10\%$ and $9\%$, respectively. To be conservative, we adopt the larger of the two uncertainty estimates. We have estimated the telescope efficiency to be $70\%$ for both 2–1 and 3–2 transitions based on past determinations. Because the frequencies of the two lines in each frequency range are so close, this should add little uncertainty to the ratios. A larger factor is the uncertainty in the sideband ratio, since we have double-sideband receivers. We estimate this uncertainty to be $10\%$ for each measurement or $14\%$ for the ratio. Added in quadrature to the previous uncertainties, we have $17\%$ uncertainty for the 2–1 line intensity ratio and $19\%$ for 3–2.

Using standard LTE column density formula, we find for both the 2–1 and 3–2 lines that $F = 0.92$. We can also estimate this correction factor using a large velocity gradient (LVG) calculation. Then we find $F = 0.91$ for 2–1 and $F = 0.94$ for 3–2, so uncertainty in determination of $F$ is small and can be neglected.

We have estimated the optical depth of the $^{13}$CO lines using an LVG model for the $^{13}$CO (2–1) and (3–2) line intensities and ratio. The temperature and density are both constrained on the low ends by the line ratio, which gives $T > 70$ K and $n(H_2) > 1.6 \times 10^4$ cm$^{-3}$. We adopt the best fit for the temperature given by the brightness temperature of the CO (2–1) line ($T_B = 104$ K, $n(H_2) = 3 \times 10^4$ cm$^{-3}$), which has opacities of 0.09 and 0.27 and escape probabilities of 0.96 and 0.88 for the 2–1 and 3–2 lines, respectively. These lie near the center of the possible range as derived from the LVG model. As a measure of the uncertainties, we use the ranges of the escape probabilities, determined by the LVG calculation with different densities and temperatures. We find an uncertainty of $\sim 3\%$ for the 2–1 lines and $\sim 9\%$ for the 3–2 lines. The total uncertainty for $N(C^{18}O)/N(C^{15}O)$ is $\sim 17\%$ for the 2–1 line and $\sim 21\%$ for the 3–2 line.

Finally, combining all the factors, we find that $N(C^{18}O)/N(C^{15}O) = 77 \pm 12$ from the 2–1 lines and $72 \pm 15$ from 3–2, with a weighted average of $75 \pm 9$. In comparison, values of the $^{12}$C-to-$^{13}$C ratio toward the Orion molecular cloud previously derived from observations of CO and $^{13}$CO (2–1) and (1–0) range from 79 $\pm 7$ near IRC2 (LP90) to 63 $\pm 6$ at a position $\sim 14''$ S of IRC2 (LP93). Our value lies within this range and closer to the IRC2 value as befits its position close to the H II region. The average for the solar neighborhood is $62 \pm 2$ (LP93), so the positions near the M42 H II region in Orion appear to be truly different from the average neighborhood value, possibly because of the strong UV field of the Trapezium.

### 4. DISCUSSION

As mentioned in § 1, there are two major physical phenomena that can modify the abundance ratios of the various atomic and molecular forms of carbon and its isotopes. The first is chemical fractionation of $^{12}$CO and $^{13}$CO, because of the rapid exothermic exchange of $^{12}$C$^+$ with $^{13}$C in CO preferentially forming $^{13}$CO (Watson, Anicich, & Huntress 1976). Since $^{13}$C is formed by the recombinations of $^{13}$C$^+$, $^{13}$C will be depleted in favor of $^{12}$CO. This process is most effective where there is a large abundance of $^+$ ions and where the temperature is low, i.e., in the transition zone between ionized and molecular forms of carbon near the edges of molecular clouds. Here ionized, atomic and molecular forms of carbon coexist, and the temperature is reduced because of the enhanced cooling by atomic and molecular species. However, if the temperature were high, the rapid ion exchange would push the $^{13}$CO-to-$^{12}$CO ratio toward the elemental ratio.

The second process is the isotopic-selective photodissociation of CO. Again, this is generally most effective near the edges of molecular clouds. It occurs because CO and its isotopes are partially self-shielding, in that the photodissociation of CO occurs through discrete lines in the ultraviolet. H$_2$ molecules and dust act to partially shield CO—H$_2$ through its heavily saturation-broadened UV absorption lines and dust through continuum UV absorption. $^{12}$CO is also very effective at shielding itself, because of its large abundance, but $^{13}$CO is much less so, resulting in a greater photodissociation rate for $^{13}$CO and enhancement of $^{13}$C and $^{12}$C abundances at the expense of $^{12}$CO. The situation for photodissociation of $^{13}$CO and $^{12}$CO seems to be similar, although the overall rates are higher for the less abundant species (van Dishoeck & Black 1988).

We have used the PDR model of Le Bourlot et al. (1993) to interpret our observations. This model incorporates both chemical fractionation and isotopic-selective photodissociation, and we have used full radiative transfer, explicitly computing the mutual- and self-shielding of H$_2$ and all the CO isotopomers. We ran this model for a cloud of constant density $n(H_2) = 2.5 \times 10^4$ cm$^{-3}$, with an impinging UV field of strength $G_0 = 4 \times 10^4$ (Tauber et al. 1994) and abundances from Flower, Pineau des Fôret, & Walmsley (1995). The total gas-phase isotopic abundance ratios were taken to be $^{12}$C/$^{13}$C = 60 and $^{16}$O/$^{18}$O = 500. The results are shown in Figure 2.

Figures 2a and 2b show abundances and column densities of the majority carbon species as a function of extinction in the model cloud. Figures 2c and 2d show the abundance and column density ratios of the $^{12}$C-bearing species to their respective $^{13}$C-bearing species, normalized by their input ratios. Although most of the variation in the isotopic ratios in Figure 2c takes place at visual extinctions between about 2 and 7, we
have observed a region of high column density, $A_V > 50$ as estimated from the C$^{18}$O column density marked in Figure 2b ($2.5 \times 10^{16}$ cm$^{-2}$), so that these surface effects are seen integrated with the cloud interior, as shown in Figure 2d, and are thus, except for the atomic $^{12}$C-to-$^{13}$C ratio, greatly diluted.

An important feature of the model is that, at extinctions between about 2 and 7, both $^{13}$CO and $^{12}$C$^{18}$O are enhanced through chemical fractionation relative to their $^{12}$C isotomers by factors of up to 2.5 (Fig. 2c). The double ratio $n(^{13}$CO)/$n(^{12}$C$^{18}$O) displays much more extreme behavior. This ratio is affected in the same sense by both chemical fractionation and isotopic-selective photodissociation. The first increases the abundance of $^{13}$CO, while the second decreases the abundance of C$^{18}$O. The result is that $^{13}$CO is enhanced relative to C$^{18}$O by a factor of up to 20 in the same range of extinction.

Another important feature is that the local abundance ratio of $n(^{13}$C)/$n(^{12}$C) closely follows that found in C$^+$ (Fig. 2c). These ratios vary in the opposite sense to the ratios found in CO. In this model, where the temperature is low in the PDR ($\sim$25 K), chemical fractionation dominates over isotopic-selective photodissociation so that $^{13}$C is underabundant in both atomic carbon and C$^+$ but is overabundant in CO.

Finally, although the local abundance ratios of C and C$^+$ track each other very well (Fig. 2c), there is no effect due to the PDR visible in the column density ratio in C$^+$ (Fig. 2d), because C$^+$ is most abundant outside the molecular cloud where it is a majority species and where this effect is negligible. Therefore, according to this model, the isotopic column density ratio measured in C$^+$ should give the true isotopic gas-phase abundance ratio. Boreiko & Betz (1996) have measured the $^{12}$C$^+$-to-$^{13}$C$^+$ ratio for the average of several positions in the Orion Nebula region. The value they find for the ratio is $58 \pm 6$. In contrast, atomic carbon is most abundant in the model where the isotopic fractionation effects are most important. Therefore, there should be a large effect on the isotopic column density ratio of atomic carbon, as seen in the model (Fig. 2d). Yet the value we measure for the $^{12}$C-to-$^{13}$C ratio is $58 \pm 12$, the same as the ratio in C$^+$.

Our model in Figure 2d does not provide a good match to the observations indicated. The observed ratio of $^{12}$C to $^{13}$C is the same as the intrinsic ratio measured in C$^+$ by Boreiko & Betz (1996) and is lower than that in CO as measured using the rare isotopomorphic species. The deviation is in the sense that this model evidently has a great deal too much chemical fractionation, which pushes the model ratio of $^{12}$C to $^{13}$C to a larger value than is consistent with our observations.

We were able to achieve better agreement between our data and the model by artificially increasing the temperature within the model cloud. This higher temperature suppresses chemical fractionation within the PDR. That such a high temperature ($\sim$120 K) may be present is indicated from observations of $^{13}$CO (6–5) toward the Orion Bar (Lis, Schilke, & Keene 1997), but how it can be achieved physically is beyond the scope of this Letter to discuss.

In summary, we have measured the $^{12}$C-to-$^{13}$C ratio in atomic carbon ($58 \pm 12$) and find it to be the same as that in ionized carbon ($58 \pm 6$; Boreiko & Betz 1996), and probably smaller than that found in C$^{18}$O ($75 \pm 9$). The ratio of $^{12}$C$^+$ to $^{13}$C$^+$ should indicate the intrinsic isotopic abundance ratio since this is a majority species outside molecular clouds and it should not be significantly influenced by chemical fractionation or isotopic-selective photodissociation at cloud edges. From the PDR model, we see that the agreement between the isotopic ratios in ionized and atomic carbon implies that in this highly illuminated region, chemical fractionation must be unimportant or is compensated for by isotopic-selective photodissociation.

The CSO is supported by the NSF under contract AST 96-15025. We thank the staff of the CSO for their support, Richard Chamberlin and Maryvonne Gerin for help in the observations, Jacques Le Bourlot for help with the PDR model, Bill Langer and Ewine van Dishoeck for reading and commenting on the manuscript, and Henrik Klein and Frank Lewen for sharing their data before publication.
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