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ISOTOPES OF C, N, O AND CHEMICAL EVOLUTION

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Galactic structure, stellar dynamics, interstellar matter
main journal

SUMMARY

Recent observations of CO and other interstellar molecules have conclusively shown that differences in the isotopic ratios of C N and O exist between the interstellar medium and the solar system. In particular, the interstellar medium is very probably enriched in ^{13}C by a factor ~ 2 with respect to ^{12}C, in comparison with the solar system. These observations are examined together with those of gradients of C, O and especially N abundances with galactocentric distance in spiral galaxies.

Since the processes occuring during the formation of the solar system seem to be unable to significantly fractionate the $^{13}C/^{12}C$ ratio, it is assumed that the interstellar gas has been enriched into ^{13}C during the last 4.6×10^9 years.

It is emphasized that ^{13}C, ^{14}N and possibly also ^{17}O are mainly formed in the external regions of stars losing their mass in the red giant, Mira, planetary nebula or supernova phase, while ^{15}N is produced in novae outbursts. Simple evolution models allows to reconcile the time variation of the $^{12}C/^{13}C$ ratio together with the strong spatial gradient of nitrogen and absence of spatial gradient of $^{12}C/^{13}C$. Some implications regarding the loss of mass by stars and the chemical evolution of the Galaxy are discussed. Furthermore since the comets seem to have a $^{12}C/^{13}C$ ratio similar to that of the solar system they probably do not originate from outside the solar system.

Key-words : - Interstellar medium abundances - nucleosynthesis -
red giants - cold stars and planetary nebulae - stellar
mass losses-chemical evolution of the Galaxy - comets -

1 - INTRODUCTION

The chemical evolution of galaxies is presently the subject of many observational and theoretical studies. In this context, one must note that the present observations are not yet sufficient to allow the selection of a very specific solution regarding this problem. Several attempts have been made however to try to restrict the possible models. For example crude solutions like considering a galactic zone such as the solar neighborhood made initially of gaseous hydrogen and helium, and simply processing it into stars appear to be incompatible with the paucity of metal-poor stars (see e.g. : Thuan et al. 1975). One needs to invoke more complicated scenarios such as for instance massive production of stars before the formation of the Galaxy (Truran and Cameron 1971). Or the presence of a massive halo sheding the disk with already processed matter (Ostriker and Thuan 1975).

Further constraints based upon the behaviour of some chemical species like the light elements ($A < 12$) or the s-process elements have also been proposed (Audouze and Tinsley 1974, Schramm and Tinsley 1974). An analysis of these and other constraints for the chemical evolution of the solar neighborhood has been presented by Tinsley (1974).

In this paper we propose to use the available observational data regarding the so-called M elements (carbon, nitrogen and oxygen) and their isotopes to get some insight on the chemical evolution of the interstellar gas. The main advantage of those elements lies in the fact that their abundances are rather large : the main part of the so-called " metals " is represented by them. Moreover their isotopic composition has been measured in various astrophysical locations : the solar system (sun, meteorites, moon and planets), red giant stars and in many regions of the interstellar medium. A key-point for the present study is that the interstellar medium abundances are those of the present gas (the zero-age abundances), while the abundances measured at the surface of the stars (or in the solar system) are those of the galactic gas at the formation time of the considered object (apart from possible changes due to the star itself). In particular the abundances measured in the solar system or at the surface of the sun are representative of the 4.6×10^9 years old gas.

Furthermore one must realize the importance of isotopic determinations relatively to elemental ones. Contrary to the elemental ratios which generally suffer large chemical or physical fractionation processes (see e.g. the comparison which can be made between the Copernicus determinations and the solar or " universal " abundances), the isotopic ratios are much less submitted to such effects and can be considered (when available) as better tools to study the chemical evolution of the Galaxy. It must be stressed also that C N O and their isotopes are formed by a variety of nucleosynthetic processes the comparison of which appears to be very fruitful.

As it will be developed throughout this paper the two most striking observational facts are : i) the difference between the values of $^{12}C/^{13}C$ observed in various locations of the interstellar medium and the solar system ; ii) and the spatial gradients shown by the N/H and N/O ratios contrary to the $^{12}C/^{13}C$ ratio. The purpose of this paper is to offer simple explanations of those two observational features which may give some light on different aspects of the chemical evolution of galaxies.

In section II the relevant observations of the C N O isotopes in the interstellar matter and other astrophysical locations are reviewed as well as the existence of abundance gradients with galactocentric distance. Section III is devoted to a short presentation about the nucleosynthetic processes involved in the synthesis of these nuclear species. In section IV mass losses suffered by the different types of stars are evaluated and the way by which they affect the observed isotopic or elemental ratios in the solar neighborhood is discussed. In section V the behaviour of the C N O abundances such as their isotopic or elemental ratios is investigated in terms of simple models of chemical evolution. In particular, it is possible to account in a simple way for the differences between the evolutions of ^{14}N and ^{13}C. Finally this study is summarized and the main conclusions are presented in section VI.

II - THE OBSERVATIONS

Recently a large body of information has been gathered on the C N O isotopic ratios in the interstellar matter and also on the interstellar O/H and N/H ratios in a few external galaxies.

A - Interstellar isotopes of C, N and O

Data on interstellar isotopes of C, N and O come mainly from radio observations of interstellar molecules ; some information also comes from visible and ultraviolet spectroscopy (for a review of data prior to 1974, see Bertojo et al., 1974). In particular, CO has been observed as $^{12}C\ ^{16}O$, $^{13}C\ ^{16}O$, $^{12}C\ ^{17}O$, $^{12}C\ ^{18}O$ and $^{13}C\ ^{18}O$, HCN as $H\ ^{12}C\ ^{14}N$, $D\ ^{12}C\ ^{14}N$, $H\ ^{13}C\ ^{14}N$ and $H\ ^{12}C\ ^{15}N$, H_2CO as $H_2\ ^{12}C\ ^{16}O$, $H_2\ ^{13}C\ ^{16}O$ and $H_2\ ^{12}C\ ^{18}O$ and OH as ^{16}OH and ^{18}OH. It has been suspected for a long time that the interstellar $^{12}C/^{13}C$ ratio might be smaller than the corresponding solar-system ratio of 89. However, optical-depth effects have made difficult the interpretation of most observational results.

Recently, a careful and extensive study of the CO isotopic species has been performed by Wannier et al. (1975), from observations of the $J = 1 \rightarrow 0$, 2.6 mm line of $^{12}C\ ^{16}O$, $^{13}C\ ^{16}O$ and $^{12}C\ ^{18}O$ in 14 molecular clouds distributed in a large range of distances from the galactic center. Optical depth effects have been carefully discussed, and the results are given only when it is reasonably certain that lines which are sufficiently optically thin are available. Since the $^{12}C\ ^{16}O$ is nearly always saturated, only the $^{13}C\ ^{16}O$ and $^{12}C\ ^{18}O$ lines can be used. In all clouds ratios $^{12}C\ ^{18}O/^{13}C\ ^{16}O$ significantly less than the solar system ratio of 0.178 are obtained, and are all consistent within the errors with an uniform ratio of 0.080. If the $^{13}C\ ^{16}O$ line were more saturated than Wannier et al. thought (Goldsmith et al. 1974) the true $^{12}C\ ^{18}O/^{13}C\ ^{16}O$ ratio would be even smaller than 0.080 since the $^{13}C\ ^{16}O$ line is stronger than the $^{12}C\ ^{18}O$ line and the abundance of $^{13}C\ ^{16}O$ would be more underestimated than that of $^{12}C\ ^{18}O$. This result is confirmed in the case of Sgr B2 by the formaldehyde isotope studies of Gardner et al. (1971) who give $^{12}C\ ^{18}O/^{13}C\ ^{16}O = 0.10 \pm 0.01$.

Table 1 gathers the most significant relevant data on interstellar matter and on the solar system. Wannier et al. (1975) give ample evidence that the difference is due to a smaller $^{12}C/^{13}C$ ratio in the interstellar medium (40 instead of 89) instead of a larger $^{16}O/^{18}O$ ratio. Most of the observational data are reported in this paper. We only want to summarize and complement here its conclusions by adding a few other observational points.

There is a remarkable consistency between the relevant isotopic ratios measured in various locations of the solar system. Quoting Owen (1972) " It appears that $^{12}C/^{13}C$ is essentially uniform in the solar system : the Sun, Venus, Earth, Mars, meteorites, Jupiter and at least two comets all giving the same value to within 10 or 15 percent ". We should add that the $^{12}C/^{13}C$ ratio has also the same value in the solar wind trapped in lunar fines (Geiss, 1973). The same can be said about the $^{15}N/^{14}N$, $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios which however have not been measured in such a large variety of objects. The uniformity of these ratios in the whole solar system is the best proof that isotopic separation effects at the formation of the solar system were minor and that the measured ratios are well representative of the interstellar ratios at the birth of the Sun : chemical and physical fractionation effects in the meteorites are indeed less than 10 % for the C and O isotopic ratios : Anders 1972, Onuma et al. 1972, Clayton et al. 1973.

In the interstellar matter, information about the $^{12}C/^{13}C$ ratio comes from radio observations of formaldehyde at 2 mm and at 6 cm (see references in Wannier et al. 1975, and in Table I) and of HC_3N (Gardner and Winnevisser, 1975). Very recently, $^{13}C\ ^{18}O$ has been detected in the molecular cloud near NGC 2024, and the ratio of the unsaturated $^{12}C\ ^{18}O$ and $^{13}C\ ^{18}O$ lines gives $^{12}C/^{13}C = 50$ (preliminary value : Lucas, private communication). The $^{13}C\ ^{32}S/^{12}C\ ^{34}S$ ratio in Orion gives also $^{12}C/^{13}C = 40$ if the $^{32}S/^{34}S$ ratio is terrestrial, which is a very likely hypothesis (even if ^{32}S and ^{34}S are produced by different nucleosynthetic processes they must come both from the same objects, namely the supernovae). All estimates are consistent with a

$^{12}C/^{13}C$ ratio of about 40, with the single exception of the lower limit roughly equal to the terrestrial value quoted by Whiteoak and Gardner (1972) in the local interstellar gas in the direction of Sgr B2.

Another information comes from optical studies of the 4232 Å interstellar lines of $^{12}CH^+$ and $^{13}CH^+$; the $^{13}CH^+$ component is exceedingly weak and major errors come from the determination of the underlying continuum. Probably for this reason, the values of its equivalent width obtained by Bortolot and Thaddeus (1969) and Vanden Bout (1972) in ζOph are not in agreement : their respective measurements give 0.68 ± 0.14 and 0.35 ± 0.10 mÅ. Moreover, Bortolot and Thaddeus (1969) have strongly overestimated the effect of saturation on the main $^{12}CH^+$ line, the profile of which is known from Hobbs (1973) ; once corrected from this effect, the $^{12}C/^{13}C$ ratios become 44^{+29}_{-8}, and 72^{+24}_{-15} respectively, using Hobb's profile for the $^{12}CH^+$ line. These discrepant ratios cannot be considered as inconsistent with a small interstellar $^{12}C/^{13}C$ ratio.

All what has been said previously strongly supports a variation of the $^{12}C/^{13}C$ *ratio by a factor of about 2 between the interstellar* medium and the solar system.

Information on the isotopes of N and O is not as good as that concerning the carbon isotopes. The $^{16}O/^{18}O$ ratio is probably roughly terrestrial, as it has been stated before. Theoretical arguments concerning the destruction of ^{18}O which will be developed below indicate that a strong deficiency of ^{18}O in the interstellar medium is unlikely. The ratio $^{17}O/^{18}O$ is 0.28 ± 0.08 in Orion A compared to a terrestrial value of 0.183. Finally the $^{13}C\ ^{14}N/^{12}C\ ^{15}N$ ratio as determined from the study of HCN is not very different from the terrestrial ratio. This suggest a $^{14}N/^{15}N$ smaller in the interstellar medium in the same proportion as $^{12}C/^{13}C$. According to Wannier et al. (1975), it is important to realize that an appreciable isotopic separation is not likely to occur for C, N and O in the interstellar medium ; this conclusion can also be derived from the fact that the same isotopic ratios are observed in different molecules (see Table 1).

To summarize this section, observations clearly show that ^{13}C is enriched relatively to ^{12}C by a factor of ∿ 2.3 in the interstellar medium compared to the solar system. ^{17}O has possibly also been enriched relatively to ^{16}O, such as ^{15}N relatively to ^{14}N and ^{18}O may not have varied significantly. A very important result is that the $^{12}C\ ^{18}O/^{13}C\ ^{16}O$ and then the $^{12}C/^{13}C$ ratios exhibit no significant variation with galactocentric distance although local relative deviations from the mean $^{12}C/^{13}C$ can be as large as 30 %.

B - Abundances of nitrogen and oxygen in external galaxies.

Peimbert (1974, 1975) has recently presented two reviews of the abundance determinations in the gas of external galaxies. These papers contain a thourough survey of references up to 1973 to which one must add the contributions by Comte (1975), Comte and Monnet (1974), Dufour (1975), Shields (1974) and Smith (1975). In spite of difficulties with the photometry of emission lines in extragalactic HII regions as well as with their interpretation in terms of abundances, the following conclusions seem to rest on firm grounds :

1 - There exist important N/H and O/H gradients across the disk of spiral galaxies , N and O being more abundant in the central parts. O/H typically varies by a factor of ∿ 10 from the outermost regions ro the center.

2 - The N/H gradient is more important than the O/H gradient : the N/O ratio increases by a factor ∿ 4 in the central regions compared to outer regions.

3 - The Sbc galaxies are richer in O and N than the Scd galaxies and the depletion in these elements observed in irregular galaxies (LMC and SMC) is similar to that observed in the external parts of the spiral galaxies. From these observations it seems that the relative amount of interstellar matter and of matter locked into stars is a factor playing a major role in determining the evolution of these elements.

4 - Neon and sulfur behave like O rather than N.

These results confirm clearly that N (i.e. mainly ^{14}N) is for a large part a secondary product of nucleosynthesis since the N/O ratio is an increasing function of O/H.

In the following sections we will assume that ^{12}C (a primary product of the nucleosynthesis like ^{16}O) which is unfortunately not observed in external galaxies, shows also a spatial gradient similar to ^{16}O and that such gradients exist also in our Galaxy although they are much more difficult to observe (see however in this respect Ryter et al. 1975). Since ^{13}C as ^{14}N is a secondary product of the nucleosynthesis it appears rather surprising at first glance that the ratio $^{13}C/^{12}C$ does not increase toward the galactic center as the ratio $^{14}N/^{16}O$. An explanation for this different behaviour will be offered in section V.

III - NUCLEOSYNTHESIS OF THE C, N, O ISOTOPES

Before discussing the implications of the observations presented in the previous section let us summarize briefly the nucleosynthetic processes responsible for the formation of these isotopes. Some information regarding these processes can be found in Truran 1972, Wollman 1973 or Talbot and Arnett 1973.

1 - ^{12}C and ^{16}O (as well as ^{20}Ne) are the products of helium burning occuring in the inner regions of stars. They are thus primary products of nucleosynthesis. They are supposed to be ejected by rather massive stars ($M \geq 5\ M_\odot$ for instance) the only ones which are able to eject such inner regions (see in this respect Truran and Cameron 1971 and Talbot and Arnett 1973).

2 - ^{14}N can be synthetized in several ways : 1) some primary ^{14}N can be produced in red giants by the partial mixing of the hydrogen burning zone with the helium burning zone (Truran, 1972). This occurs for instance during the shell flashes experienced by red giants (Ulrich and Scalo 1972, Sackmann et al. 1974) ; 2) it can be considered as a secondary product

i.e. it is produced through the CNO cycle occuring in the center of massive (M > 1 M⊙) main sequence stars. This cycle of reactions not only operates the transformation of hydrogen into helium but also that of preexisting ^{12}C and ^{16}O into ^{14}N. The CNO cycle can also take place in the hydrogen burning zone of evolved red giant stars. The secondary ^{14}N produced in this way is eventually mixed in the outer envelope by convection. ^{14}N can also be produced in the hot CNO cyle ($T > 10^8$ K) (see e.g. Audouze et al. 1973). Thus ^{14}N contrary to ^{12}C and ^{16}O may come from at least three kinds of objects : i) the massive stars M ≥ 5 M⊙ which eject their envelope plus some material which has been processed in inner regions when they explode as supernovae, ii) less massive stars (1 < M < 5 M⊙) lose only their envelope in a less dramatic way through instability during or after the red giant phase (Paczynski and Ziolkowski, 1968); then all stars with M > 1 M⊙ are intrinsically able to enrich the interstellar medium with secondary ^{14}N present in their envelope ; iii) finally ^{14}N is also produced in nova outbursts (Starrfield et al. 1972, 1974) by the hot CNO cycle.

3 - ^{13}C can be built by an incomplete proton burning on ^{12}C which could occur as the result of the helium flash in red giant stars, inducing an incomplete mixing of the hydrogen rich and the helium rich zone. If the mixing between these zones is more complete ^{13}C is itself transformed into ^{14}N as examined above. ^{13}C is then released by ejection from stars of any mass as in the case of ^{14}N. ^{13}C is then always a secondary product which can be also produced during the novae explosions by the hot CNO cycle.

4 - ^{17}O can be formed from ^{16}O in the same way as ^{13}C from ^{12}C. However ^{17}O is formed in deeper regions then ^{13}C (Wollman,1973). Thus it might be released only from massive stars (M > 3-5 M⊙). The hot CNO cycle reactions triggering novae explosions produce also substantial amounts of secondary ^{17}O.

5 - Presently the production of ^{18}O is not yet well understood : a) ^{18}O can be formed in the helium burning zone by the reaction $^{14}N(\alpha, \gamma)$ $^{18}F(\beta^+)$ ^{18}O. This may occur either during stable phases of helium burning or possibly during an explosive phase (see e.g. Howard et al., 1971) ;

b) ^{18}O can be formed through reactions starting from ^{17}O for instance $^{17}O(p, \gamma)^{18}F$. Its formation rate depends then upon the rate of ^{17}O production. Since nuclear physics work suggests now that the ^{17}O (p, α)^{14}N rate is smaller than the value used previously (Rolfs and Rodney, 1974) one can think that the production of ^{18}O might be more efficient this way. At present preliminary results obtained independantly by Truran and Arnould (private communications) seem to shows that hot CNO cycle reactions (such as those studied in Audouze et al., 1973) might significantly contribute to the formation of ^{18}O.

6 - Finally ^{15}N is an element which can be very easily destroyed by $^{15}N(p, \alpha)^{12}C$ during the CNO cycle occuring either in hydrogen rich zones or due to the helium flashes inducing partial mixing of the helium and hydrogen rich zones of red giants. The only way to produce it is by the action of hot CNO cycles producing large amounts of its parent ^{15}O as shown for instance by Audouze et al. 1973, and occuring during the fast explosive phases of novae.

We have already mentioned the possibility that ^{17}O and ^{15}N are destroyed by (p, α) reactions; ^{13}C and ^{18}O can also be destroyed in stars by (p, γ) or (p, α) reactions at temperatures $T \geq 10^8$ K which may be reached during the mixing of helium and hydrogen zones. As far as ^{13}C is concerned this possible depletion must be very unimportant since low $^{12}C/^{13}C$ ratios as small as ∿ 6 are observed at the surface of the red giant stars. The case of ^{17}O is not as clear.

A key point for the following study is that in any mechanism the $^{12}C/^{13}C$ ratio cannot be smaller than 0.3 (hot CNO cycle) or ≃ 2 (proton capture on ^{12}C at moderate temperatures $T < 10^8$ K). It is not possible to see $^{12}C/^{13}C$ decreasing as much as $^{12}C/^{14}N$, which can go down to values smaller than 0.01 when the CNO cycle operates.

To summarize the previous remarks, ^{13}C and ^{14}N can be produced both from ^{12}C (and also from ^{16}O in the case of ^{14}N). The enrichment in ^{13}C with respect to ^{12}C is limited while there is nearly no limit to the enrichment in ^{14}N relatively to ^{12}C and ^{16}O in a zone submitted to the CNO cycle.

IV - MASS LOSS AND CNO PRODUCTION RATES FROM STARS

We have seen in the previous section that many kinds of objects can produce ^{13}C and ^{14}N. What we want to do here is to evaluate the rate of mass loss by these different objects in the solar neighborhood and show that the time variation of the $^{12}C/^{13}C$ ratio is easy to explain.

A - Mass losses, ejection and destruction of CNO isotopes.

From the previous paragraph, it appears that stars of mass as low as 1 M⊙ are able to eject at the end of their evolution matter enriched into ^{13}C and ^{14}N while stars of mass higher than 3-5 M⊙ eject matter enriched into ^{12}C, ^{13}C, ^{14}N, ^{16}O, ^{17}O and possibly ^{18}O. Furthermore novae are, in principle, able to enrich the interstellar gas into ^{13}C, ^{15}N, ^{17}O, and possibly ^{18}O. These three types of stars lose their mass and enrich the interstellar gas in CNO isotopes in very different ways which are analyzed now.

a - Stars with $M \lesssim 5$ M⊙

Paczynski and Ziolkowski (1968) have thoroughly studied the evolution of post main sequence stars of masses between 1 to about 5 M⊙. They propose that, when these stars reach the top of the giant branch, their envelope become unstable, triggering Mira-type pulsations, and is ejected eventually as a planetary nebula ; the dense core is left as a hot and small nucleus of ∿ 1 M⊙ which will become a white dwarf. This picture is confirmed by several observational evidences. As discussed by Osterbrock (1974), the rate of formation of planetary nebulae in the solar neighborhood (7×10^{-10} pc^{-2} yr^{-1} in a column perpendicular to the galactic plane) is similar to the rate of star death with M > 1 M⊙ 5.7 10^{-10} pc^{-2} yr^{-1} following Schmidt, 1963). On the other hand an estimate of the formation rate of the Mira-type stars is much more difficult to do since there is no direct way to estimate the life time of this stage.

Mass losses suffered by low mass stars can be estimated from the formation rate of planetary nebulae. A minimum value is obtained by assuming that every planetary nebula is an ejected shell of ∿ 0.2 M⊙, which leads to a minimum mass loss of 1.4×10^{-10} M⊙ pc^{-2} yr^{-1}. This is a lower limit since the mass estimated above corresponds only to ionized material ; the planetary nebulae also contain blobs of dense neutral material, the mass of which is unknown (Danziger and Goad, 1973). An upper limit of the mass lost by low-mass stars can however be obtained by assuming that those objects eject all their matter in the interstellar medium, with the exception of a stellar nucleus for which the mass has been guessed by Paczynski (1970). This upper limit corresponds to a rate of mass ejection of 5×10^{-10} pc^{-2} yr^{-1}. At this point, one may mention that a large fraction of this mass can be ejected during the Mira phase. By using the new scale of absolute magnitude for Miras obtained by Foy et al. (1975) and the statistics extracted from the Kurkarkin et al. (1969) catalogue we obtain a projected local density of 1.3×10^{-4} Mira pc^{-2}. If each Mira ejects 2×10^{-6} M⊙ yr^{1} (Gehrz and Woolf, 1971) the corresponding rate of mass loss for Mira is 2.6×10^{-10} MO yr^{-1} pc^{-2} which is about 50 % of the maximum rate of mass lost by evolved stars . However, the rate of mass loss calculated for Miras is very model dependent and uncertain (Fix and Alexander, 1974).

Let us discuss now the chemical composition of the ejected matter. The composition of the surface of red giant and super giant stars is indeed a fair approximation of the composition of ejected material since the envelope is fully convective.

Let us summarize first the available observations regarding isotopic ratios : the $^{12}C/^{13}C$ ratio has been measured in a large number of red giants and supergiants of spectral types ranging from KO to M8 (references in Table II). This ratio turns out to be of the order of 5-20 and is close to 6 in the most accurate determinations which concern mainly supergiants An explanation of the saturation of the $^{12}C/^{13}C$ ratio to these small values has recently been proposed by Dearborn et al. (1975). There seems to be a correlation between the surface $^{12}C/^{13}C$ ratio and the mass of the star, the more massive stars showing a smaller $^{12}C/^{13}C$ (Lambert and Tomkin, 1974). Table II also contains the available information (unfortunately scanty) on the abundances of ^{17}O and ^{18}O in the envelope of red giants and supergiants.

To estimate the rate of ejection of ^{13}C, ^{14}N, ^{17}O and ^{18}O by these stars we need to know the elemental abundances of C, N, O in their atmosphere. Available information is rather poor ; it only suggests that carbon and oxygen have roughly solar abundances while N/H is possibly enhanced by factors 2-3, at least in relatively massive stars (Greene 1969, Ridgway 1974, Lambert 1974). A recent study of planetary nebulae (Boeshaar, 1975) confirms that in population I planetary nebulae O/H is solar (or perhaps slightly smaller) while N/O varies largely from one object to another : N/O is ~ 6 times larger than the solar ratio in young (population I) planetaries while it is down by factors 1 to 4 in old population II planetaries (characterized by low O/H values and by their kinematic properties). As a result of this analysis the matter ejected by a typical population I red giant can be observationnaly characterized by $^{12}C/H$ and $^{16}O/H \sim$ solar, $^{12}C/^{13}C \sim 6 - 20$, $^{16}O/^{17}O \sim 270 - 540$ and $^{14}N/H \sim 2$ to 3 times the solar value (see Table II). We can assume rather safely that in the solar neighborhood the major part of the mass ejected from that type of star comes from these relatively young population I stars : this is expressed for instance by the stellar death rate function determined by Schmidt (1963) in which more than 80 % of the mass lost by stars of 1 to 5 M⊙ comes from stars younger than the Sun. Then using as a reference the solar abundances of Whitbroe (1971) stars with $1 < M < 5$ M⊙ eject in the local interstellar matter amounts of C, N, O between 10^{-15} up to a few 10^{-12} M⊙ yr^{-1} pc^{-2} of each isotope. These quantities are listed in Table II.

b - Stars with $M > 5$ M⊙

The final evolution of these stars is extremely uncertain (see e.g. Ostriker et al., 1974). It is usually believed that stars with $5 < M < 8$-10 M⊙ end as supernovae and leave a pulsar but that the major fraction of products of explosive nucleosynthesis come from higher masses (Arnett and Schramm, 1973). Although this is rather crude, we consider here that stars with $M > 5$ M⊙ eject entirely their processed material leaving only a neutron star of 1-2 M⊙.

The production rate of CNO isotopes coming from these stars is rather uncertain, but one can show that the production of ^{13}C and ^{14}N coming from their envelopes is of the same order in the solar neighborhood as the corresponding rates coming from less massive stars : if we combine the rate of stellar death for that type of stars (taken from Ostriker et al., 1974) with the masses of envelopes guessed by Talbot and Arnett (1973), the corresponding rate of ^{13}C enrichment by these stars would be about 0.7×10^{-13} $M_\odot$ yr^{-1} pc^{-2} (if we take $^{12}C/^{13}C = 6$) : this is of the same order as the rate of enrichement by lower mass stars (Table III). The conclusion for ^{14}N would be similar. It must be noted that the use of stellar death rates given by Schmidt (1963) would raise somewhat the contribution of the massive stars.

There is some observational evidence that oxygen (and possibly carbon) are produced in massive stars : Peimbert and Van den Bergh (1971) as well as Peimbert (1971) have determined some trends of the chemical composition of the fast-moving knots of Cas A. They found oxygen (and also argon and sulfur) overabundant relatively to H by factors as high as 30. Carbon unfortunately, cannot be measured, but one may assume that it behaves like ^{16}O. On the other hand ^{14}N does not seem to be overabundant, which means that the production of ^{14}N in the central regions of massive stars (where ^{16}O comes from) is not important. One can note however that these authors find N overabundant relatively to O in the stationary flocculi of Cas A, which they interpret as ejecta of the interstellar envelope before the explosion. These flocculi would correspond chemically to the external envelopes of red giants.

To summarize this section stars with $M > 5$ $M_\odot$ eject in the interstellar matter ^{13}C, and ^{14}N produced in their envelopes in quantities comparable to less massive stars. They eject also some ^{17}O, they produce ^{16}O and ^{12}C in not well known quantities : the highest mass stars ($M > 10$ $M_\odot$) seem to be the only efficient objects to enrich the interstellar gas into ^{12}C, ^{16}O and heavier elements (Arnett and Schramm, 1973).

c - Novae

As stated before, the nucleosynthesis occuring during the outburst of a nova might induce an important production of ^{13}C, ^{15}N and ^{17}O (Starrfield et al., 1972, 1974). The surface of the prenova i.e. the white dwarf which is to suffer the nova outburst appears to be considerably enriched into CNO nuclei relatively to their abundances in the solar system (Antipova, 1974). As studied by various authors (Starrfield et al., 1972, 1974, Audouze et al., 1973, Arnould and Beelen, 1974, etc..) hot CNO cycle reactions occuring at $T > 10^{8}$ K may trigger the nova explosion and transmutes the CNO nuclei mainly into ^{13}C, ^{15}N, ^{17}O (and possibly also ^{18}O). These elements might then be enhanced by factors larger than 100 relatively to their solar abundances. There does not exist any observational check for that type of nucleosynthesis, but it appears that novae are the only reasonable site for producing ^{15}N. Table II gives estimates of the chemical composition of the ejecta and of their contribution to the enrichment of the solar neighborhood.

These contributions correspond to an ejected mass between 10^{-6} and 2×10^{-4} $M_\odot$. The rate of nova explosions in the vicinity of the Sun is poorly known. By using the data listed in Payne-Gapeschkin (1957) and taking into account various selection effects we arrive at a rate of about 4×10^{-8} yr^{-1} pc^{-2}. A combination of this rate with the rate of mass ejection given above allows to obtain the rate of enrichment listed in Table II, column 6. Then if the mean mass ejected by each nova is as high as 2×10^{-4} $M_\odot$, novae can compete with ordinary low mass stars to produce ^{13}C, ^{14}N and ^{17}O. In any case they constitute the only source of ^{15}N.

After this analysis of the production in CNO isotopes, we can rather simply assume that the destruction of ^{13}C, ^{15}N and ^{17}O inside the successive generations of stars are negligible : these elements are likely to be less easily destroyed than Be or B, for which observational evidences and theoretical estimates show that their destruction inside stars do not seem to play an important role (see e.g. Audouze and Tinsley, 1974). Rough calculations of the amount of matter processed in stellar envelopes where these elements might be partly destroyed lead also to the same conclusions.

B - The local rate of isotopic enrichment

We have seen that various types of stars are able to eject significant quantities of ^{13}C, ^{14}N, ^{15}N, ^{17}O and perhaps ^{18}O. The results of the analysis discussed above differs somewhat from that of Wollman (1973) in the fact that the major contribution to ^{13}C, ^{15}N and possibly also ^{14}N does not necessarily comes from high mass stars. In order to account for the observed change in the ^{12}C/^{13}C ratio since the birth of the solar system, we must get an estimate of the rate of injection of the primary elements ^{12}C and ^{16}O in the interstellar medium. We just want to show here that a ^{13}C enrichment is likely ; we do not need yet a specific evolution model as those which will be considered in the next section. For the present purpose, it seems safe to assume that ^{12}C/H and ^{16}O/H have not increased by more than a factor two during the last 4.6 10^9 years and that the mass of interstellar matter near the Sun has not decreased by more than a factor 2 in this time interval. We are also aware that metals can even decrease with respect to time (Jennens and Helfer, 1975) : one explanation might be infall of extragalactic matter on the galactic disk, this has no consequence on the variation of the ^{13}C/^{12}C and of the N/O ratios.

Let us then first assume for simplicity that the local mass of gas has been constant since 4.6 x 10^9 years. Its projected mass is about of 7 $M\odot$ pc^{-2} (Radakhrishnan et al., 1972), if we neglect molecular hydrogen. If in the same time ^{12}C and ^{16}O have remained constant the change of the ^{12}C/^{13}C ratio from 89 to 40 requires the injection of $\sim 10^{-13} M\odot\ yr^{-1}\ pc^{-2}$ of ^{13}C : as it has been seen in section A, ordinary stars or perhaps novae alone can easily do the job. At the same time ^{14}N increases by ∿ 25 % if low mass stars are responsible for most of the enrichments (Table II). No conclusion can yet be reached for ^{17}O.

Finally ^{15}N must be produced at a rate of $\sim 2 \times 10^{-14}\ M\odot\ yr^{1}\ pc^{-2}$ during the same time, which requires a relatively small rate of mass loss through novae and in turn indicates that ordinary stars are the main producers of ^{13}C. If ^{12}C and ^{16}O would have increased by a factor 2 during the last

4.6 10^9 years the requirements would be slightly larger (for example a rate of $\sim 1.4\ 10^{-13}\ M_\odot\ yr^{-1}\ pc^{-2}$ is needed to account for the $^{13}C/^{12}C$ variation) but the conclusions would remain essentially unchanged. A decrease of the mass of interstellar gas during the same time certainly make the above requirements easier to fulfill.

We have shown in this section that within (large) uncertainties the decrease with time of the interstellar $^{12}C/^{13}C$ ratio can satisfactorily be accounted for by mass losses from stars. In this picture ^{13}C and ^{15}N can be easily enriched in the solar neighborhood, but not very much ^{14}N unless massive stars are able to eject large quantities of ^{14}N, an hypothesis which is somewhat contradicted by the observations of the chemical composition of Cas A.

The existence of a large N/O ratio in the central regions of galaxies obviously requires that the interstellar gas has been processed much more efficiently into stars. This fast processing has the consequence to make the gas/star mass ratio small, to create a large abundance of heavy elements, and a large proportion of relatively low-mass stars with long life-times. All these consequences are actually observed, and we give in the Appendix and in Table III some data for the galactic center. We recall here that a larger N/O ratio is not necessarily accompanied by a large $^{12}C/^{13}C$ ratio, since there is in any CNO cycle a limit to the $^{12}C/^{13}C$ ratio and essentially none for the N/C and the N/O ratios. The following section will discuss these features more precisely.

V - CNO ISOTOPES AND A SIMPLE CHEMICAL EVOLUTION MODEL.

The final purpose of our study is to try to find a simple explanation accounting simultaneously for three observed facts : i) the time variation of the $^{12}C/^{13}C$ ratio in the solar vicinity ; ii) the strong spatial gradient of the N/O ratio ; iii) the lack of strong spatial dependance of the $^{12}C/^{13}C$ ratio. A complete discussion of this rather tricky problem is out of the scope of this paper. However, we can show that a naive picture of the chemical evolution of galaxies (using models with crude analytical approximations) provides a satisfactory description of these observational data.

The model used here is based upon two basic assumptions : a) a uniform initial mass function (hereafter designated as IMF) ; b) an instaneous recycling approximation in which the life-times of the stars are assumed to be negligible compared to the evolution time scale of the interstellar medium. We have seen in the previous section that this last assumption is reasonable for the solar neighborhood. We are aware that it is not valid for the galactic center so that the model presented here is only illustrative. More elaborate presentations are currently studied (Vigroux, thesis in progress).

We have seen in the previous section that the minimum $^{12}C/^{13}C$ ratio observed at the surface of evolved stars is about 6. We thus assume that the mass ejected from stellar envelopes is a mixture of well processed material with $^{13}C/^{12}C = 6$ and of unprocessed material with negligible ^{13}C enrichment. The same can be said also for the ^{14}N enrichment. Thus we have adopted a simple model somewhat differen from those of Talbot and Arnett (1973) or Wollman (1973). We define the following mass fractions :

i) The mass fraction β_2 corresponding to the ejected but unprocessed material (as far as CNO are concerned) $\beta_2 \sim 0.35-0.40$.

ii) A mass fraction β_1 of mass ejected from envelopes of $M > 1\ M_\odot$ stars and enriched into ^{13}C and ^{14}N : in this simple model we treat ^{13}C and ^{14}N independantly but we use the same β_1 for both elements. β_1 is taken as about the third of the ejected mass $0.10 < \beta_1 < 0.15$.

iii) A mass fraction p corresponding to the mass ejected by very massive stars ($M > 5\ M_\odot$) consisting in pure ^{12}C and ^{16}O ($p' = 7.1\ 10^{-3}$ from Talbot and Arnett, 1973).

iv) α is the total mass fraction locked into stars of any mass (very low mass stars of $M < 1\ M_\odot$, white dwarfs, neutron stars, black holes). From the mass conservation (if we neglect infall) we have :

$$\alpha = 1 - \beta_1 - \beta_2 - p' \text{ (negligible)} \simeq 0.50 \qquad (1)$$

the total ejected mass of matter processed into stars is thus approximately equal to the mass locked into stars.

As far as ^{12}C and ^{16}O are concerned, we assume that they are formed in the solar ratio ($^{16}O/^{12}C \sim 2.3$). We also assume that they keep this ratio throughout the life of the Galaxy : this might be justified by the fact that when they are processed through the CNO cycle they are entirely destroyed. (An exception can be carbon stars but they do not represent a large fraction of the stellar populations). Subscripts 0 and 1 designate the abundances in the envelope respectively prior and after that the CNO cycles take place. We can then write the following relations, where ^{12}C represents numbers of ^{12}C atoms per unit of mass, etc..

$$^{12}C_o = 6\ ^{13}C_1 \qquad (2)$$

$$\frac{^{15}O_o}{^{12}C_o} = \frac{^{16}O_1}{^{12}C_1} = 2.3$$

$$^{14}N_1 - {}^{14}N_o = x\,(^{12}C_o + {}^{16}O) \qquad \text{with } x \gtrsim 0.1$$

and

$$^{12}C_o + {}^{14}N_o + {}^{16}O_o = {}^{12}C_1 + {}^{13}C_1 + {}^{14}N_1 + {}^{16}O_1$$

expressing the fact that the envelopes have not been contaminated by the products of helium burning and that the ^{13}C abundance is negligible before the occurence of CNO cycle.

Now we can follow the evolution of these nuclear species by using the formation presented by Pagel and Patchett (1975). If $\mu(t)$ is the mass of interstellar gas at the time t (with $\mu(0) = 1$) and S(t) the total mass of stars formed up to the time (t) (normalized to 1 as μ) the mass conservation can be written as :

$$\mu = 1 - \alpha S \qquad (3)$$

and if the variation of the mass into stars is given by :

$$\frac{dS}{dt} = \nu\,\mu^{k} \qquad (4)$$

We get the differential equation governing the mass of interstellar gas :

$$- \frac{1}{\alpha} \frac{d\mu}{dt} = \nu \mu^{k} \qquad (5)$$

which leads to :

$$\begin{aligned} &\text{if} \quad k = 1 && \mu = e^{-t/\tau} \\ &\text{or if} \quad k \neq 1 && \mu = \left\{ (k-1) \frac{t}{\tau} - 1 \right\}^{\frac{1}{1-k}} \end{aligned} \qquad (6)$$

with $\tau = \frac{1}{\nu \alpha}$ is the characteristic time of gas evolution.

The use of previous equations allows to write relations governing the evolution of ${}^{12}C$, ${}^{14}N$ and ${}^{16}O$ (neglecting first ${}^{13}C$) :

$$\begin{aligned} &\frac{d}{dS} ({}^{12}C\mu) = p'_{{}^{12}C} + \{(1 - x) \beta_1 + \beta_2 \}\, {}^{12}C - {}^{12}C \\ &\frac{d}{dS} ({}^{16}O\mu) = p'_{{}^{16}O} + \{(1 - x) \beta_1 + \beta_2 \}\, {}^{16}O - {}^{16}O \\ &\frac{d}{dS} ({}^{14}N\mu) = x\beta_1 \left(\frac{{}^{16}O + {}^{12}C}{{}^{12}C}\right) {}^{12}C_o + (\beta_1 + \beta_2)\, {}^{14}N - {}^{14}N \end{aligned} \qquad (7)$$

These equations can be transformed, after dividing, by α, into :

$$\begin{aligned} &\frac{d\, {}^{12}C}{d(\log (\frac{1}{\mu}))} = \left(\frac{{}^{12}C}{{}^{16}O + {}^{12}C}\right) p - \gamma \beta_1\, {}^{12}C \\ &\frac{d\, {}^{16}O}{d(\log (\frac{1}{\mu}))} = \left(\frac{{}^{16}O}{{}^{16}O + {}^{12}C}\right) p - \gamma \beta_1\, {}^{16}O \\ &\frac{d\, {}^{14}N}{d(\log \frac{1}{\mu})} = \frac{x\, ({}^{16}O + {}^{12}C)\, \beta_1}{\alpha\, ({}^{12}C)}\, {}^{12}C \end{aligned} \qquad (8)$$

with $p = p'/\alpha$ and $\gamma = \frac{x}{\alpha}$

these equations give immediatly

$${}^{12}C = \frac{{}^{12}C}{{}^{16}O + {}^{12}C}\, p \left\{ 1 - \mu^{\gamma \beta_1} \right\}$$

$$^{16}O = \frac{^{16}O}{^{16}O + {}^{12}C} \; p \; \{ 1 - \mu^{\gamma \beta_1} \} \tag{9}$$

$$^{14}N = \gamma \, p \, \beta_1 \; \{ \frac{1}{\gamma \beta_1} \; (\mu^{\gamma \beta_1} - 1) - \log \mu \; \}$$

when the Galaxy evolves μ goes down to zero, i.e. ^{12}C and ^{16}O reach limit values while ^{14}N increases indefinitely as - log μ .

In the same way we can follow the evolution of ^{13}C by writing :

$$\frac{d(^{13}C \; \mu)}{dS} = \frac{1}{6} \; \beta_1 \; {}^{12}C - {}^{13}C \tag{10}$$

by the same treatment we get :

$$^{13}C = \frac{1}{6} \left(\frac{^{12}C}{^{16}O + {}^{12}C}\right) \frac{\beta_1 \, p}{\alpha} \left\{ \left(\frac{\alpha}{\alpha - 1} - \frac{1}{\gamma \beta_1 + (\alpha - 1)/\alpha}\right) \mu^{-(\alpha - 1)/\alpha} - \left(\frac{\alpha}{\alpha - 1} - \frac{\mu^{\gamma \beta_1}}{\gamma \beta_1 + (\alpha - 1)/\alpha}\right) \right\} \tag{11}$$

In this case ^{13}C reaches also a limit when μ goes down. The limit for $^{12}C/^{13}C$ is $\frac{6 \, (1 - \alpha)}{\beta_1}$.

Calculations have been made for a wide range of parameters such as K, τ, β, x and α. Satisfactory results are obtained for $1 < \kappa < 1.4$, $0.4 < x < 0.5$, $4 \times 10^9 < \tau$ (solar neighborhood) $< 6 \times 10^9$ yr, τ(galactic center)$\simeq 1 \times 10^9$ yr, $\beta_1 \sim 0.10 - 0.15$, $0.45 < \alpha < 0.55$. An example of the evolution of N/O, ^{12}C / ^{13}C and the gas content with time for the solar neighborhood and the galactic center is presented in fig. 1. As it can be seen on this figure : 1) the $^{12}C/^{13}C$ ratio varies by a factor 2 between t = 2.8 10^9 yrs (corresponding to the birth of the solar system) up to t = 7.4 10^9 yrs (now). This time scale which has been chosen so that $^{12}C/^{13}C$

is 89 at the formation of the Sun is not very critical in the view of the crudeness of the analysis presented here. In any circumstances : i) the present age defined here this way is consistent with the age of the universe estimated by other methods (see e.g. Schramm 1973) ; ii) satisfactory solutions have been also obtained for present times of the order of 10 x 10^9 years. 2) As stated already the $^{12}C/^{13}C$ ratio has a limit which is 24 in this case. 3) In the galactic center the calculated present $^{12}C/^{13}C$ ratio is 28 close to the above limit, not very different from the value 44 calculated for the solar neighborhood. 4) The $^{14}N/^{16}O$ ratio is four times larger in the galactic center than in the solar neighborhood. 5) The gas/star mass ratio is 0.15 in the solar neighborhood at present and 4 10^{-4} in the galactic center in good agreement with the values reported in Table III.

Since for k = 1 the gas/star mass ratio μ is proportional to $e^{-t/\tau}$ the different characteristic time scale τ_0 and τ_{CG} (respectively at the Sun and at the galactic center) must be in the ratio log μ_0/log μ_{CG} i.e. ~ 4. 6) The agreement is only qualitative when are compared the ratios of star formation (per unit of mass gas) monitored by supernovae explosions observed near the Sun and in the galactic center (Table III) ($\sim 1/20$). With the predicted ratio (inversely proportional to τ and then $\sim 1/4$) the N/O ratio at the Sun is also too small by a factor 2. This latter slight discrepancy could be easily removed by increasing slightly the parameter x.

In the frame of our rather simple-minded analysis (which is quite usual in any type of studies of chemical evolution) it is very encouraging to see that we explain together the time dependance of the $^{12}C/^{13}C$ ratio together with the lack of important spatial gradient, the importance of the gradient for the N/O ratio with a reasonable space dependance of the gas/star mass ratio.

CONCLUSION

Observational evidence based upon the study of various interstellar molecules conclusively shows that the $^{12}C/^{13}C$ ratio is significantly different in the interstellar gas and in the solar system. We interpret this difference as due to an enrichment of the interstellar medium in ^{13}C since the birth of the Solar System.

We have shown that ^{13}C, as well as ^{14}N and other rare isotopes of C N and O, can be produced by a variety of nucleosynthetic processes in ordinary stars of all masses and in novae. We present an analysis of mass losses by these objects in the solar neighborhood and show that the enrichment of the interstellar matter in ^{13}C can be easily explained.

We have extended this analysis by using simple models of the evolution of the Galaxy - and have shown that it is possible to explain simultaneously the time variation of the ^{12}C/^{13}C ratio in the solar neigborhood, the gradient of the N/O ratio with galactocentric distance observed in several spiral galaxies and the lack of appreciable spatial gradient in ^{12}C/^{13}C in our Galaxy. The N/O gradient is linked to different time-scales of processing of gas through stars, this processing being more rapid at the galactic center. ^{14}N, a secondary nucleosynthetic product, can be enriched up to very large values, but not ^{13}C because of the existence of a lower limit to the ^{12}C/^{13}C ratio in CNO cycle nucleosynthesis. Consequently, the ^{12}C/^{13}C ratio can only decrease to some limit which is nearly reached both in the solar neighborhood and at the galactic center. Although very crude, our models give a quantitative agreement for about all the observed parameters ; we are presently building more sophisticated modes relaxing in particular the instant recycling approximation which has been used in the present paper. The effect of relaxing this assumption would presumably be to produce more ^{14}N at the galactic center. For the present problem, it does not seem necessary to introduce different initial mass functions close to the Sun and at the galactic center.

In the context of this work, it is important to realize that the comets present a solar ^{12}C/^{13}C isotopic ratio. This fact can be considered as a proof that comets are of solar origin (or at least have been formed at approximatively the same epoch as the Sun).

The conclusions of this investigation can, of course, be checked by further abundance determinations in the interstellar gas, and especially by further measurements of isotopic ratios ; it is a great advantage to work on isotopic - rather than elemental - ratios since they are more likely to be determined accurately and are much less subject to fractionation. In particular, the space variations in the $^{12}C/^{13}C$ ratios should be carefully studied, both for investigating any possible gradient with galactocentric distance and for looking for possible local enrichments in the vicinity of red giants and planetary nebulae. It is interesting to note that our analysis can be subjected to observational checks : this analysis will meet serious difficulty if one discovers some interstellar $^{12}C/^{13}C$ ratios (especially in the galactic center) lower than about 20. More observational data are badly needed for ^{15}N, ^{17}O and ^{18}O, in stars, novae and the interstellar matter. These isotopes are much less known than ^{13}C and also require extensive theoretical works.

ACKNOWLEDGEMENTS

We thank Drs. P.G. Wannier, R. Lucas, P.J. Encrenaz, and G. Winnevisser for communicating us their exciting results prior to publication. We thank also Dr. B.M. Tinsley for helpful remarks on an earlier version of this work and Jeannette Caro for an efficient help in the presentation of the manuscript.

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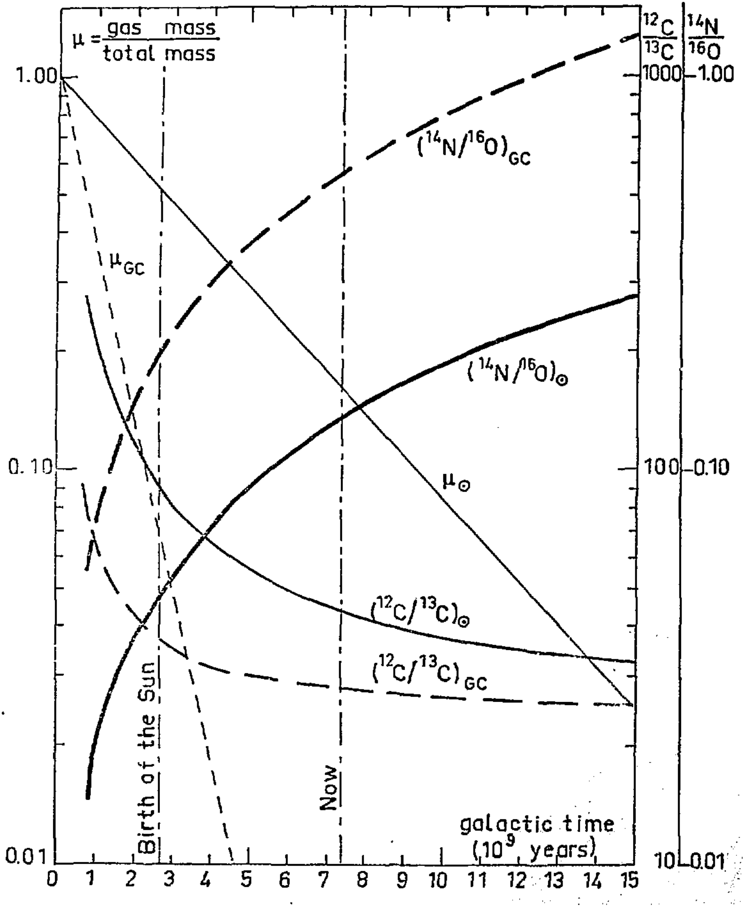
FIGURE CAPTION

Figure 1 - Time evolution of the $^{12}C/^{13}C$ and $^{14}N/^{16}O$ isotopic ratios in the *interstellar* gas close to the Sun and at the galactic center.

The curves gives the results of the calculations using the model described in the text with the following values of the parameters : $\alpha = 0.50$; $\beta_1 = 0.123$; $p' = 7.1 \times 10^{-3}$; $k = 1$; $x = 0.40$; τ (solar neighborhood) $= 4 \times 10^9$ yr ; τ (galactic center) $= 10^9$ yr. Solid lines refer to the solar neighborhood, dotted lines to the galactic center.

It can be easily seen that the $^{12}C/^{13}C$ ratio nearly reaches asymptotic values in the galactic center and the solar neighborhood at the present time while the $^{14}N/^{16}O$ ratios in the same locations continue to increase. The spatial gradient of this last ratio is apparent and much larger than for the $^{12}C/^{13}C$ ratio in agreement with the observations.



$\mu = \frac{\text{gas mass}}{\text{total mass}}$
1.00
0.10
0.01
$\frac{^{12}C}{^{13}C}$
$\frac{^{14}N}{^{16}O}$
1000
100
10
1.00
0.10
0.01
$(^{14}N/^{16}O)_{GC}$
μ_{GC}
$(^{14}N/^{16}O)_{\odot}$
$\mu_{\odot}$
$(^{12}C/^{13}C)_{\odot}$
$(^{12}C/^{13}C)_{GC}$
Birth of the Sun
Now
galactic time (10^9 years)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

APPENDIX

Stellar population and gas content in the galactic center.

As explained in sections IV and V, the existence of a large N/O gradient with galactocentricdistance implies that the processing of gas through stars has been more active at the center of galaxies ; consequently, the gas/star ratio should be smaller at the center, and the stellar population should be dominated there by relatively old low-mass stars. Let us examine these points in the case of the Galaxy.

Schmidt (1965) and more recently Sanders and Lowinger (1972) have discussed the mass distribution in the central regions of the Galaxy. Information on the distribution of the interstellar gas can be found in Scoville et al. (1974) and in Sanders and Wrixon (1974). Inside 500 pc from the center there are 10^7 - 10^8 $M\odot$ of interstellar gas, while the mass of stars in an equidensity spheroïd is 1.5×10^{10} $M\odot$ thus the gas/star ratio is 7×10^{-3} to 7×10^{-4}. Inside 130 pc there are perhaps 10^6 $M\odot$ in gaseous form against 2.5×10^9 $M\odot$ in stars (ratio 4×10^{-4}), and in the central object Sgr A W, the gas /star ratio is similar (Downes, 1975). The local value of the gas/star mass ratio (projected masses) being about 10^{-1}, it is clear that the galactic center is very deficient in gas relatively to the solar neighborhood.

Turning now to the stellar population, recent detailed infrared observations of the galactic center (Becklin, 1975) have shown the presence, within 30" (i.e. 1.5 pc) of the nucleus, of four objects with infrared properties apparently similar to those of the planetary nebula NGC 7027. From this, we can get an estimate of the mean rate of formation of planetary nebulae per unit mass if the four infrared objects are planetary nebulae with a life time of about 1.6×10^4 years (Osterbrock, 1974) formed in a region of total mass $\sim 1.2 \times 10^7$ $M\odot$: the corresponding rate is 2×10^{-11} planetary nebula $\mathrm{yr}^{-1}\ M\odot^{-1}$, not significantly different from the local rate of 10^{-11} $\mathrm{yr}^{-1}\ M\odot^{-1}$.

Data on young massive stars can be obtained by gathering information on supernovae. Estimates of the rate of explosion of supernovae in different parts of galaxies, including ours (Ilovaisky and Lequeux, 1972 a ; Tammann, 197 Mac Carthy, 1974) suggest only a moderate gradient of supernovae explosions per unit area of the Galaxy, which increase by a factor of 5 - 10 at most between the Sun and the region inner to 1 kpc (although the projected total mass density varies by a factor larger than 50). Another information comes from the existence within 1.1° ≈ 190 pc from the galactic center of 3 non-thermal radio sources which can be interpreted as supernovae remnants (Downes, 1974). Taking a mean life time of 10^{4} yr for these remnants, this corresponds to 5×10^{-14} SN yr^{-1} M$\odot^{-1}$, a rate 10 times smaller than in the solar neighborhood where it is about 4×10^{-13} SN yr^{-1} M$\odot^{-1}$ (Ilovaisky and Lequeux, 1972 a and b).

Thus the rate of formation (and death) of high-mass stars per unit total mass seems 10 times smaller at the galactic center then close to the Sun, while the rate of death of lower-mass stars, as monitored by the planetary nebulae, is similar : this confirms that the young stars are relatively scarce in the galactic center. Thus ^{14}N is likely to be presently produced mainly by low-mass stars, as first studied by Torres-Peimbert and Peimbert (1971).

However, the rate of star formation per unit mass of interstellar gas is quite higher at the galactic center than in the solar neighborhood : the rate of supernovae explosions per unit mass of gas is $\sim 10^{-10}$ yr^{-1} M$\odot^{-1}$ at the galactic center, against 4×10^{-12} yr^{-1} M$\odot^{-1}$ locally. This is the proof that the processing of gas through stars is more rapid at the galactic center, due to higher gas density or to other causes.

Table III summarizes the data contained in this appendix.

TABLE I

Observed isotopic ratios of C, N and O

Ratio	Interstellar medium				Solar system			
	ratio	location	method	authors	ratio	location	method	authors
$\frac{^{12}C\ ^{18}O}{^{13}C\ ^{16}O}$	0.080	14 clouds	CO	Wannier et al., 75	0.178	Earth		Wedepohl, 69
	0.10±.01	Sgr B2	H_2CO	Gardner et al., 71	0.20±.06	Sun	CO	Hall, 73
$^{12}C/^{13}C$	36±5	Sgr B2	HC_3N	Gardner et al., 75				
	36±8	Ori A	H_2CO 2mm	Wannier et al., 75	89±4	Earth		Wedepohl, 69
	≈ 50	Ori B	$^{13}C^{18}O$	Lucas, 75				
	≈ 37	Ori A	CS	Penzias et al.,72	89±2	Meteorites		Boato, 54
	22 - 45	Ori A	HCN	Wannier et al., 75	≈ 89	Moon		Epstein et al., 71
	> 20	Sgr B2	H_2CO	Fomalont et al., 73	90±15	Sun	CO	Hall et al., 72
	25±5	Sgr A	"	"	110±35	Jupiter	CH_4	Fox et al., 72
	> 30	"	"	Whiteoak et al., 74	≈ 100	Venus	CO	Connes et al., 68
					≈ 100	Mars	CO	Kaplan et al., 69
	12 - 82	Various clouds	H_2CO	Zuckermann et al.,74 Evans et al., 75	70 - 135	3 Comets	C_2	Danks et al., 74
	> 80	local cas	H_2CO	Whiteoak et al., 72				
	42^{+29}_{-8} (1)	ζ Oph	CH^+	Bortolot et al., 72				
	72^{+24}_{-15} (1)	ζ Oph	CH^+	Vanden Bout, 72				
	> 20 to > 77	6 stars	CH^+	Hobbs, 73				

$^{16}O/^{18}O$	≃ 390	Sgr A	OH	Wilson et al., 72	500±25	Earth		Wedepohl, 69
	> 300	Sgr A	OH	Gardner et al., 70	500±25	Meteorites		Taylor et al., 65
	> 200	Sgr B2	OH	"	490±25	Moon		Epstein et al., 71
					460±150(2)	Sun	CO_2	Hall, 73
					≃ 500	Venus	CO_2	Connes et al., 67
$^{17}O/^{18}O$	0.28±.08	Ori A	CO(2)	Encrenaz, 73	0.183	Earth		Wedepohl, 69
				Wannier et al., 75				
	0.25±.13	ρ Oph	CO(2)	Encrenaz, 73	0.11 – 0.33(2)	Sun	CO_2	Hall, 73
$\frac{^{12}C^{15}N}{^{13}C^{14}N}$	0.38±.12	Ori A	HCN	Wilson et al., 72	0.32	Earth		Wedepohl, 69
	0.28±.06	"	HCN	Wannier et al., 75				
	0.22	"	HCN	Clark et al., 74				

(1) Revised values, see text.

(2) Indirect measurement. What is actually measured is $^{12}C\,^{18}O/^{13}C\,^{16}O$ and $^{12}C\,^{17}O/^{12}C\,^{18}O$ (or $^{12}C\,^{17}O/^{13}C\,^{16}O$).

TABLE II

Stellar mass loss and CNO enrichment in the solar neighborhood

Isotope	Assumed chemical composition (10^{4} X/H by number)		Local rate of mass loss (10^{-13} $M_\odot$ yr^{-1} pc^{-2})			Mass loss needed for enriching the interstellar matter (10^{-13} $M_\odot$ yr^{-1} pc^{-2}) (12)
	Stellar envelopes	Novae (6)	Stars $1<M<5M_\odot$ (8)	Stars $M > 5$ $M_\odot$ (10)	Novae (11)	
^{12}C	3.7 (1)	-	(6 - 20)	>	-	-
^{13}C	0.2 - 0.5 (3)	50 - 90	0.3 - 3	≃	0.02 - 10	1
^{14}N	3 (2)	140 - 180	6 - 21	≃?	0.08 - 20	?
^{15}N	0	100 - 300	0	0	0.06 - 34	∿ 0.2 (13)
^{16}O	7.6 (1)	-	(17 - 60)	>	-	-
^{17}O	0.014 - 0.028 (4)	(20 - 70)? (7)	? (9)	? (9)	(0.01 - 9) ? (7)	?
^{18}O	? (5)	?	?	?	?	?

(1) Solar abundance (Withbroe, 1971)

(2) 2-3 times the solar abundance

(3) Average $^{12}C/^{13}C$ in stellar envelopes taken as ≈ 6 to 20 (Lambert and Dearborn, 1972 ; Geballe et al., 1972 ; Maillard, 1974 ; Lambert, 1974 ; Ridgway, 1974 ; Lambert and Tomkin, 1974).

(4) Maillard, 1974 ; Rank et al., 1974

(5) Discrepant results from Maillard (1974) in α Her and from Rank et al. (1974) in IRC + 10° 216

(6) Lower and upper limits in the various models of Starrfield et al., 1974

(7) Underestimated if one uses the new rate of the $^{17}O(p, \alpha)\ ^{14}N$ reaction

(8) From the composition of column 2 and the rates of mass loss given in the text

(9) Very uncertain ; in principle only massive stars can eject ^{17}O (Wollman, 1973) ; the two objects where ^{17}O has been observed are α Her and IRC + 10° 216 ; both seem to have $M \gtrsim 5 M_\odot$

(10) Quantitative statements are very difficult (see text) ; symbol refer to a qualitative comparison with the rates of mass loss by stars of lower mass, column 4

(11) From the composition of column 3 and the rates of mass loss given in the text

(12) Assuming that the mass of interstellar matter and C/H, O/H are constant ; see text for discussion of the small effect of changes in these quantities

(13) From $^{14}N/^{15}N$. The change in ^{14}N has been neglected (see text)

TABLE III

Compared properties of the galactic center (inside $\sim$ 200 pc) and the solar neighborhood. Supernovae explosions monitor the rate of formation and death of massive stars ($M \geq 5\ M_\odot$), planetary nebulae monitor the death rate of less massive stars ($1\ M_\odot < M \leq 5\ M_\odot$)

	Galactic center	Solar neighborhood
gas/star mass ratio	4×10^{-4}	10^{-1}
rate of supernovae explosions		
- per unit total mass	$5 \times 10^{-14}\ yr^{-1}\ M_\odot^{-1}$	$4 \times 10^{-13}\ yr^{-1}\ M_\odot^{-1}$
- per unit mass of gas	$10^{-10}\ yr^{-1}\ M_\odot^{-1}$	$4 \times 10^{-12}\ yr^{-1}\ M_\odot^{-1}$
rate of formation of planetary nebulae		
- per unit total mass	$2 \times 10^{-11}\ yr^{-1}\ M_\odot^{-1}$	$10^{-11}\ yr^{-1}\ M_\odot^{-1}$
- per unit gas mass	$5 \times 10^{-8}\ yr^{-1}\ M_\odot^{-1}$	$10^{-10}\ yr^{-1}\ M_\odot^{-1}$