INTERPRETATION OF ISOTOPIC ABUNDANCES IN INTERSTELLAR CLOUDS

Michel Guélin and James Lequeux
Département de Radioastronomie
Observatoire de Paris

1. INTRODUCTION

The abundances of elements in the interstellar medium (ISM) result from a complex sequence of nucleosynthetic processes which started some ten billion years ago in the Big Bang and are still going on. Their study and in particular their comparison with the stellar and the solar system abundances may give clues to: i) the properties of the early Universe, ii) the evolution of galaxies (rate of star formation, Initial Mass Function of stars, stellar nucleosynthesis and rate of ejection of matter by stars), and iii) the flux of low-energy cosmic rays.(See e.g. Reeves 1974, Audouze and Tinsley 1976).

Abundance determinations of a number of atomic species in the ISM can be made directly by studying their optical and radio lines. These determinations however require a precise knowledge of the physical conditions and are often insecure. In the cold ISM, moreover, absolute elemental abundances are difficult to derive from such studies, since a large fraction of the atoms is likely to be depleted into grains and molecules.

The difficulties with the derivation of elemental abundances are partly avoided by using ratios of closely related isotopic species which are usually much less affected by depletion and excitation effects. In return, since the atomic lines of isotopic species cannot in general be resolved in astronomical objects (except, mainly, for hydrogen and helium), the study of isotopic abundances in the ISM has to be carried out essentially through observations of molecular lines, mainly in the millimeter to decimeter range. While optical or UV observations of atomic and molecular isotopic interstellar lines are presently restricted to the lines of sight of bright nearby stars, radio observations can reach all the dense ISM and distant regions in the Galaxy, opening the possibility of addressing the problem of chemical evolution on a truly galactic scale.

The derivation of isotopic elemental abundances from molecular observations, and their interpretation in terms of nucleosynthesis and galactic evolution, have been discussed at length in the literature, and in

B. H. Andrew (ed.), Interstellar Molecules, 427–438.

https://doi.org/10.1017/S0074180900073010 Published online by Cambridge University Press

particular at the special session of the IAU in Grenoble three years ago (Audouze 1977). Since that time, the major change in the modelling of chemical evolution has been the recognition that the abundance of an element depends more upon the lifetime of the stars responsible for its synthesis than upon its primary or secondary nature (see e.g. Tinsley 1979, Vigroux 1979). It has also been fully realized that mass exchanges between the different parts of the Galaxy cannot be neglected and introduce extra free parameters in the computations.

On the observational side (see the reviews by Penzias and Watson in this symposium), although improved technical means allow the line intensity ratios of a growing number of molecular species to be measured very accurately, it has become clear that optical depth effects, line confusion and isotopic fractionation often prevent the derivation of the actual isotopic abundance ratios. In the past three years, not only have observations confirmed that deuterium is currently enhanced by several orders of magnitude in the dense IS clouds, but they have provided evidence that ^{13}C also may be strongly enhanced in parts of the cool gas -- a result which forces a reconsideration of the meaning of isotopic ratios involving this species.

2. NUCLEOSYNTHESIS OF OBSERVED INTERSTELLAR ISOTOPES

In this section, we will briefly review the most important processes of nucleosynthesis of the isotopes observed in the interstellar medium (isotopes of H, He, C, N, O, Si and S), and tentatively ascribe the most probable astrophysical sites for their production.

Synthesis of elements is still going on in stars (through thermonuclear reactions) and in the interstellar medium (through spallation). Evidence that element abundance changes are still taking place comes from differences in chemical composition of the atmospheres of stars of various places of origin, abundance gradients in galaxies, and abundance anomalies in probable sites of nucleosynthesis: red giants, novae and supernovae (cf the different chemical composition of the two kinds of filaments in Cas A). It should be noted at this point that there is no reason why the ISM abundances, which result from nucleosynthesis up to the present time, should be the same as the solar system abundances which rather reflect local ISM abundances 4.6 10^9 years ago. Models of the chemical evolution of the Galaxy indeed predict local variations in isotopic ratios up to upper limits of about a factor 2 since that epoch (e.g. Vigroux et al. 1976).

2.1. Equilibrium nucleosynthesis

This type of nucleosynthesis corresponds to the quiet phases of stellar evolution. The most important stages are helium-burning, which produces ^{12}C and ^{16}O in the cores of red giants, and the CNO cycles which transform these species into other C, N and O isotopes.

https://doi.org/10.1017/S0074180900073010 Published online by Cambridge University Press

The CNO cycles consist of a network of proton-capture and beta-decay reactions. While the rates for β-decay are nearly constant, those for p-capture depend drastically on temperature and density. (For example, the rate of the $^{12}C(p,\gamma)$ ^{13}N reaction varies as T^{15} near 2.5 10^7K). At the temperatures and densities which prevail in the H-burning zone of red giants ($T \ll 10^8$K), the rates for p-capture (k_p) are several orders of magnitude smaller than those for β-decay and control the production of CNO isotopes. For typical temperature and density of 2.5 10^7K and 10^{-2} g cm^{-3}, one has at equilibrium: $^{15}N/^{14}N = k_p(^{14}N)/k_p(^{15}N) = 4\ 10^{-5}$, $^{12}C/^{14}N = 10^{-2}$ and $^{13}C/^{12}C = 1/3$. Since for these conditions equilibrium is reached in some 10^6 years, a time short with respect to stellar lifetimes, most of the pre-existing CNO isotopes are transformed into ^{14}N, and in particular the pre-existing ^{15}N is destroyed rather than new ^{15}N produced; as is well known, ^{15}N has to be produced in drastically different conditions (explosive nucleosynthesis). Substantial amounts of ^{13}C and ^{17}O are synthesized in the "cold" CNO cycles but their observed abundances are difficult to achieve simultaneously at equilibrium. For this, one has to invoke incomplete cycles resulting from a partial mixing of hydrogen from the envelope with the material from the helium shell (Dearborn et al. 1976). During this mixing incomplete p-p reactions may also produce ^3He in zones of low temperature - i.e. $T<10^7$K (Rood et al. 1976).

2.2. Explosive nucleosynthesis

In explosive nucleosynthesis, matter is compressed and raised to very high temperatures, then cooled and diluted rapidly. It is necessary that the cooling be fast enough to prevent proton- or α-capture of the fragile or unstable nuclei formed at high temperaturess.

p-p explosive nucleosynthesis occuring in the Big Bang, supernova (SN) shells, and possibly supermassive objects (SMOs) may produce not only the stable ^4He but also D, ^3He and ^7Li. Deuterium is so fragile that an extremely fast cooling and dilution is required to save any appreciable amount of it. These conditions seem hard to realize in SN blast waves and SMOs, and the Big-Bang is believed to be the main producer of D as well as of a large part of ^3He and ^7Li (Reeves 1974).

When the temperature in the H-burning zone in a star exceeds 2 10^8K (Nova, SN, SMO) the p-capture reaction rates become comparable to or even larger than the β-decay rates (k_e) in the CNO cycles. Then, large quantities of ^{17}F, ^{15}O, ^{14}O and ^{13}N are quickly built up. If the cooling which follows the explosion is fast enough, these unstable species will decay into ^{17}O, ^{15}N, ^{14}N and ^{13}C respectively without further processing. In this way, one can achieve a $^{15}N/^{14}N$ abundance ratio as high as $k_e(^{14}O)/k_e(^{15}O)$ = 1.7 (Lazareff et al. 1979).

Explosive He-burning episodes, like those occuring during the SN blast and in He-rich novae, produce ^{18}O from ^{14}N by the reaction $^{14}N(\alpha,\gamma)^{18}F$ followed by β-decay of ^{18}F. The same reactions also yield some ^{18}O in non-explosive conditions, but this ^{18}O is probably destroyed by subsequent α-capture reactions before getting a chance to reach the surface

(Truran, in Audouze 1977, p.145); negligible amounts of it will thus be released in space, unless the star evolves into a supernova (Dearborn et al. 1978).

The isotopes of Si and S are products of explosive nucleosynthesis in stars. According to Arnett (1973, 1978) ^{29}Si, ^{30}Si and ^{33}S are probably produced in explosive carbon-burning, while their neighbours ^{28}Si, ^{32}S and ^{34}S result from neon and oxygen-burning. Observation of variations in the ratios of silicon and sulfur isotopes would tell us much about the importance of these processes during the successive stages of galactic evolution.

2.3. Possible sites of nucleosynthesis of interstellar isotopes

Deuterium is generally believed to be produced in the Big Bang. It is completely destroyed in the interior of practically all stars, so that D/H must decrease with increasing degree of evolution (i.e. for example be smaller in the galactic center than in the solar neighbourhood), at least if most D is of cosmological origin.

^{3}He can be synthesized in the Big Bang, in SN and SMOs, and in the H-burning shell of red giants. In this latter case, convective mixing may carry it into the stellar envelope from which it will eventually be expelled into the ISM via stellar winds or at the planetary nebula (PN) or SN stage. Unlike D, ^{3}He is not much destroyed by further processing in stars.

^{12}C and ^{16}O are produced by He-burning in the deep interior of stars of mass $>2\ M_{\odot}$. They are certainly expelled into the ISM in large quantities during the final explosion of the most massive of these stars. At the present time, however, it is not clear whether they can also be released by the longer-lived lower-mass stars ($M < 6\ M_{\odot}$). It is believed that, at least in carbon stars, deep mixing significantly enriches the stellar envelope with ^{12}C; since these stars are known to experience important mass losses, they could be an effective source of interstellar ^{12}C. There is some evidence that carbon stars end their life as PN, and abundance measurements in these objects should in principle allow us to assess the amount of ^{12}C released by this process into the ISM. So far, unfortunately, the results are discrepant: while visible permitted lines of multiply-ionized carbon tend to indicate a large overabundance of this element in several PN, UV observations tend to show in the very same objects a nearly solar abundance (e.g. Natta et al. 1979). It should be noted that the abundances observed in the hot gas may not reflect those of the expelled matter since some carbon may be in the form of dust grains or hidden inside dense molecular envelopes, such as the ones which are known to surround some of the PN. In summary, it cannot be ruled out that a major fraction of ^{12}C is produced by low mass long-lived stars, a possibility which would strongly affect the time behaviour of the $^{13}C/^{12}C$ ratio in the Galaxy (Tinsley 1979).

Release of ^{16}O by low mass stars seems more difficult than for ^{12}C. In fact ^{16}O abundance measurements in PN, which are more reliable than those of ^{12}C, never show any enrichment in this element. Thus, it is thought that the interstellar ^{16}O comes mainly from high mass stars.

^{13}C is mainly a secondary product of the incomplete CNO cycles in red giants, where the enrichment in ^{13}C can be seen directly because convection has mixed it into the envelope (Dearborn et al. 1976). It is difficult to know the relative contribution of stars of different masses, the present consensus being that most ^{13}C comes from low mass stars ($M < 4\ M_{\odot}$). Consequently, it is not easy to predict the exact rate of increase of the $^{13}C/^{12}C$ ratio with galactic evolution, although there should be an increase. However, an increase by a factor 2 of this ratio since the birth of the sun, such as the one suggested by the early ^{13}C observations, seems difficult to achieve even with favorable assumptions (Vigroux et al. 1976, Vigroux 1979). A gradient with galactocentric distance is also predicted, but quantitative estimates are uncertain.

^{14}N was believed to be only a secondary product of the CNO cycles in red giants (mainly of low masses), and its overabundance in many PN is well observed (Peimbert 1978). There is increasing evidence however, from the study of the N/O gradients in external galaxies, that this secondary process is not the only one: the N/O ratio does not decrease with O/H as expected, indicating production of ^{14}N by massive stars (Alloin et al. 1979, Talent and Dufour 1979). "Primary" ^{14}N could be synthesized in these stars through the dredge-up mechanism, which incorporates fresh ^{12}C from the core into the H-burning zone where it is converted into ^{14}N .

^{15}N is produced almost entirely by explosive CNO nucleosynthesis in novae and (less likely) in SN. It should be possible to decide between these two sources by studying its abundance gradient with galactocentric distance, since novae and supernovae do not appear to have the same distribution in time and space (Audouze et al., in Audouze 1977, p.155).

^{17}O, a secondary product, can be synthesized both by the cold CNO cycles in massive red giants and the explosive CNO cycles in novae and perhaps SN . Models (Dearborn and Schramm 1974) as well as the few existing observations of ^{17}O enrichment in red giants (Rank et al. 1974, Maillard 1974) seem to indicate only a modest total production in these objects. Thus the usual consensus is that novae are the main producers of ^{17}O . One expects the $^{17}O/^{16}O$ ratio to increase with galactic evolution.

^{18}O appears to be mainly released by SN (no enrichment in this isotope has been observed in red giants), but it could also be produced in large quantities by He-rich novae. Its evolutionary behaviour is not easy to predict, although the $^{18}O/^{16}O$ ratio is expected to increase with galactic evolution since ^{18}O is a secondary (or even tertiary) product. The behaviour of the $^{17}O/^{18}O$ ratio obviously depends on the nature of the sites of synthesis: if ^{17}O is produced mainly in novae and ^{18}O in supernovae, this ratio will increase with the degree of evolution.

3. ISOTOPE FRACTIONATION IN MOLECULES

Isotopic molecular ratios may differ from the true ISM ratios due to chemical fractionation. This effect has been thoroughly investigated only for hydrogen and carbon (Watson, this symposium).

Substitution of hydrogen by deuterium in molecules results in relatively large differences in abundance, weight and zero-vibrational energy which in turn may change the rates of formation and destruction. This is particularly the case for the light ions H_3^+ and CH_3^+ which, in the dense clouds, are believed to be at the origin of most hydrides, including HCN, HCO^+, HNC, N_2H^+, NH_3 and H_2CO, all of which are observed to exhibit large overabundances of the deuterated species. As an example, the deuterium enrichment of H_3^+ is thought to result from the competition between the intrinsically slow formation reaction:

$$HD + H_3^+ \rightleftarrows H_2 + H_2D^+ + \Delta E \quad , \tag{1}$$

and faster H_2D^+ destruction reactions such as dissociative electron recombination and Langevin-rate reactions with other molecules. Thus, the observation of large deuterium enhancements in HCN, HCO^+, etc. sets stringent upper limits on the abundances of the free electrons and of the trace molecules reacting with H_2D^+ and CH_2D^+ (i.e. N_2, C_2H_2, etc.).

In diffuse clouds, the abundance of HD results from the balance between its formation through $H_2 + D^+ \rightarrow HD + H^+$, and its destruction by selective photodissociation. The measure of the HD/H_2 ratio can be used to set limits to the ionization rate of hydrogen (Watson 1973).

Watson et al. (1976) have suggested that CO may be enriched in ^{13}C through the reaction:

$$^{13}C^+ + {}^{12}CO \rightleftarrows {}^{12}C^+ + {}^{13}CO + \Delta E \quad . \tag{2}$$

The rate constants of reactions (2) and (1) are about equal (2 and 3 10^{-10} cm^3s^{-1} respectively). However, the excess energy ΔE is much smaller for (2) than for (1), and C^+,the reservoir of ^{13}C,is seldom more abundant than CO in molecular clouds: both factors limit the efficiency of CO fractionation. A detailed analysis (Langer 1977) shows that only the outer regions of the clouds, where the visual extinction A_V is < 4, have enough C^+ to allow a CO enhancement in ^{13}C by more than a factor 3. In the inner regions, there is little C^+ and fractionation becomes ineffective in changing the ^{13}CO abundance; it can however efficiently deplete C^+ in ^{13}C so that molecules formed from this ion could also be depleted in ^{13}C . Observational evidence for such CO fractionation has just been reported by Goldsmith et al. at this symposium: the $^{13}CO/^{12}CO$ ratio increases by factors 6-10 from the center to the edge of three dark clouds, while the CO enrichment in ^{13}C appears to be smaller than a factor 1.5 at the center.

While the lack of an abundant reservoir of ^{13}C limits the fractionation

https://doi.org/10.1017/S0074180900073010 Published online by Cambridge University Press

of CO, no such restriction exists for much less abundant molecules. An interesting example is that of HCO^+ for which CO itself acts as a ^{13}C reservoir. One has (Langer et al. 1978) :

$$^{13}CO + H^{12}CO^+ \rightleftarrows H^{13}CO^+ + {}^{12}CO + \Delta E \quad . \qquad (3)$$

Adams and Smith (private communication) have measured a rate constant $\alpha = 3\ 10^{-10}\ cm^3 s^{-1}$ at 100 K for this reaction, similar to those of reactions (1) and (2). We estimate $\Delta E/k = 17$ K from the ab-initio calculations on HCO^+ of Henning et al. (1977) with an uncertainty of $\pm$ 1 K (Kraemer, private communication). α and ΔE are large enough for a substantial enrichment of HCO^+ in ^{13}C in the center of very cold clouds. However no direct evidence exists for such an enhancement : in TMC1, the only cloud for which a good $H^{13}CO^+/HC^{18}O^+$ ratio has been determined (Langer et al. 1978), any enhancement larger than a factor 1.5 seems to be ruled out.

Oxygen and nitrogen isotopic fractionations are not well known. The reaction which would seem the most promising in the case of oxygen is analogous to reaction (3) and involves $C^{18}O$ (or $C^{17}O$) and HCO^+. Its rate for $C^{18}O$ is similar to that of (3) (Adams and Smith, private communication) but its $\Delta E/k$ is only 7 $\pm$ 1K, again using the HCO^+ vibrational constants of Henning et al..It is therefore unlikely that ^{18}O is significantly fractionated in this way ; ^{17}O fractionation is expected to be even smaller. As for nitrogen, N_2 and perhaps atomic N appear interesting reservoirs of ^{15}N. The proton-exchange reaction analogous to (3):

$$^{14}N^{15}N + {}^{14}N_2H^+ \rightleftarrows {}^{14}N^{15}NH^+ + {}^{14}N_2 + \Delta E \qquad (4)$$

probably has a similar rate constant. Again, from the calculations of Henning et al., we find a $\Delta E/k$ probably too low for appreciable fractionation to occur via this reaction ($\Delta E/k = 10 \pm 1$ K). In view of the importance of ^{15}N as a test of galactic evolution, laboratory work on nitrogen-bearing ions would be very valuable.

Finally, in the case of sulfur, the reaction of $^{34}S^+$ on $C^{32}S$ might have a large cross section (Watson 1977, ibid). S^+ is likely to be abundant in the outer parts of IS clouds since sulfur is readily ionized by interstellar UV radiation, but whether enough CS remains in these unshielded regions to be detected is questionable.

4. DISCUSSION

The above considerations, coupled to the simplest possible closed-box model of galactic evolution, lead to the predictions on IS isotope abundances listed in Table 1. It should be understood that in this simple model, the "solar system" and "disk ISM" conditions represent only two stages on the same evolutionary track which are separated by 5 billion years, and do not include local inhomogeneities. The "galactic center"

https://doi.org/10.1017/S0074180900073010 Published online by Cambridge University Press

conditions,on the other hand, refer to a much more evolved stage where low mass stars dominate strongly the gas production.

TABLE 1.: Predicted versus observed ISM relative isotopic abundances.

		D/H	$^{13}C/^{12}C$	$^{15}N/^{14}N$	$^{18}O/^{16}O$	$^{17}O/^{18}O$
solar system		1	1	1	1	1
disk ISM	predicted	$\gtrsim 0.5$	1 to 1.5	<1?	>1	$\gtrsim 1$
	observed	$\simeq 0.5$	1.3	0.7	0.8	1.6
galactic center	predicted	0	1 to 3	<1	>1	>1
	observed	some?	3?	$\lesssim 0.3$	1?	1.6

Let us now discuss the observational results just presented by Penzias (or derived from Copernicus data) in the light of these predictions.

The amount of deuterium produced in the Big Bang is extremely sensitive to the density of matter in the early stages of the Universe, so the measure of the d=D/H abundance ratio provides an unique way of determining this important parameter. For this purpose, the value of d at the time of the Big Bang should be estimated from the present one by correcting for deuterium processing in stars. It is fortunate, since D is strongly fractionated in molecules, that the atomic D/H ratio can be directly observed in the solar neighbourhood. Copernicus observations in the line of sight to 10 nearby stars indicate an average d of 1.4 10^{-5}, with apparently real variations by a factor 2 (Laurent et al. 1979). When the assumption is made that most D is of cosmological origin and the astration correction is applied (a decrease of d since the Big Bang by a factor of two), a density much smaller than the "critical" one needed to close the Universe is found (see e.g. Reeves 1974). It has been argued (Ostriker and Tinsley 1975) that SN and possibly SMOs may produce deuterium, in which case this result could be erroneous; were this true, however, the astration correction should be positive and one should observe an increase of d towards the inner parts of the Galaxy. Unfortunately, at these large distances from the Sun, the only estimates of d result so far from molecular observations (Penzias 1979) and are too uncertain for this prediction to be checked.

Astration is much more severe in the galactic center itself, so that any primordial deuterium has essentially disappeared, unless there is an infall of external gas. Audouze et al. (1976) have shown that the mere detection of D implies either such an infall, or a local production by SN and SMOs, or spallation by a large flux of low-energy cosmic rays (an unlikely possibility). Marginal detections of DCN, DCO^+ and NH_2D in Sgr A and/or Sgr B have been reported (Penzias 1979, Turner et al. 1978). Confirmation of these detections, or detection of any other deuterated molecule in the galactic center would be important.

The probable detection of the 3.5 cm hyperfine line of $^3He^+$ in W51 (Rood et al. 1979) seems to imply a $^3He/H$ abundance ratio in this giant HII region roughly comparable to the protosolar ratio. If confirmed, this result would probably exclude substantial ^3He production in red giants.

As derived from giant molecular clouds, the $^{13}C/^{12}C$ abundance ratio (about 1/70 in the disk sources, according to Penzias's review) shows only a moderate enhancement in ^{13}C with respect to the solar system ratio of 1/89. Such a moderate difference, in contrast with the larger one ($\sim$ 1/40) proposed by Wannier (in Audouze 1977, p.71) is easily explainable by chemical evolution models, but could also at least partly result from fractionation effects. We conclude that: first, the relatively small amplitude of this difference, as it is observed, second, the difficulties due to fractionation in deriving the true isotopic ratio, and third, the present ambiguities in the interpretation of this ratio in terms of stellar nucleosynthesis, make the $^{13}C/^{12}C$ ratio much less interesting than has been thought. It must be recalled that ^{13}C observations of molecules less abundant than CO should be considered with caution since even a moderate ^{13}C enhancement in CO can result in large ^{13}C depletions in molecules which form from C^+ (e.g. Langer 1977). Rather than serving as a dubious test for evolution models, these observations in fact may turn out as valuable tools for studying molecule formation.

As discussed in section 2, ^{15}N is probably the best tracer of explosive nucleosynthetic events either in novae, or in SN . The difference in the $HC^{15}N/H^{13}CN$ ratio observed between the galactic center and the disk IS clouds seems too large to be accounted for by fractionation alone. Taken at its face value, it would rather imply ^{15}N production in high mass stars, i.e. SN or high mass novae (Audouze et al., in Audouze 1977, p.155). Observation of this ratio in other molecules than HCN would be of great interest. Already, the observation of $^{15}NH_3$ in Orion (Wilson and Pauls 1979) might imply a $^{15}N/^{14}N$ ratio smaller than the solar system one.

Although oxygen-bearing molecules such as CO, H_2CO, HCO^+ and OH are widely observed in IS clouds, and although no significant fractionation of oxygen isotopes is expected, a precise determination of the $\underline{a}$= $^{18}O/^{16}O$ and $\underline{b}$= $^{17}O/^{16}O$ abundance ratios remains an arduous problem. By themselves, the very small values of $\underline{a}$ and $\underline{b}$ (1/490 and 1/2670) make them difficult to measure directly. $\underline{a}$ and b alternatively can be derived from double isotopic ratios, such as the $^{12}C^{18}O/^{13}C^{16}O$ ratio, but these usually involve the $^{13}C/^{12}C$ ratio which is not too well known; in fact, even the double isotopic ratios are hard to measure since the best suited lines for their studies (those of ^{13}CO and $H^{13}CO^+$ for example) are often optically thick. Thus it appears premature to worry about the mild discrepancy between the predicted and observed values of $\underline{a}$ in Table 1 .

More promising seems to be the $^{17}O/^{18}O$ ratio. The consistency observed from source to source for this ratio, which seems to indicate that line opacity does not pose an insurmountable problem for $C^{18}O$, and the very fact that one would expect oxygen fractionation to decrease rather than

https://doi.org/10.1017/S0074180900073010 Published online by Cambridge University Press

to increase this ratio, seem to give confidence that ^{17}O is slightly overabundant with respect to ^{18}O in the disk clouds. This would imply a marked difference of origin for these two isotopes and in particular would agree with a production of ^{17}O predominantly in novae and of ^{18}O in supernovae.

The $^{29}Si/^{30}Si$ and $^{33}S/^{34}S$ ratios are relatively easy to determine since the abundance of each isotope in the pair is not much different. Observations are consistent with solar system ratios, a not unexpected result since only small variations are forseen. As said before, fractionation is possible and may hide chemical evolution effects.

5. CONCLUSION

To conclude this session, let us emphasize the few but important astrophysical problems which can be efficiently handled by the present (or near future) observational and theoretical means.

The first of these is the geometry of the Universe as derived from the cosmological D/H ratio: some theoretical considerations, and the moderate yet disturbing variations in the D/H ratio in local diffuse clouds, still raise the possibility of some deuterium production after the Big Bang. Direct measurements of this ratio in diffuse clouds at different galactocentric distances and in the Magellanic Clouds are of fundamental importance in this respect. Of lesser interest, since they can hardly give clear-cut answers, are molecular D/H observations; these however are the only ones that can reach the innermost regions of the Galaxy (inside the 4 kpc ring). One undisputable detection of a deuterated molecule in the galactic center would be important.

The second problem which has been and should be further addressed by isotopic measurements is the formation of molecules, in particular of species which could be formed as well on grains as by gas phase reactions. The detection of HDCO reported in this symposium illustrates the kind of work to do. It would be of high interest to observe the deuterated forms of C_2H, HC_3N and other simple carbon-chain molecules. ^{13}C measurements can help also in studying the abundance of C^+ and may serve to point out those molecules formed through this ion.

An important insight into physical conditions inside molecular clouds, in particular the degree of ionization, can be obtained through D/H measurements in molecules. Analysis of DCO^+ and HCO^+ observations in dense clouds, for example, indicate a surprisingly low fractional electron abundance (see e.g. Guélin et al. 1977, Langer et al. 1978). Much can be said from these studies about the flux of low-energy cosmic rays.

Finally, $^{15}N/^{14}N$, $^{17}O/^{16}O$ and $^{18}O/^{16}O$ observations can still be interpreted in terms of nucleosynthesis and chemical evolution, provided that they are coupled with studies of the abundance gradients of ^{14}N and ^{16}O obtained from observations of HII regions, for example. Good galactic gradients as well as a study of possible cloud-to-cloud variations are quite important for advanced studies of galactic evolution.

We thank J. Audouze for discussions and a critical reading of the manuscript.

REFERENCES

Alloin,D., Collin-Souffrin, S., Joly, M., Vigroux,L. : 1979,Astron. Astrophys. 78, p.200.
Arnett, W.D.: 1973, Ann. Rev. Astron. Astrophys. 11, p.73.
Arnett, W.D.: 1978, Ap. J. 219, p. 1008.
Audouze, J., Tinsley, B.M.:1976, Ann. Rev. Astron.Astrophys. 14, p.43.
Audouze, J., Lequeux, J., Reeves,H., Vigroux, L.: 1976, Ap. J. (Letters) 208, p.L51.
Audouze, J.: 1977 (editor) CNO Isotopes in Astrophysics, D. Reidel, Dordrecht.
Dearborn, D.S., Schramm, D.N.: 1974, Ap. J. (Letters) 194, p.L67.
Dearborn, D.S., Eggleton, P.P., Schramm, D.N.: 1976, Ap. J. 203, p.455.
Dearborn, D.S., Tinsley, B.M., Schramm, D.N.: 1978, Ap. J. 223, p.557.
Guélin, M., Langer, W.D., Snell, R.L., Wootten, H.A.: 1977, Ap. J. (Letters) 217, p.L165.
Henning,P., Kraemer,W.P., Diercksen,G.H.F.:1977, M.P.I. internal report.
Langer, W.D.: 1977, Ap. J. (Letters) 212, p.L39.
Langer, W.D., Wilson, R.W., Henry, P.S., Guélin, M.: 1978, Ap. J. (Letters) 225, p.L139.
Laurent, C., Vidal-Madjar, A., York, D.G.: 1979, Ap. J. 229, p.923.
Lazareff,B., Audouze,J., Starrfield,S., Truran, J.W.:1979, Ap.J. 228,p875.
Maillard, J.P.: 1974, in Highlights in Astronomy 3, p.269, ed. G. Contopoulos, D. Reidel, Dordrecht.
Natta, A., Pottasch, S.R., Preite-Martinez, A.: 1979, Astron. Astrophys. in press.
Ostriker, J.P., Tinsley, B.M.: 1975, Ap.J. (Letters) 201, p.L51.
Peimbert, M.: 1978, in Planetary Nebulae, IAU Symp. 76, p.215, ed. Y. Terzian, D. Reidel, Dordrecht.
Penzias, A.A.: 1979, Ap. J. 228, p.430.
Rank, D.M., Geballe, T.R., Wollman,E.R.: 1974, Ap.J.(Letters) 187,p.L111.
Reeves, H.: 1974, Ann. Rev. Astron. Astrophys. 12, p.437.
Rood, R.T., Steigman,G., Tinsley, B.M.: 1976, Ap.J.(Letters) 207,p.L57.
Rood, R.T., Wilson,T.L., Steigman,G.: 1979, Ap.J.(Letters) 227, p.L97.
Talent, D.L., Dufour, R.J.: 1979, preprint.
Tinsley, B.M.: 1979, Ap. J. 229, p.1046.
Turner, B.E., Zuckerman, B., Morris, M., Palmer, P.: Ap. J. (Letters) 219, p.L43.
Vigroux, L., Audouze,J;, Lequeux,J.: 1976, Astron. Astrophys. 52, p.1.
Vigroux, L.: 1979, Thèse de Doctorat, Université de Paris XI, Orsay.
Wilson, T.L., Pauls, T.: 1979, Astron. Astrophys. 73, p.L10.
Watson, W.D.: 1973, Ap. J. (Letters) 182, p.L73.
Watson, W.D., Anicich, V.G., Huntress, W.T.: 1976, Ap. J. (Letters) 205, p.L165.

DISCUSSION FOLLOWING GUÉLIN

Mouschovias: Have you assumed that explosive nucleosynthesis does not change the isotope ratios established by the CNO cycle prior to the explosion?

Guélin: No. What we refer to as "explosive nucleosynthesis" explicitly takes into account a part of these changes.

Townes: It is not clear how you consider variability from source to source. Are you allowing each large cloud to be quite old, which I believe is the case, so that it develops individually, or are you allowing only a variation with radial distance from the galactic center? What is the significance of your prediction of "probably small" variations of $^{12}C/^{13}C$ from cloud to cloud when the experimental data seems to indicate the opposite?

Guélin: In view of the modest differences observed between the abundance in the solar system and the average abundance in the galactic disk, marked abundance variations from one cloud to another dependent on the age of the clouds should occur only in cases where clouds are at least 5 billion years old. So far, except for Sgr A and B2, no source seems to exhibit in all molecules a consistently high or low $^{12}C/^{13}C$ abundance ratio with respect to the average disk value of 68, at least in the data presented by Penzias this morning. If I were asked to predict the relative importance of such variations in the case of extremely old clouds, I would describe the $^{12}C/^{13}C$ variations as relatively small because of the small difference both observed and predicted between the solar system and the disk for this ratio.

W. Watson: It seems to me that the reactions (3) and (4) are more likely to be important than you indicated. An approximate criterion is that the forward reaction should compete with dissociative electron recombination. Admittedly, application of "currently accepted" data would indicate an effect of only a few per-cent. However the coefficient for dissociative recombination may not continue to increase below 100 K as rapidly as suggested by higher temperature data.

Guélin: ^{13}C exchange between CO and HCO^+ is attractive since it may provide a way to enhance this isotope in the very dense parts of the clouds. Yet, as I said, the observed $H^{13}CO^+/HC^{18}O^+$ ratio (in only one cloud, it is true!) seems to rule out a strong and common effect. More observations have to be made to settle this interesting question.

Scoville: Why do you assume that the gas clouds seen in the galactic center have always been there?

Guélin: Taking into account an infall of fresh gas into the galactic centre introduces extra free parameters and makes it difficult to compare predicted and observed ratios. With the exception of deuterium whose presence in this region has yet to be proven, the observed ratios can be easily explained without infall. In fact, the ^{15}N data even set an upper limit on the importance of such an infall (Audouze et al. in Audouze 1977, p. 155).