ISOTOPIC ABUNDANCES IN INTERSTELLAR CARBON MONOSULFIDE

R. W. WILSON, A. A. PENZIAS, P. G. WANNIER, AND R. A. LINKE Bell Telephone Laboratories, Crawford Hill Laboratory, Holmdel, New Jersey Received 1975 September 29; revised 1975 December 30

ABSTRACT

Measurements of relative abundances of the rare isotopic species ${}^{13}C^{32}S$ and ${}^{12}C^{34}S$ have been made by means of their 2 mm rotational line emission in five dense interstellar clouds. The abundance ratio $[{}^{13}C^{32}S]/[{}^{12}C^{34}S]$ shows a significant source-to-source variation. Measurements of ${}^{12}C^{33}S$ in two of the five clouds are consistent with a relative $[{}^{33}S]/[{}^{34}S]$ abundance equal to the terrestrial value. *Subject headings:* interstellar: abundances — interstellar: molecules

I. INTRODUCTION

As part of our continuing program to measure the relative isotopic abundances of the dominant elements in interstellar space, we report the results of our investigation of carbon and sulfur in interstellar carbon monosulfide, CS. This molecule has three readily observable transitions, the $J = 1 \rightarrow 0$, $2 \rightarrow 1$, and $3 \rightarrow 2$ near 6, 3, and 2 mm wavelengths, respectively. The last was selected for our observations because it yielded the best signal-to-noise ratio with our antenna and receiver. The most abundant isotopic species ${}^{12}C^{32}S$ (CS) at 146,969.102 MHz and the other species ${}^{13}C^{32}S$ (${}^{13}CS$) at 138,738.97 MHz and ${}^{12}C^{34}S$ (${}^{C^{34}S}$) at 144,617.116 MHz have single lines while ${}^{12}C^{33}S$ (${}^{C^{33}S}$) is a multiplet with seven transitions centered about 145,755.6 MHz (Lovas and Krupenie 1974).

The relatively high intensity of the interstellar lines of CS have permitted its study in a number of molecular clouds (Penzias *et al.* 1971; Turner *et al.* 1973). However, quantitative comparisons between the rarer isotopic species have been previously made only in two strong sources (Penzias *et al.* 1972; Turner *et al.* 1973). These observations were limited by the poor signal-to-noise ratios and spectrometer baselines yielded by the equipment available at the time.

Because the CS line may be saturated, measurement of the CS/C³⁴S line intensity ratio cannot be used to directly determine the $[^{32}S]/[^{34}S]$ abundance ratio. Instead, our determinations of $[^{32}S]/[^{34}S]$ are based upon the double ratio $[^{13}C][^{32}S]/[^{12}C][^{34}S]$ in analogy with our recent study of carbon monoxide (Wannier *et al.* 1975) (WPLW). The rarer isotopic species ^{13}CS , C³⁴S, and C³³S all have opacities which are low enough to permit the direct conversion of line intensity ratios into abundance ratios. The moderate opacities of the CS lines were determined by Liszt and Linke (1975) who measured the relative intensity ratios of the three lowest rotational transitions of CS in three of the sources included in our survey.

All the observations described herein were made using the 16-foot (5 m) antenna of the Millimeter Wave Observatory, Fort Davis, Texas.¹ The observing techniques and equipment used were the same as those of our CO study. Forty channel spectrometers of 0.25 or 2 MHz resolution were used according to the extent of velocity dispersion. Frequency switching was used in all the observations, and position switching was used in addition for the observations made with the wider bandwidth spectrometer to improve the baselines. The receiver calibration and atmospheric extinction were measured frequently, and appropriate corrections were made in data reduction.

II. DATA REDUCTION

The moderate opacity of the CS line can be advantageously applied to our problem by using this line to improve the weighting of data used in making the ratio determination. Since the CS spectra have the best signal-to-noise ratios and are thought to be only slightly broadened by saturation, they can be used to approximate the shapes of the corresponding lines of the rarer species. Thus

$$R\left(\frac{{}^{13}\text{CS}}{{}^{C^{34}\text{S}}}\right) = \frac{\int I(\text{CS})I({}^{13}\text{CS})dv}{\int I(\text{CS})I({}^{C^{34}\text{S}})dv},$$
(1)

where the integration is carried out over the velocity range where I(CS) is greater than 12 percent of its peak value. For C³³S we can construct a similar but somewhat more complicated relation to take account of its hyperfine structure, namely,

$$R\left(\frac{\mathrm{C}^{34}\mathrm{S}}{\mathrm{C}^{33}\mathrm{S}}\right) = \frac{\int'(\mathrm{C}\mathrm{S})I'(\mathrm{C}^{34}\mathrm{S})dv}{\int I'(\mathrm{C}\mathrm{S})I(\mathrm{C}^{33}\mathrm{S})dv},\tag{2}$$

where I'(CS) and I'(C³⁴S) are each the sum of seven spectra, each having the measured line shape, but displaced in frequency and normalized in amplitude to correspond to the components of the C³³S multiplet.

The results obtained (Table 1) are only weakly

L135

¹ The Millimeter Wave Observatory is operated by the Electrical Engineering Research Laboratory of the University of Texas at Austin, with support from the National Aeronautics and Space Administration, the National Science Foundation and McDonald Observatory.

L136

dependent upon the method of data reduction employed. Using a constant weighting in place of I(CS) in

TABLE 1

Calculated Line Intensity Ratios and Their Statistical Uncertainty (3 σ)

Source	¹³ CS/C ³⁴ S	C ³³ S/C ³⁴ S
Sgr B	$\begin{array}{c} 0.61 (+0.20, -0.14) \\ 0.38 (+0.23, -0.19) \end{array}$	0.19±0.13
Ori A	0.38(+0.07, -0.06)	0.21 ± 0.06
M17	0.62(+0.12, -0.10)	
NGC 2264	0.37 (+0.14, -0.13)	

NOTE.—Based upon the considerations outlined in the discussion, we estimate that systematic errors are probably less than 10 percent of the final values. equation (1) changed the values of $R(^{13}CS/C^{34}S)$ by less than 6 percent. The equivalent change in equation (2) changed $R(C^{33}S/C^{34}S)$ somewhat more, reflecting the higher noise level in the $C^{33}S$ observations.

For the data of Sgr B we used constant weighting because the shapes of the CS and ¹³CS lines are markedly different, as can be seen in Figure 1*a*. The values in Table 1 are derived by integrating over the velocity range where the $I(C^{34}S)$ is greater than half of its peak value. The result is not changed significantly if $I(C^{34}S)$ is used for weighting or if the full line width is used with constant weighting.

The errors given in Table 1 are 3 σ values derived from the rms fluctuation of both the weak and strong lines of each ratio. In each case we have taken into account the weighted summation over channels of the



FIG. 1.—CS, C³⁴S, and ¹³CS antenna temperatures corrected for antenna efficiency and atmosphere absorption are plotted against LSR velocity for five sources in Fig. 1. The CS spectra have been reduced in height as indicated. ("CS/2" denotes that the amplitude of the CS curve has been reduced by a factor of two.) The bottom plots are of C³³S and C³⁴S where the C³⁴S spectra have been modified to match the C³³S hyperfine structure as described in the text. The spectral resolution is 0.25 MHz (0.5 km s⁻¹) except in Sgr B and W51 where it is 2.0 MHz (4.0 km s⁻¹). The Sgr B spectra are remarkable in that the C³⁴S peak intensity exceeds that of CS at the central velocity, clearly suggesting absorption by cold intervening gas in the more abundant species, one of two alternative models proposed for this cloud (Scoville Solomon, and Penzias 1975).

© American Astronomical Society • Provided by the NASA Astrophysics Data System

line, the channel-to-channel correlation, and the number of channels of baseline information available.

III. DISCUSSION

The relative abundances of the sulfur isotopes are predicted to be in rather good agreement with their terrestrial values by a model based upon the production of sulfur by explosive nucleosynthesis (Arnett and Clayton 1970; Woosley, Arnett, and Clayton 1973). In this model the three isotopes are all produced in welldetermined relative proportions by explosive oxygen burning and are ejected together into the interstellar medium. Consequently, the relative abundances of the sulfur isotopes remain invariant even in the presence of extensive stellar processing.² Thus a determination that the relative isotopic abundances of interstellar sulfur were equal to their terrestrial values would lend support to the notion that explosive oxygen burning plays the dominant role in the processing by which interstellar sulfur is enriched.

All the values of $R(^{13}CS/C^{34}S)$ in Table 1 fall into two distinct groups of about 0.4 and 0.6. These values are both larger than the terrestrial abundance ratio of 0.26. On the other hand, the two measurements of $R(C^{33}S/C^{34}S)$ are not significantly different from the terrestrial value of 0.18. The data are consistent with an approximately terrestrial value of the interstellar sulfur isotopic abundance ratios and a greater than terrestrial, although variable, abundance of 13 C relative to 12 C. Specifically, our [13 C]/[12 C] abundance ratio is then taken to vary from ~ 1.4 to ~ 2.6 times its terrestrial value, in apparent contradiction to the much more uniform $[C^{18}O]/[^{13}CO]$ abundance ratio obtained in our carbon monoxide study (WPLW). (The small, \sim 20 percent residual source-to-source variation in [C¹⁸O]/[¹³CO] shows no correlation with the variable values of [13CS]/[C34S].) In two of the sources, Sgr B and M17, the values of $R({}^{13}CS/C{}^{34}S)$ are consistent with a terrestrial value of $[{}^{32}S]/[{}^{34}S]$ and the higher [¹³C]/[¹²C] ratio suggested by our earlier work. The remaining three sources exhibit considerably lower values of $R(^{13}CS/C^{34}S)$. In Ori A, for example, $R(^{13}CS/C^{34}S)$ $C^{34}S$) is only some 1.4 times its corresponding terrestrial

²We note that explosive oxygen burning involves massive stars while the processing associated with the ^{13}C enrichment discussed in WPLW is thought to be due to lower-mass longperiod variable stars (Audouze, Lequeux, and Vigroux 1975).

value, while the value of [13CO]/[C18O] was determined to be 2.6 times its corresponding terrestrial value (WPLW).

The possibility that the variation in our carbon monosulfide results is an artifact of the observations was investigated in a number of ways. First, the Sgr B2 and Ori A observations made in 1975 January were repeated in 1975 April, and essentially identical values were obtained. Observations were made with several different reference frequencies in order to check for interfering lines. No evidence of interfering lines was found within the limits set by our noise and the rather restricted total bandwidth of our spectrometer. Because the line intensity ratio varied from source to source, the variation cannot be explained in terms of a frequency dependence of the radiometer calibration. In fact, the receiver was usually retuned in only a minor way—if at all—when going from one source to the next. Additionally, effects due to possible temporal variations, such as antenna pointing and weather, were minimized by interleaving the observations of the different isotopic species. A remaining possibility is that the observed line intensities do not accurately reflect molecular abundances, owing to preferential excitation of the more abundant species, for example. However, since any such effect ought to modify the closely comparable ¹³CS/C³⁴S and C³³S/C³⁴S ratios in almost exactly the same way, we see that this explanation cannot easily account for the observed variations between Ori A and Sgr B.

Thus our data seem to indicate a source-to-source variation of the relative isotopic abundance in CS. While this is not a result that we expect from observations of other molecules, principally carbon monoxide, it nonetheless cannot be completely ruled out. Although the arguments against isotopic fractionation effects made for carbon monoxide (WPLW) can be equally well applied to carbon monosulfide, the present state of knowledge of the subject remains incomplete. Further theoretical work is called for and ought to be supported by a variety of observational investigations of isotopic distributions. It would seem prudent to verify the carbon monosulfide results by observation of the 3 mm $J = 2 \rightarrow 1$ lines. In addition, measurements of several molecules which share common atomic constituents or reactions would add significantly toward our emerging understanding of chemical evolution in the Galaxy.

REFERENCES

- Arnett, W. D., and Clayton, D. D. 1970, Nature, 227, 780. Audouze, J., Lequeux, J., and Vigroux, L. 1975, to be published. Liszt, H. S., and Linke, R. A. 1975, Ap. J., 196, 709. Lovas, F. J., and Krupenie, P. H. 1974, J. Phys. and Chem. Ref. Data, 3, 1.
- Penzias, A. A., Jefferts, K. B., Wilson, R. W., Liszt, H. S., and Solomon, P. M. 1972, Ap. J. (Letters), 178, L35.
 Penzias, A. A., Solomon, P. M., Wilson, R. W., and Jefferts, K. B. 1971, Ap. J. (Letters), 168, L53.
- Scoville, N. Z., Solomon, P. M., and Penzias, A. A. 1975, Ap. J., in press
- Turner, B. E., Zuckerman, B., Palmer, P., and Morris, M. 1973,
- Turner, D. D., Jackelman, B., Fanner, F., and Morris, M. 1975, Ap.J., 186, 123. Wannier, P. G., Penzias, A. A., Linke, R. A., and Wilson, R. W. 1975, Ap.J., in press (WPLW). Woosley, S. E., Arnett, W. D., and Clayton, D. D. 1973, Ap.J. Suppl., 26, 231.

R. A. LINKE, A. A. PENZIAS, P. G. WANNIER, and R. W. WILSON: Bell Telephone Laboratories, Crawford Hill Laboratory, Box 400, Holmdel, NJ 07733