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Nuclear Processing and Isotopes in the Galaxy

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The study of the nuclear processes by which the stars generate energy and form the chemical elements of our galaxy continues to be an active and fruitful area of astrophysics. In the simplest picture (*1*, *2*), cosmologically produced ^{4}He is fused into ^{12}C and ^{16}O, the "primary" products of stellar processing. "Secondary" products, like ^{14}N and ^{13}C, are then formed by ar species; the detection of these species and the measurement of their abundances can serve to trace these nuclear processes and related stellar phenomena.

The types of processing and the amount of processed material ejected into interstellar space are themselves strong functions of stellar mass. The

Summary. The galactic distributions of the stable isotopic species of hydrogen, carbon, nitrogen, oxygen, sulfur, and silicon have been derived from the study of interstellar molecules which contain them. The resulting observational framework appears consistent with our general understanding of stellar evolution and nuclear processing in the galaxy. The greater amount of star formation that has taken place near the center of our galaxy is reflected in an enhanced abundance of processed material, notably carbon-13, in this region. Significant differences between abundances of isotopes in the solar system and corresponding values in interstellar space are also evident. Although some of these differences merely reflect the results of additional stellar processing since the condensation of the presolar nebula some 5 billion years ago, others suggest that a significant amount of atypical nuclear material is associated with the solar system.

burning in the celebrated carbon-nitrogen-oxygen (CNO) cycle, in which additional helium is produced by the cyclical series of hydrogen-burning (that is, proton-adding) reactions first described by Bethe (*3*), namely

$$
\begin{aligned}
&^{12}\mathrm{C} + \mathrm{p} \rightarrow {}^{13}\mathrm{N} + \gamma,\ {}^{13}\mathrm{N} \rightarrow {}^{13}\mathrm{C} + \mathrm{e}^+ \\
&^{13}\mathrm{C} + \mathrm{p} \rightarrow {}^{14}\mathrm{N} + \gamma \\
&^{14}\mathrm{N} + \mathrm{p} \rightarrow {}^{15}\mathrm{O} + \gamma,\ {}^{15}\mathrm{O} \rightarrow {}^{15}\mathrm{N} + \mathrm{e}^+ \\
&^{15}\mathrm{N} + \mathrm{p} \rightarrow {}^{12}\mathrm{C} + {}^{4}\mathrm{He}
\end{aligned}
\qquad (1)
$$

where p, γ, and e^+ stand for proton, photon, and positron, respectively. Subsequent work has revealed that this process lies at the core of a network of interrelated cycles whose relative roles are determined by ambient stellar conditions. Each of these processes has a particular influence over one or more nucle- more massive stars dominate the scene by virtue of their short and violent lifetimes until the gas from which they are born is largely used up; from that point on, the slower emission of the long-lived low-mass stars becomes the dominant feature in the composition of interstellar matter. Because of its faster rate of star formation, the central region of our galaxy has been more depleted of its original interstellar gas than has the rest of our galaxy, including the solar neighborhood, which still contains relatively large amounts of interstellar gas and numerous young stars (Fig. 1).

The effects of nuclear processing are reflected in comparisons between the nuclear compositions of the matter in three key regions, the solar system, the galactic plane, and the galactic center (for the purpose of this discussion, I will use the unmodified term galactic plane as excluding the galactic center region). A comparison between the first two provides an indication of the results of stellar processing since the condensation of the presolar nebula some 5 billion years ago. Similarly, the effects of stellar processing in the galaxy should be greater near the galactic center than in the galactic plane, owing to the much greater number of generations of stars produced near the center.

A powerful tool in tracing the results of nuclear processing in our galaxy has been realized through the use of molecular line observations. The various interstellar molecules existing throughout our galaxy can only be studied by means of their radio spectra. Because many of the more common species are abundant enough to produce detectable spectra even in their rarer isotopic species, molecular data can be used to determine the underlying isotopic abundances of the constituent atoms. Isotopic abundance data have been obtained for seven of the most abundant elements in interstellar space: hydrogen, helium, carbon, nitrogen, oxygen, sulfur, and silicon. This group of elements represents three fundamental processes of element buildup: cosmological production (hydrogen-deuterium and helium), the CNO processes (carbon, nitrogen, and oxygen), and explosive nucleosynthesis (sulfur and silicon).

The particular advantage of comparing isotopes of the same chemical species is that it permits comparisons between nuclei while largely avoiding the complications associated with chemical differences. In the traditional study of the relative abundances of the primary nucleus ^{16}O and the hydrogen-burning product ^{14}N by means of their optical spectra, for example, extensive corrections are required because of their different ionization potentials. In contrast, a comparison between the common ^{12}C^{16}O and ^{13}C^{16}O species of carbon monoxide involves a primary and a secondary nucleus whose chemical properties are essentially identical. (While some chemical fractionation can result from the mass differences between isotopes of the same element, as discussed

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Fig. 1. This spiral galaxy (NGC 7331) in the Pegasus constellation illustrates the central concentration of stars characteristic of all galaxies including our own. The dark patches indicate concentrations of interstellar dust usually associated with clouds of molecular gas. [Hale Observatories photograph]

below, such processes are weak enough to be ignored in the present context for all isotopes except deuterium.) With this simplification, the problem is then reduced to the still formidable task of inferring underlying abundances from observed spectra, discussed in the next section.

Spectral Line Formation

The increasing clarity of our 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 transitions with small optical depths, while at the same time better analytical treatment has been employed to deal with the saturation problems characteristic of high optical depth. (Optical depth is a measure of attenuation. Radiation passing through a medium with optical depth τ will be attenuated by a factor $e^{-\tau}$.)

Line intensity is normally expressed in units of temperature. The familiar transfer equation

$$T_B(\nu) = T_{ex}(1 - e^{-\tau}) \tag{2}$$

relates the frequency (ν) behavior of the observed brightness temperature, T_B, to the excitation temperature, T_{ex}, of the transition in question (*4*) and the optical depth, τ, of the line. This last quantity is proportional to the column density—that is, the number of molecules per unit area of sky in the direction of observation—and inversely proportional to the excitation temperature. Thus in the case of small τ the exponential may be expanded, yielding an expression for T_B which is proportional to the column density and independent of the excitation temperature. It is easiest to interpret data from optically thin (low optical depth) lines, and therefore often tempting, but less often appropriate, to use the optically thin approximation. The careful reader will do well to approach each observational result with concern about adequate treatment of optical depth effects.

While optically thin lines have weak intensities, the converse is not always true. An excellent example of such a situation was reported by Langer *et al.* (*5*). The molecule HCO^+ (*6*), like its electronic isomers HCN and HNC, exhibits very weak spectra in many dark clouds, while its rarer isotopic species $H^{13}CO^+$ and DCO^+ have much stronger lines. (This has, in fact, led some authors to conclude erroneously that deuterium fractionation in these regions is so strong as to enhance the abundance of the deuterated species to a level which exceeds that of the corresponding common species.) However, comparison of the various HCO^+ isotopic spectra revealed a clear difference between the line shapes of the common and the rarer species; the marked diminution in the HCO^+ line was shown to be due to absorption by intervening gas with a low excitation temperature (*5*).

Excitation temperature is rarely, if ever, constant along the line of sight. If the cloud in question is surrounded by a tenuous outer layer, then the low collisional excitation rate in this layer will produce a very low excitation temperature for HCO^+ within it. If the HCO^+ optical depth in this outer region is appreciable, then the observed brightness temperature of its spectra will be very low because the emission from inside the cloud will be absorbed in the outer layer. On the other hand, the less abundant species will have much lower optical depths in the outer region and hence their brighter spectra originating in the denser, more highly excited, portion of the cloud will be seen by the observer.

While the tenuous outer layer of cloud may be a region of low excitation for HCO^+ and similar molecules, the physical temperature of the ambient gas in the outer region need not be lower than that of the cloud interior. Indeed, it is a truism in astronomy that diffuse gas is hotter, because cooling is accomplished by collision processes whose rates are proportional to the square of the density while heating is linearly proportional to the density. Thus the latter process is relatively more effective at low densities.

The existence of a diffuse outer layer can have a quite different effect on the observed spectra of the important molecule carbon monoxide. Among the common molecular species, CO has a uniquely long radiation lifetime in its first excited rotational state ($J = 1$ level) owing to its small dipole moment (0.1 debye compared to ~ 3 debye for HCO^+). Thus its collisional excitation is accomplished almost three orders of magnitude more easily. Furthermore, because of the details of the CO collision cross sections (for collisions with the ambient gas, mainly molecular hydrogen), it is actually possible to excite the $J = 1$ level to an extent which is in excess of that given by the kinetic temperature of the exciting gas, in effect superheating the transition in regions of low gas density. Thus for CO one might see abnormally strong CO emission from the same intervening material that so severely reduced the observed HCO^+ intensity. The observed emission of ^{13}CO would arise from deeper inside the cloud, where the greater density would bring its excitation temperature into equilibrium with the kinetic temperature of the core. Thus even when ^{13}CO has an appreciable optical depth, it can still have a much lower brightness temperature than the common species (*7*). In the face of such possibilities, the only prudent course is to collect supporting data from a number of species and, where possible, more than one transition in each species.

Since data from a single line only reflect the populations of the pair of levels involved in the observed transition, determination of the total population of the species in question requires a knowledge of the population distribution among all energy levels. A difference in excitation can occur when one of the species has an appreciable optical depth in one or more of its transitions. In the optically thin case each collision excites at most a single molecule, while in the optically thick case the effect of each exciting collision is multiplied by the number of times the resulting photon is reabsorbed before it escapes from the emitting region. The effect of high optical depth in a particular transition is therefore to enhance the effect of collisional excitation. The more abundant species will experience greater excitation, since the higher optical depths of its lines will cause it to reuse each collisional excitation more often.

Even when two isotopes are compared in optically thin transitions, other transitions of these isotopes may be optically thick; the resulting excitation difference could result in an appreciable difference between the observed line intensity ratio and the relative abundances of the corresponding species (*8*). This radiative trapping mechanism should make us treat comparisons between isotopic species having any optically thick transitions with caution, and comparisons between species having greatly different abundances with suspicion.

Once isotopic abundances have been established they may be used, in turn, to probe the effect of optical depth on line intensity in other clouds with the same nuclear history. The isotopic species of a given molecule can provide the molecular line observer with a series of lines of known relative optical depths, a powerful tool in the study of line formation processes and the cloud structure they reflect.

Chemical Fractionation

The great power of comparisons between isotopes of the same species rests in the fact that they share common chemical properties, thus greatly simplifying the interpretation of the measurements. There are, however, two potentially important exceptions. These involve the key elements hydrogen (*9*) and carbon (*10*) through the process of chemical fractionation—that is, reactions whose rates differ for isotopes of the same element.

Chemical fractionation arises from slight changes in molecular binding energy due to the dependence of the zero-point vibration energy on the masses of the constituent atoms. The influence of this effect on abundances is blocked for most elements, however, by the activation energies required for the reactions involved. Chemical fractionation is thus restricted to the elements for which an ionized intermediary exists (*11*) because ion-molecule reactions do not have activation energy barriers. These ionized intermediaries are H_3^+ and C^+ for hydrogen and carbon, respectively; they can react, for example, by

$$H_2D^+ + HCN \rightleftarrows H_3^+ + DCN + \Delta E \quad (3)$$

and

$$^{13}C^+ + CO \rightleftarrows C^+ + {}^{13}CO + \Delta E \quad (4)$$

where ΔE is the difference between the change in binding energy caused by isotopic substitution into the molecule in question and that caused by the corresponding substitution in the principal reservoir of the atom.

Because carbon is the key element in much of the work described here, the evaluation of chemical fractionation effects in this element is of prime importance. Carbon monoxide plays a unique role in carbon fractionation because it alone is stable enough to survive the exchange reaction (Eq. 4) intact. As a result, ^{13}C can be expected to be most highly concentrated in carbon monoxide, with the observed abundance ratio ^{13}CO/CO to be regarded as an upper limit to the relative abundance of ^{13}C to C in the corresponding region of interstellar space. It is therefore significant that a comparison of ^{13}C abundance data from ^{13}CO with data from other molecules not formed from CO reveals satisfactory agreement. This argues strongly against the necessity of considering fractionation effects when interpreting the CNO data reviewed below.

It should be emphasized, in this regard, that these 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.* (*12*) reported studies of three such clouds in which the isotope ratios in the diffuse 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 there.

Chemical fractionation in deuterium, on the other hand, is a far larger effect than in carbon. The difference in binding energy between DCN and HCN is ~ 450 K greater than the corresponding difference between HD and H_2 (for convenience, energy is expressed in units of temperature by dividing by Boltzmann's constant). Thus if HCN were in a state of thermal equilibrium with a reservoir of H_2 at a temperature T, then the deuteration of the former would be enhanced by the factor $\exp(450/T)$. Given the relatively low temperatures of interstellar clouds, typically ~ 5 to 50 K, it is easy to see that a large enhancement is possible. Under the nonequilibrium conditions of interstellar space, however, the large size of the exponential factor merely means that the reverse of Eq. 3 proceeds more slowly than other H_2D^+ destruction reactions such as (*13*)

$$H_2D^+ + CO \rightarrow HCO^+ + H_2 \quad (5)$$

or

$$H_2D^+ + e^- \rightarrow HD + H \quad (6)$$

where e^- is an electron. Thus the destruction rate, and hence the population of H_2D^+, is determined by quantities like the relative CO abundance and by the fractional ionization of the gas, which are relatively insensitive to the kinetic temperature. Nevertheless, the factors involved in the deuterium enhancement of interstellar molecules are difficult to evaluate separately. Thus much of the abundance data that can be derived from deuterated molecules is only qualitative in nature. Such qualitative data can prove extremely useful, as discussed in the next section.

Deuterium/Hydrogen

The production of deuterium is a sensitive parameter in the evolution of the early universe (*14*) in the "standard" big bang models (*15*). Thus the determination of the abundance of deuterium, relative to ordinary hydrogen, and the test of its cosmological origin have been two key tasks of observational astrophysics.

The local interstellar abundance of deuterium has been determined by means of the ultraviolet spectra of H, D, H_2, and HD obtained with the Copernicus satellite. A series of measurements of bright O and B stars has yielded a D/H ratio of ~ 10^{-5} in the region within a few hundred parsecs (*16*) of the sun [see Laurent *et al.* (*17*) for a recent summary and

Table 1. Relative abundances of deuterated molecules in the galaxy.

Source	Radius (kiloparsec)	DCN/HCN × 1000	DCN/HCN × 1000	DCO^+/HCO^+ × 1000	NH_2D/NH_3 × 1000
Sgr A	0.0		1.1 ± 0.4		
Sgr B	0.1	0.8 ± 0.5		0.4 ± 0.3	17
W33	5.7		2.3 ± 0.4		
W51	7.6	1.8 ± 0.7			
M17	8.0	1.8 ± 0.6		0.7 ± 0.3	
DR 21 (OH)	9.9	2.9 ± 1.2			
DR 21	9.9	1.2 ± 0.3		5.3 ± 0.5	
Orion A	10.9	2.9 ± 0.6	6.8 ± 0.6	1.7 ± 0.6	50
NGC 2264	11.1			10.2 ± 0.7	
W3 (OH)	12.2		4.3 ± 0.9		
NGC 7538	12.7		4.6 ± 1.0		
Reference		*(19)*	*(20)*	*(20)*	*(21)*

a list of the earlier references]. The test *(18)* of the cosmological origin of deuterium is the determination of the sign of the radial gradient of its galactic distribution relative to hydrogen. Cosmologically produced material should have a greater relative abundance in unprocessed gas, hence a positive radial gradient.

In addition to HD, the deuterated equivalents of several common hydrogen-containing molecules have been detected in interstellar space. Data on three of these, DCN, DCO^+, and NH_2D, can be used to yield information about the galactic distribution of deuterium. Of these, DCN has the most intense spectra. It was the first deuterated molecule to be detected in interstellar space and has been the subject of two sets of galactic measurements *(19, 20)*. DCO^+ and NH_2D have been the subjects of similar but somewhat less extensive studies *(20, 21)*. The data from these studies are summarized in Table 1.

The two sets of DCN/HCN data differ by a scale factor used in the data reduction *(20)*. Because the factor is common to all the data in a column, the gradient determination results are unaffected. Comparisons of DCN and DCO^+ were made with the relatively rare $H^{13}CN$ and $HC^{18}O^+$ species to avoid problems with line saturation, and then transformed into the tabulated data by use of factors reflecting the $C/^{13}C$ and $O/^{18}O$ abundance ratios derived from the data reviewed in the next section. NH_2D was compared directly with the common species with corrections for optical depth and excitation effects taken into account *(21)*. In all cases, there is a marked decrease in the relative abundance of the deuterated species with decreasing galactic radius, which provides support for the picture of a reduced deuterium abundance in the galactic center region.

The existence of any deuterium at all near the galactic center is something of a puzzle, since most models call for all the gas there to have been processed through stars unless an appreciable amount of fresh gas is introduced through infall. The best evidence of a deuterated molecule in this region is the weak 85.93-gigahertz line of NH_2D observed by Turner *et al.* *(21)* in Sagittarius (Sgr) B. This spectral feature has been confirmed by Linke and Frerking's *(22)* line survey; the possibility of a misidentification owing to coincidence with an unidentified line seems unlikely. A CH_3OD search in the same source resulted in a possible line at the appropriate frequency *(23)* which appears to be absent in the corresponding survey spectrum *(22)*. While both the DCN and DCO^+ data yielded positive residuals at the level of ~ 2 standard deviations in the galactic center, these should not be regarded as detections.

The above results can be summarized as follows. Deuterium is widely distributed in the galaxy. It exhibits a positive radial gradient in its galactic distribution, indicating a pregalactic rather than a stellar origin. The "local" interstellar D/H ratio, ~ 10^{-5}, can thus be used to infer the matter density in the early universe *(2)* leading, in the standard big bang models *(15)*, to an open (that is, ever-expanding) universe.

The CNO Isotopes

Carbon, nitrogen, and oxygen are the most abundant elements after hydrogen and helium. Of the seven stable CNO isotopes, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, and ^{18}O, two, ^{12}C and ^{16}O, may be regarded as primary elements, in that they are produced directly from He in the envelopes of massive stars. Three, ^{13}C, ^{14}N, and ^{17}O, are secondary elements produced from ^{12}C and ^{16}O by hydrogen burning in stellar envelopes, ^{14}N being particularly enhanced by the equilibrium CNO process. While ^{15}N is readily destroyed in this process, nonequilibrium or explosive *(24)* hydrogen burning (as in nova explosions) is regarded as the most likely source of the species. Finally, ^{18}O is produced by helium burning on ^{14}N. Since the same process converts ^{18}O into ^{22}Ne, it is not clear how much of the ^{18}O produced by this process can survive to reach the stellar surface [see *(25, 26)* for recent reviews of the subject].

Of these isotopes, those of carbon have traditionally received the most attention. Until recently, the best available data [see *(28, 29)* for earlier reviews] indicated a relative $C/^{13}C$ abundance ratio of about 50, or roughly half the terrestrial ratio, throughout the galactic plane, with a somewhat smaller ratio in the center of the galaxy. This conclusion was largely based on the results of two surveys of giant molecular clouds in our galaxy. The first of these surveys was a comparison of the common and $H_2{}^{13}CO$ isotopic species of formaldehyde; the second was a double comparison of the ^{13}CO and $C^{18}O$ species of carbon monoxide. More recent work has permitted a refined interpretation of these results and has yielded more accurate data leading to somewhat modified abundance values.

In the case of formaldehyde, Henkel *et al.* *(8)* have shown that the rotational level population distributions are different in the two isotopic species. This is due to the fact that the millimeter wavelength rotational transitions of this molecule are 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-centimeter lines 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 Table 2.)

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 need for a separate determination of the $O/^{18}O$ abundance. An investigation which avoids this requirement has been completed by Linke *(30)*. 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 (column 2 of Table 2) which agrees with the corrected formaldehyde results (column 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, 23 ± 3, a result which is supported by data for the other molecules in Table 2.

I turn now to the data involving the isotopes of oxygen and nitrogen; they are tabulated in Table 3. The double-ratio results such as $^{13}CO/C^{18}O$ have been converted into single ratios by multiplying by the $C/^{13}C$ ratios given above, 23 for the two galactic center sources and 67 for the others. This is indicated in Table 3 by the notation × R in the column headings.

An examination of the ^{18}O data (columns 7 to 10 of Table 3) clearly demonstrates that the interstellar abundance of this species differs markedly from its corresponding solar system value. For the two galactic center sources we find good agreement with a relative $O/^{18}O$ abundance of 250 ± 100, where the uncertainty represents ~ 90 percent confidence limits, indicating that ^{18}O is enhanced in this region by a factor of 2 relative to its solar system abundance.

In the galactic plane there is a much smaller, but still evident, effect in the opposite direction. This result depends heavily on the CO results of column 7. The CO data have been only roughly corrected for line formation effects, and it is expected that the final results will have less scatter and uncertainty. To the extent that saturation in the ^{13}CO line has been incompletely removed in the present results, the final average value for these data might even prove to be somewhat higher than the tabulated one, 675. While the other $O/^{18}O$ molecular data (columns 8 to 10 of Table 3) support this result on balance, the agreement is not wholly satisfactory, especially with the H_2CO data of column 8. It is unlikely that this discrepancy is due to chemical fractionation because of the agreement between the single-ratio CO and H_2CO results (columns 1 and 2 of Table 2).

The measurements on which the OH results are 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 of the two species. Since the common species has heavily saturated rota-

Table 2. Carbon isotope data. Tabulated uncertainties are generally the cited authors' estimates. Averages are unweighted and exclude the two galactic center sources. Additional references and details may be found in *(50)*.

Source	Radius (kilo-parsec)	(1) $H_2CO/H_2{}^{13}CO$	(2) $C^{18}O/{}^{13}C^{18}O$	(3) $HCO^+/H^{13}CO^+$	(4) $HC_3N/H^{13}CC_2N$	(5) $NH_2CHO/NH_2{}^{13}CHO$	(6) $OCS/O^{13}CS$
Sgr A	0.0	20 ± 10	26 ± 5	21 ± 2			
Sgr B	0.1	25 ± 10	23 ± 3	26 ± 4	22 ± 1	24 ± 3	14 ± 2
W43	5.5	42 ± 6					
W33	5.7	74 ± 11	42 ± 4				
W51	7.6	70 ± 11	32 ± 4				
W31	8(?)	37 ± 6					
M17	8.0		91 ± 20				
NGC 6334	8.3		91 ± 28				
W49	9.4	53 ± 8					
DR 21	9.9	73 ± 11	143 ± 43				
Orion A	10.9		> 74	83 ± 24	50 ± 5		
NGC 2024	11.0	72 ± 11	56 ± 8				
NGC 2264	11.2		83 ± 31				
W3	12.2	86 ± 13	111 ± 40				
NGC 7538	12.7		77 ± 21				
Average		68	66				
Solar system	10	89	89	89	89	89	89
Reference		*(8, 43, 44)*	*(30)*	*(45)*	*(46)*	*(47)*	*(48)*

Table 3. Oxygen and nitrogen isotope data. The data of columns 7, 8, 9, and 12 have been multiplied by $C/^{13}C$ abundance ratios as explained in the text.

Source	Radius (kilo-parsec)	(7) $^{13}CO/C^{18}O$ (× R)	(8) $H_2{}^{13}CO/H_2C^{18}O$ (× R)	(9) $H^{13}CO^+/HC^{18}O^+$ (× R)	(10) $OH/^{18}OH$	(11) $C^{18}O/C^{17}O$	(12) $H^{13}CN/HC^{15}N$ (× R)
Sgr A		267 ± 31	191 ± 28		275	3.4 ± 0.4	≳ 600
Sgr B	0.1	359 ± 118	149 ± 7	≲ 230	240	3.2 ± 0.2	≳ 500
W43	5.5	549 ± 59					
W33	5.7	644 ± 500	422 ± 54			3.6 ± 0.2	287
W51	7.6	540 ± 10	349 ± 54			2.8 ± 0.1	386
W31	8(?)	620 ± 300					
M17	8.0	684 ± 92		368 ± 40		3.5 ± 0.3	
NGC 6334	8.3	453 ± 15					
W49	9.4	859 ± 400					
DR 21	9.9	985 ± 261		536 ± 54		3.4 ± 0.3	319
Orion A	10.9	670 ± 54		1407 ± 268		3.6 ± 0.3	388
NGC 2024	11.0	1241 ± 200	> 442		900	3.5 ± 0.2	362
NGC 2264	11.1	558 ± 23		590 ± 67		3.5 ± 0.3	485
W3	12.2	905 ± 73				3.2 ± 0.3	294
NGC 7538	12.7	798 ± 123				3.5 ± 0.3	360
Average		675					373
Solar system	10	500	500	500	500	5.5	272
Reference		*(27)*	*(49)*	*(45, 51)*	*(52, 53)*	*(32)*	*(33)*

Table 4. Summary of CNO results: estimated isotopic abundances and corresponding ~ 90 percent confidence uncertainties derived from the data of Tables 2 and 3 normalized to their solar system values.

Region	Interstellar/solar system				
	$^{13}C/^{12}C$	$^{14}N/^{15}N$	$^{17}O/^{18}O$	$^{18}O/^{16}O$	$^{17}O/^{16}O$
Galactic plane	1.3 ± 0.2	1.4 ± 0.2	1.6 ± 0.1	0.7 ± 0.3	1.2 ± 0.4
Galactic center	3.9 ± 1.0	2.0 ± 0.6	1.6 ± 0.1	2.0 ± 0.6	3.2 ± 1.0

tional 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 2 (*31*).

In light of the difficulties cited above, it is probably best to regard a terrestrial $O/^{18}O$ abundance in the galactic plane as unlikely but not impossible. We thus adopt a value of 675 ± 175, where the uncertainty represents ~ 90 percent confidence limits.

The third isotope of oxygen, ^{17}O, has been extensively surveyed in a $C^{18}O/C^{17}O$ comparison (column 11 of Table 3). A remarkably low source-to-source variation is evident in these data; with a single exception, all the abundance ratios obtained lie within some 6 percent of the median value, 3.4 ± 0.2. While this low scatter is due in part to the high signal-to-noise quality of the spectra employed, the absence of line formation problems is probably the more important factor (*32*). The measurements were made in optically thin lines arising from a simple collision-dominated excitation mechanism. Since the two species are thought to originate from two distinct stellar formation processes, the uniformity of the results tabulated in column 11 provides support for the approach, adopted herein, of averaging over most source-to-source variations in nuclear isotope data. The one spatial variation in nuclear abundance clearly evident in the other data—that is, the different sets of values obtained in the galactic center and galactic plane for the other isotopes—is, remarkably, evidently absent in the $^{18}O/^{17}O$ ratio.

Finally, the HCN data (column 12) in the galactic plane show $^{14}N/^{15}N$ to be enhanced, relative to the terrestrial value, by a factor of ~ 1.4, with a considerably larger enhancement (a factor of ~ 2) in the galactic center region. The tabulated data are still preliminary in nature (*33*). Each of the quoted values has a root-mean-square error of about 10 percent, except for the galactic center sources, where the uncertainty is somewhat larger.

The CNO isotopes are thus seen to exhibit three distinct sets of abundance values for the solar system, galactic plane, and galactic center. These results are summarized in Table 4. A progressive increase, from solar system to galactic plane to galactic center, is evident for the relative abundances of the secondary hydrogen-burning products ^{13}C and ^{17}O with respect to the corresponding primary nuclei ^{12}C and ^{16}O. The $^{14}N/^{15}N$ ratio relates a primary hydrogen-burning product of the equilibrium CNO cycle to a product of the hot CNO cycle. This ratio exhibits the same progressive increase that the two secondary/primary ratios do, indicating that nonequilibrium hydrogen burning in the explosive CNO cycle had a greater relative role in the early history of the galaxy.

Conclusions about ^{18}O are the most tentative, owing to the somewhat ambiguous state of the observational data and the incompleteness of our understanding of its production. It is thought to be primarily produced by helium burning on ^{14}N, a process which should also produce ^{22}Ne. The relative amount of ^{18}O and ^{22}Ne produced in a given star is a highly variable function of stellar temperature and density (*34*). It may therefore be significant that while the interstellar medium has a relatively lower abundance of ^{18}O than did the presolar nebula, quite the opposite appears to be true in the case of ^{22}Ne. It was recently reported (*35*) that ^{22}Ne is three times as abundant, relative to the common species, in cosmic rays as in the solar system.

The enhancement of ^{18}O relative to ^{16}O toward the galactic center is to be expected, but why the enhancement closely follows that of ^{17}O, which is presumably produced by an entirely different process, is a puzzle.

Sulfur and Silicon Isotopes

We now turn to the explosive nucleosynthesis products, sulfur and silicon. An examination of the CS data (column 13 of Table 5) corrected for the $C/^{13}C$ results shows good agreement with a terrestrial abundance of ^{34}S in the galactic plane and a suggestion of a somewhat enhanced abundance in the galactic center. The small amount of data (column 14) for the ^{33}S isotope is consistent with a terrestrial abundance for this species as well.

Sulfur, silicon, and the other heavy elements are thought to be the result of processes having the following general outline (*1*). The core of a massive star burns its hydrogen to exhaustion in the CNO process, leaving its preexisting CNO elements (generally taken to be 2 percent of its initial mass) mainly in the form of ^{14}N. The rest of the material is in the form of helium, which burns to ^{12}C and ^{16}O, which in turn combine to form ^{24}Si, ^{32}S, and so on, in an explosive process. The important point for our purpose is that the ^{14}N (which in the meantime has been converted to ^{18}O) provides the neutrons for elements resulting from the explosive burning, since this process is too rapid to permit intervening β-

Table 5. Sulfur and silicon data. The data of column 13 have been multiplied by $C/^{13}C$ abundance ratios as explained in the text.

Source	Radius (kiloparsec)	(13) $^{13}CS/C^{34}S$ ($\times R$)	(14) $C^{34}S/C^{33}S$	(15) $^{28}SiO/^{29}SiO$	(16) $^{29}SiO/^{30}SiO$
Sgr A	0.0	16 ± 1		8.4 ± 0.5	1.3 ± 0.1
Sgr B	0.1	15 ± 1	5.3 ± 1.0	10.8 ± 6.0	1.6 ± 0.2
W43	5.5	31 ± 3			
W33	5.7	23 ± 2			
W51	7.6	21 ± 2		11.8 ± 1.5	
W31	8(?)				
M17	8.0	25 ± 1			
NGC 6334	8.3	35 ± 3			
W49	9.4	20 ± 2			
DR 21	9.9	13 ± 1			
Orion A	10.9	24 ± 1	4.8 ± 0.5	9.0 ± 0.5	1.4 ± 0.1
NGC 2024	11.0	16 ± 3			
NGC 2264	11.1	21 ± 2			
W3	12.2				
NGC 7538	12.7	29 ± 3			
Average		23			
Solar system	10	23	5.5	20	1.5
Reference		(*40*)	(*54*)	(*37*)	(*37*)

decays to convert protons into neutrons. One present view of nuclear evolution in the galaxy calls for the production of the 2 percent CNO elements at an early epoch in galactic evolution, with subsequent stellar processing acting mainly to rearrange the relative abundances of these elements rather than to produce them in appreciable amounts. An alternative model features a steady infall of unprocessed gas into the galactic disk, permitting element production with little change in relative abundances (*25, 26*).

Naïvely, one might suppose that any enhancement in the relative abundance of the CNO elements would serve to enhance the neutron-rich isotopes of sulfur and silicon, but no quantitative work on this notion has yet been attempted (*36*). If the results of such a calculation became available, the $^{34}S/^{32}S$ abundance ratio, among others, might be used in the future as a probe of the production of CNO elements in the galaxy. For the present, however, the apparent uniformity of these isotopes serves mainly as a reference against which to trace the variations of the other isotopes in double-ratio line measurements.

The case of silicon, on the other hand, presents us with a set of observations which simply do not fit within the present framework of our theoretical understanding. While the galactic abundances of ^{29}Si and ^{30}Si (column 16 of Table 5) exhibit a relative proportionality equal to the solar system value, the relative abundance of the common ^{28}Si species (column 15) is strikingly different. In both the galactic center and the galactic plane this species appears to be twice as abundant, relative to the rare species, as it is in the solar system.

Wolff (*37*) presents arguments against the simplest explanation for this apparent anomaly, namely saturation of the relatively strong ^{28}Si spectra. Because of the importance of the conclusions to be based on this contention, an independent set of observations has been undertaken. While these new results (*38*) provide support for the validity of the raw data of the earlier observations (*39*), they also provide evidence that these spectra must be corrected for saturation effects. These results point to approximately terrestrial values for the relative abundances of all three silicon isotopes, and thus serve to confirm our theoretical expectations.

Discussion

The data reviewed in the preceding sections reflect various aspects of the effects of nuclear processing in the galaxy. With the exception of the galactic center sources, no clearly consistent variation of 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. The most persuasive of these correlations was revealed in a systematic investigation of the subject by Frerking (*39*). A correlation was found between the source-to-source variations in her recent CS survey (*40*) and an earlier HCN survey (*41*). However, when a new HCN survey was made with better sensitivity (*33*), the correlation disappeared. It therefore seems premature to interpret any of these anomalies in terms of nuclear differences in the galactic disk. This absence of clear differences suggests that we can obtain representative abundance values by averaging among sources.

In attempting to justify our averaging over the galaxy, however, we should not be led to the conclusion that all clouds, particularly the presolar nebula, are uncontaminated samples of the average abundances in the interstellar medium. We know that some variations in nuclear abundances do exist. The cloud around the evolving star IRC + 10216 is a well-studied example (*42*). Although such circumstellar clouds are several orders of magnitude smaller than the giant molecular clouds employed in the studies reported here, one of them would certainly be big enough to make its presence felt in a body of gas many times larger than the presolar nebula. If, as some of our data suggest, the presolar nebula was not typical of general interstellar matter at the time of its formation, much of the above data will find application in studies of the early solar system in addition to galactic astrophysics. The apparent anomalies in ^{18}O seem particularly appropriate subjects for further investigation.

On a galactic scale, the results of stellar evolution are reflected in the distribution of the products of the associated nuclear processes. Comparisons between the galactic center region and the rest of the galactic plane delineate the effects of present star formation and provide a basis for an extrapolation back to the early nuclear history of our galaxy. Thus, the results of the observations described here help to define the outlines of our emerging understanding of the astrophysical evolution of matter.

References and Notes

1. D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis* (McGraw-Hill, New York, 1968).
2. A. A. Penzias, *Science* **205**, 549 (1979).
3. H. A. Bethe, *Phys. Rev.* **55**, 434 (1939).
4. Excitation temperature is a measure of relative populations of a pair of energy states, in that the ratio of their populations is given by $\exp(-\Delta E/kT_{ex})$, where ΔE is the energy difference between the two states and k is the Boltzmann constant. At thermal equilibrium T_{ex} is equal to the physical temperature of the ambient medium. Under the nonequilibrium conditions generally prevailing in interstellar space, however, the excitation temperature of each pair of states is determined separately by the rates at which molecules enter and leave these states (collisional excitation, spontaneous emission, and so on).
5. W. D. Langer, R. W. Wilson, P. S. Henry, M. Guelin, *Astrophys. J.* **225**, L139 (1978).
6. Following the usual convention, the most common isotope of each atomic species has its atomic weight omitted. Thus $^{13}C^{16}O$ and $^{1}H^{12}C^{14}N$ are written ^{13}CO and HCN, respectively. Hydrogen-2 is written as D.
7. P. G. Wannier, A. A. Penzias, R. A. Linke, R. W. Wilson, *Astrophys. J.* **204**, 26 (1976).
8. C. Henkel, C. M. Walmsley, T. L. Wilson, *Astron. Astrophys.*, in press.
9. W. D. Watson, *Rev. Mod. Phys.* **48**, 513 (1976).
10. ——, V. G. Anicich, W. T. Huntress, *Astrophys. J.* **205**, L165 (1976).
11. E. Herbst and W. Klemperer, *ibid.* **185**, 505 (1973).
12. W. D. Langer, P. F. Goldsmith, E. R. Carlson, R. W. Wilson, *ibid.* **235**, L39 (1980).
13. W. Klemperer, personal communication.
14. G. Gamow, *Nature (London)* **162**, 680 (1948).
15. R. W. Wagoner, *Astrophys. J.* **179**, 343 (1973).
16. One parsec equals ~ 3×10^{18} centimeters or about 3 light-years.
17. C. Laurent, A. Vidal-Madjar, D. G. York, *Astrophys. J.* **229**, 923 (1979).
18. J. Ostriker and B. M. Tinsley, *ibid.* **201**, L51 (1975).
19. A. A. Penzias, P. G. Wannier, R. W. Wilson, R. A. Linke, *ibid.* **211**, 108 (1977).
20. A. A. Penzias, *ibid.* **228**, 430 (1979).
21. B. E. Turner, B. Zuckerman, M. Morris, P. Palmer, *ibid.* **219**, L43 (1978).
22. R. A. Linke and M. A. Frerking, in preparation.
23. C. A. Gottlieb, J. A. Ball, E. W. Gottlieb, D. F. Dickinson, *Astrophys. J.* **227**, 422 (1979).
24. The elements involved in the equilibrium process have their abundances set through their nuclear properties, such as their proton capture cross sections. In the explosive case, on the other hand, the products depend on the composition of the initial material.
25. J. Audouze, Ed., *CNO Isotopes in Astrophysics* (IAU Symp. 67, Reidel, Boston, 1977).
26. D. Dearborn, B. M. Tinsley, D. N. Schramm, *Astrophys. J.* **223**, 557 (1978).
27. M. A. Frerking, in preparation.
28. M. Bertojo, M. F. Chui, C. H. Townes, *Science* **184**, 619 (1974).
29. P. G. Wannier, in (*25*), pp. 71–78.
30. R. A. Linke, in preparation.
31. J. Cernicharo and M. Guelin, in preparation.
32. A. A. Penzias, in preparation.
33. P. G. Wannier, R. A. Linke, A. A. Penzias, in preparation.
34. A. G. W. Cameron, private communication.
35. R. A. Mewaldt, J. D. Spalding, E. C. Stone, R. E. Vogt, *Astrophys. J. Lett.* **231**, L97 (1979).
36. W. D. Arnett, private communication.
37. R. S. Wolff, *Astrophys. J.*, in press.
38. A. A. Penzias, work in progress.
39. M. A. Frerking, unpublished results.
40. ——, R. W. Wilson, R. A. Linke, P. G. Wannier, *Astrophys. J.*, in press.
41. R. A. Linke *et al.*, *ibid.* **214**, 50 (1977).
42. P. G. Wannier and R. A. Linke, *ibid.* **225**, 130 (1978).
43. F. F. Gardner and J. B. Whiteoak, *Mon. Not. R. Astron. Soc.* **188**, 331 (1979).
44. T. L. Wilson, C. M. Walmsley, C. Henkel, T. Pauls, H. Mattes, *Astron. Astrophys.*, in press.
45. A. A. Stark, in preparation.
46. P. G. Wannier and R. A. Linke, *Astrophys. J.* **226**, 817 (1978).
47. B. Lazareff, R. Lucas, P. Encrenaz, *Astron. Astrophys.* **70**, L77 (1978).
48. P. F. Goldsmith and R. A. Linke, in preparation.
49. M. L. Kutner, D. E. Machnik, K. D. Tucker, W. Massano, in preparation.
50. A. A. Penzias, in *Interstellar Molecules*, B. H. Andrew, Ed. (IAU Symp. 87, Reidel, Boston, 1980).
51. M. Guelin and P. Thaddeus, *Astrophys. J.* **227**, L139 (1979).
52. J. B. Whiteoak and F. F. Gardner, *Proc. Astron. Soc. Aust.* **2**, 360 (1975).
53. J. B. Whiteoak and F. F. Gardner, *Mon. Not. R. Astron. Soc.* **183**, 67 (1978).
54. R. W. Wilson, A. A. Penzias, P. G. Wannier, R. A. Linke, *Astrophys. J.* **204**, L135 (1976).

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