MEASUREMENTS OF ISOTOPIC ABUNDANCES IN INTERSTELLAR CLOUDS

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While an examination of the available data reveals some seemingly contradictory results, a general framework having the following outlines can be put forward:

1. With the exception of the two galactic center sources SgrA and SgrB, the relative isotopic abundances exhibited by the giant molecular clouds in our Galaxy exhibit few, if any, significant variations from the values obtained by averaging the data from all these sources.

2. The $^{13}C/^{12}C$ and $^{14}N/^{15}N$ abundance ratios are ~130% and ~150%, respectively, of their terrestrial values throughout the galactic plane and somewhat higher, ~300%, near the galactic center.

3. The $^{16}O/^{18}O$ and $^{17}O/^{18}O$ abundance ratios are ~130% and ~160%, respectively, of their terrestrial values throughout the Galaxy, although the former may be somewhat lower near the galactic center.

4. The S and Si isotopes have generally terrestrial abundances.

The data upon which these tentative conclusions are based will be discussed, together with some apparent counter-examples and unresolved questions.

Isotopic abundance data have been obtained for seven of the most abundant elements in interstellar space; hydrogen, helium, carbon, nitrogen, oxygen, sulphur and silicon. This group of elements represents the three fundamental processes of element build-up: cosmological production (hydrogen/deuterium, and helium); the CNO processes, (carbon, nitrogen and oxygen); and explosive nucleosynthesis (sulphur and silicon). Since the light elements will be treated in a separate lecture, they will receive only passing mention here, with the bulk of our attention devoted to the CNO isotopes.

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SOURCE	R	H_2CO	$C^{18}O$	HCO^+	HC_3N	NH_2CHO	OCS	$C^{34}S$	$C^{18}O$	$H_2C^{18}O$	$HC^{18}O^+$	OH	$C^{18}O$	^{28}SiO	^{29}SiO	$C^{34}S$	$HC^{15}N$
	(kPc)	$H^{13}CO$	$^{13}C^{18}O$	$H^{13}CO^+$	$H^{13}CC_2N$	$NH_2^{13}CHO$	$O^{13}CS$	^{13}CS	^{13}CO	$H_2^{13}CO$	$H^{13}CO^+$	^{18}OH	$C^{17}O$	^{29}SiO	^{30}SiO	$C^{33}S$	$H^{13}CN$
								(x23)	(x500)	(x500)	(x500)						(x272)
Sgr A		20±10	26±5	21±2				33±2	43±5	60±9		275	3.4±.4	8.4±.5	1.3±.1		2±5
Sgr B	0.1	25±10	23±3	26±4	22±1	24±3	14±2	36±3	32±11	77±4	>45	240	3.2±.2	10.8±.6	1.6±.2	5.3±1	5±5
W43	5.5	42±6						43±4	61±8								
W33	5.7	74±11	42±4					66±3	52±40	79±10			3.6±.2				
W51	7.6		32±4					68±5	62±1	96±15			2.8±.1	11.8±1.5			56±5
W31	8(?)	37±6							54±25								
M17	8.0		91±20					59±3	49±7		91±10		3.5±.3				
NGC 6334	9.3		91±28					48±3	74±3		63±7						35±7
W49	9.4	53±8						77±8	39±18								
DR21	9.9	73±11	143±43					102±12	34±9		62±6		3.4±.3				
Ori A	10.9		>74	83±24	50±5			66±3	50±4		24±5		3.6±.3	9.0±.5	1.4±.1	4.8±.5	68±5
NGC 2024	11.0	72±11	56±8					69±7	27±4	<75		900	3.5±.2				
NGC 2264	11.1		83±31					69±6	60±3				3.5±.3				
W3	12.2	86±13	111±40						37±3				3.2±.3				
NGC 7538	12.7		77±21					45±5	42±7				3.5±.3				44±8
Average*		68±18	66±11					70±5	49±13								
Solar Sys	10	89	89	89	89	89	89	89	89	89	89	500	5.5	20	1.5	5.5	89
Ref.		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)

TABLE REFERENCES

(1) Henkel et al. (1979A) - Data for SgrA and SgrB are from Gardner and Whiteoak (1979) and Wilson et al. (1979) respectively.

(2) Linke (1979).

(3) Stark (1979) - Measurements were made at more than one location in each source. The largest ratio obtained for each source has been tabulated to minimize the effects of possible saturation.

(4) Wannier and Linke (1978).

(5) Lazareff et al. (1978).

(6) Goldsmith and Linke (1979).

(7) Frerking et al. (1979) - The SgrB result is the weighted average of the data at two locations in the source.

(8) Frerking (1979) - The average was obtained giving equal weighting to each source (SgrA and B were excluded) since the dominant errors are probably systematic.

(9) Kutner et al. (1979) - These results are an extension of earlier measurements reported by Tucker et al (1979). Similar results have been obtained by Henkel et al (1979B).

(10) Stark (1979) - The SgrB value is from Guelin and Thaddeus (1979).

(11) Whiteoak and Gardner (1975, 1978).

(12) Penzias (1979).

(13) Wolff (1979) - The SgrB values are weighted averages of several positions in the source.

(14) Wolff (1979).

(15) Wilson et al. (1976).

(16) Linke et al. (1977).

Of the seven stable CNO isotopic species (^{12}C,^{13}C,^{14}N,^{15}N,^{16}O,^{17}O and ^{18}O*) the isotopes of carbon have traditionally received the most attention. In his review paper at the 1976 IAU Symposium, Peter Wannier (1977) presented data which indicated a relative C/^{13}C abundance ratio of about 50, or ~1/2 the terrestrial ratio, throughout the galactic plane, with a somewhat smaller ratio in the center of the Galaxy**. This conclusion was largely based upon the results of two surveys of giant molecular clouds in our Galaxy. The first of these surveys was a comparison of the common and ^{13}C isotopic species of formaldehyde; the second was a double comparison of the ^{13}C and ^{18}O species of carbon monoxide. More recent work has permitted the interpretation of these results to be refined and has yielded more accurate data leading to somewhat modified abundance values.

In the case of formaldehyde, C. Henkel et al (1979A), have shown that the rotation level population distributions are different in the two isotopic species. This circumstance is due to the fact that the rotation transitions involved in the excitation are themselves optically thick in the more abundant species leading to radiative trapping effects which enhance the collisional excitation. This trapping has the effect of diminishing the intensity of the observed 6 cm K-doubling absorption in the more abundant species and thus serves to diminish its apparent abundance. When appropriate corrections are made for this effect, the resulting $H_2CO/H_2{}^{13}CO$ abundance ratios are substantially increased but are still somewhat below the terrestrial value. (The results of this work are summarized in Column 1 of the Table.)

In the carbon monoxide study referred to above, comparisons were made between the ^{13}CO and $C^{18}O$ species in order to avoid the use of the heavily saturated spectra of the common CO species. This method suffers, however, from the requirement for a separate determination of the O/^{18}O abundance. An investigation which avoids this requirement has been completed by R. A. Linke (1979). In this measurement the rare $C^{18}O$ isotopic species of carbon monoxide was compared with the yet rarer $^{13}C^{18}O$ species. The results of this work yield a galactic plane C/^{13}C abundance ratio of about 66 (Col. 2) which agrees with the corrected formaldehyde results (Col. 1). It therefore seems reasonable to adopt a value of ~67±10, as more appropriate to the galactic plane than either the terrestrial value of 89 or the value of ~50 referred to above. (In the two galactic center sources, however, the C/^{13}C ratio is considerably lower, a result which is supported by data from other molecules (Col. 1-6).

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*Following the usual convention the most common isotope of each atomic species will have its atomic weight omitted. Thus $^{13}C^{16}O$ and $^{1}H^{12}C^{14}N$ will be written ^{13}CO and HCN respectively.

**For the purposes of this discussion, we will use the unmodified term "galactic plane" as excluding the galactic center region.

Returning to the $^{13}CO/C^{18}O$ work, a survey in these species has been recently carried out by M. A. Frerking (1979) with more sensitive equipment, yielding results (Col. 8) in good agreement with the earlier work, but in disagreement with the new $C/^{13}C$ value suggested above if a terrestrial ^{18}O abundance is assumed. This indicates that we must abandon the notion of a terrestrial $O/^{18}O$ abundance in the galaxy. Instead, the new $C/^{13}C$ value can be combined with the results of the $^{13}CO/C^{18}O$ double ratio work (Col. 8) to yield an $O/^{18}O$ abundance in the galactic plane which is about 1.3 times the terrestrial value. While this suggested underabundance of ^{18}O is supported by the $H^{13}CO^+/HC^{18}O^+$ data (Col. 10), the $H_2{}^{13}CO/H_2C^{18}O$ data appear to be more consistent with a terrestrial ^{18}O abundance. It is unlikely that this discrepancy is due to chemical fractionation because of the agreement between the single ratio CO and H_2CO results (Col. 1 and 2). The present state of observational data cannot provide certainty, but an underabundance (relative to terrestrial) of ^{18}O in the galactic plane seems the best fit to the data that we have.

The ^{18}O abundance in the galactic center sources is uncertain, but the data, especially H_2CO (Col. 9) suggest that the $O/^{18}O$ ratio may be appreciably smaller in this region than in the galactic plane. On the other hand, an $^{17}O/^{18}O$ determination (Col. 12) yielded a constant value (~1.6xterrestrial) for this latter ratio over both the galactic center and galactic plane. While one result does not preclude the other, an equal enhancement of ^{17}O and ^{18}O in the galactic center seems unlikely. Earlier OH work, using the 18 cm. λ-doubling transitions, had indicated a substantial ^{18}O enhancement in the galactic center sources (Col. 11). The measurements upon which the OH results were based involved comparisons of optical depths which differed by a factor of several hundred; the conversion of these optical depths into column density ratios assumed equal excitation temperatures in the two species. Since the common species has heavily saturated rotation spectra, its excitation will be different from that of the rarer species; this effect could lead to an underestimate of the relative abundance of the common species by as much as a factor of two (Cernicharo and Guelin 1979). While the weight of evidence seems to be on the side of a lower than galactic $O/^{18}O$ ratio in the galactic center, the present state of our knowledge is far from satisfactory on this point.

Turning now to the other elements, a comparison of the CS data (Col. 7) with the $C/^{13}C$ results shows good agreement indicating a terrestrial abundance of ^{34}S. Other data (Col. 15) suggests that the ^{33}S isotope has a terrestrial abundance as well. In the case of the silicon isotopes on the other hand, while the two rare species seem to have terrestrial abundances relative to each other (Col. 14), their abundances relative to the common species are indicated to be about twice the terrestrial value (Col. 13). The apparent underabundance of the common species does not seem to be an artifact of line saturation, although this possibility cannot be totally ruled out.

Finally, the HCN data in the galactic plane show $^{14}N/^{15}N$ to be enhanced, relative to the terrestrial value by a factor of ~1.5, with a considerably larger enhancement (a factor of ~3) in the galactic center region.

DISCUSSION

With the exception of the galactic center sources no clearly consistent variation of the nuclear abundances between individual sources is evident in the tabulated data. Occasionally the value of one isotope ratio or another seems to differ from those in neighboring sources by a statistically significant amount. However, these variations show little, if any, correlation between one isotopic species and another, or between one set of measurements and another. (Evidence for some source-to-source correlation between the CS and HCN data has been put forward by Frerking et al (1979) however.) It therefore seems premature to interpret any of these anomalies in terms of nuclear differences in the galactic disc. This absence of clear differences suggests that we can obtain representative abundance values by averaging among sources.

Some nuclear differences do exist, of course. The most notable ones are associated with the earth itself. As indicated above, the presolar nebula apparently had only about two-thirds as much ^{13}C, ^{14}N and ^{16}O relative to their respective counterparts ^{12}C, ^{15}N and ^{18}O as does the galactic plane at present. In addition, regions associated with evolving stars such as the envelope around IRC 10216 have been shown to possess nuclear abundances which differ from those of general interstellar space (Wannier and Linke 1977). For the great bulk of material in the Galaxy, however, we seem to see a uniformity which is characteristic of an efficient mixing, or of a common nuclear history, or a combination of the two. The galactic center region appears to be the only exception, a not unsurprising circumstance in view of the markedly greater amount of stellar processing that has taken place there. The much smaller effects due to the decrease in processing with galactic radius in the rest of the Galaxy are largely hidden by the uncertainties in the available data.

The above treatment appears able to obtain agreement between data from different molecules without invoking chemical fractionation effects. It should be emphasized, in this regard, that the tabulated data have been obtained entirely from giant molecular clouds. In the cooler dark clouds, molecular isotopic abundances can be affected by fractionation. In a recent paper, Langer et al (1980) reported studies of three such clouds in which the isotope ratios in the diffuse ($10^3/cm^3$) exteriors showed considerable carbon fractionation. The opaque core regions of these clouds, however, exhibited abundances in agreement with the giant cloud data, indicating little if any fractionation therein.

The increasing clarity of the emerging picture of isotopic abundances in the Galaxy is in considerable part due to the success of a two-pronged attack on the line formation problem. Improvements in sensitivity permit observations of very low optical depth transitions while, at the same time, better analytical treatment has been employed to deal with the saturation problems characteristic of high optical depth. While it seems reasonable that some surprises lie hidden by the uncertainties in our data, a comprehensive observational framework upon which to base our theoretical understanding appears to be in hand.

REFERENCES

Cernicharo, J., and Guelin, M.: 1979, in preparation.

Frerking, M.A.: 1979, in preparation.

Frerking, M.A., Wilson, R.W., Linke, R.A., Wannier, P.G.: 1979, submitted to Ap. J.

Gardner, F.F., and Whiteoak, J.B.: 1979, MNRAS 188, p. 331.

Goldsmith, P.F., and Linke, R.A.: 1979, to be published.

Guelin, M., and Thaddeus, P.: 1979, Ap. J. (Letters) 227, p. L139.

Henkel, C., Walmsley, C.M., and Wilson, T.L.: 1979A, Astron. and Astrophys., in press.

Henkel, C., Wilson, T.L., and Downes, D.: 1979B, Astron. and Astrophys. 73, p. L13.

Kutner, M.L., Machnik, D.E., Tucker, K.D., and Massano, W.: 1979, to be published.

Langer, W.D., Goldsmith, P.F., Carlson, E.R., and Wilson, R.W.: 1980, Ap. J., in press.

Lazareff, B., Lucas, R., and Encrenaz, P.: 1978, Astron. and Astrophys. 70, p. L77.

Linke, R.A., Goldsmith, P.F., Wannier, P.G., Wilson, R.W., and Penzias, A.A.: 1977, Ap. J. 214, 50.

Linke, R.A.: 1979, in preparation.

Penzias, A.A.: 1979, in preparation.

Stark, A.A.: 1979, to be published.

Tucker, K.D., Kutner, M.L., and Massano, W.: 1979, Ap. J. (Letters) 227, L143.

Wannier, P.G.: 1977, CNO Isotopes in Astrophysics, J. Audouze, Ed. D. Reidel, p. 71.

Wannier, P.G., and Linke, R.A.: 1977, Ap. J. 214, p. 50.

Wannier, P.G., and Linke, R.A.: 1978, Ap. J. 226, p. 817.

Whiteoak, J.B., and Gardner, F.F.: 1975, Proc. Astr. Soc. Aust. 2, 360.

Whiteoak, J.B., and Gardner, F.F.: 1978, MNRAS 183, p. 67p.

Wilson, R.W., Penzias, A.A., Wannier, P.G., and Linke, R.A.: 1976, Ap. J. (Letters) 204, p. L135.

Wilson, T.L., Walmsley, C.M., Henkel, C., Pauls, T., Mattes, H.: 1979, Astron. and Astrophys., in press.

Wolff, R.S.: 1979, Ap. J., in press.

DISCUSSION FOLLOWING PENZIAS

Kutner: As listed in column (9) of your table our latest $H_2^{13}CO$ and $H_2C^{18}O$ observations give double ratios of 8.3±1.2, 6.5±0.3, 6.3±0.8, 5.2±0.8 for Sgr A, Sgr B2, W33, W51 (vs the terrestrial value of 5.6), corresponding to carbon ratios of 60±9, 77±4, 79±10, 96±15. We noted in our Jan. 79 Ap. J. Letter that the formaldehyde results are quite consistent with a carbon ratio in the 70's. It still appears that there are some significant discrepancies between the double ratios determined from CO and H_2CO.

Penzias: I quite agree. It may be that the agreement between the single ratio H_2CO and CO data is fortuitous, and that the actual $C^{18}O/^{13}C^{18}O$ ratio is closer to the value one obtains from the double ratio, $C^{18}O/^{13}CO$, and a terrestrial oxygen abundance. In that case, the higher ^{13}C abundance in CO would be due to fractionation. However, I regard this explanation as unlikely, because the differences between the two sets of CO data referred to above seem well established, and the role of chemical fractionation in CO has now been observed to be limited to rather diffuse regions.

Townes: This excellent analysis and the newly obtained results have surely given us a better value of the average $^{12}C/^{13}C$ ratio, a value which is much easier to understand in terms of galactic history than were earlier smaller ratios. In addition to the broad results which Penzias has emphasized, there appears to be very significant information, for example, concerning the variation of isotopic ratios from source to source. The very valuable new measurements of $^{18}O/^{17}O$ ratios show rather striking uniformity. However the values found differ substantially from the terrestrial one, which raises the question whether the earth is really a representative sample of isotopic ratios in our galaxy at its formation about 5 x 10^9 years ago. In addition, one of the more reliable ratios would seem to be that of $^{13}C^{16}O/^{12}C^{18}O$. However, this varies from source to source by far more than the probable errors listed. This suggests, as has been noted before, that the large molecular clouds have developed over a long period of time in a partially isolated state.

Penzias: Your point is certainly well taken. In attempting to infer broad galactic isotope values from averages, I have pretty much neglected source-to-source variations. For a study of the individual clouds themselves, isotopic abundance differences play a far more central role. Whether the tabulated differences are due to line formation or actual abundance variations seems to be an unresolved issue. For example, NGC 2024 looks low in col. (8) but normal in the others. Similarly W51 looks out of place in col. (2) but not in (7) or (8). Checking this out with appropriate additional observations is clearly the next order of business.

Kutner: I think that within each source the H_2CO isotope data is quite self-consistent. The radiative trapping corrections in Sgr B2 are probably so uncertain that a value of 25 for the $H_2CO/H_2^{13}CO$ must be regarded as tentative.

Penzias: Wilson et al. (1979) have made optical depth measurements in the $1_{10}-1_{11}$, $2_{11}-2_{12}$ and $3_{12}-3_{13}$ transitions of H_2CO in this source. If, as you suggest, they were to have underestimated the optical depth of the lowest lying transition relative to the other two, their model would have to have yielded too high a density. Time does not permit a detailed discussion of their results, but the density they derive is on the low side already, and is unlikely to be a gross overestimate.

Vanden Bout: The $^{12}C/^{13}C$ ratio from optical observations of CH^+ toward ζ Oph, 20 Tau, and ξ Per yield values ranging from 50 to 75, with a mean value close to those in your table for material outside the galactic center.

Penzias: While the agreement between your data and the ratio suggested in my talk is gratifying, I have avoided considering diffuse regions in deriving broad isotope values because of possible fractionation effects.

Vanden Bout: CH^+ is unlikely to be affected by fractionation according to Watson, Anicich, and Huntress (1976, Ap. J. 205, L165).