Interstellar CNO Isotope Ratios

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Abstract

In an interpretation of interstellar, circumstellar, and solar system CNO isotope ratios, we find two scenarios which are free of internal inconsistencies. The first requires that the early solar system was enriched by material from massive stars, leading to enhanced $^{12}C/^{13}C$ and $^{18}O/^{17}O$ ratios and to a reduced $^{14}N/^{15}N$ ratio. The second involves infall of gas onto the galactic disk after the formation of the solar system. Both scenarios require that the bulk of the interstellar ^{16}O, ^{18}O, and ^{15}N originates from massive stars ($>8\,M_{\odot}$), with ^{18}O and perhaps ^{15}N being destroyed in lower mass stars. ^{17}O is mainly synthesized in stars of intermediate mass while ^{12}C, ^{13}C, and ^{14}N are produced in stars of high and intermediate masses.

With respect to nucleosynthesis, evolutionary models of massive stars applying the Ledoux criterion for convection and semiconvective mixing should be preferred. These yield high ^{18}O abundances above the convective He-burning core. For ^{17}O, theoretical yields and observational data are not consistent, since models predict too much ^{17}O from massive stars. The absence of an $^{18}O/^{17}O$ gradient in the galactic plane remains unexplained. Since ^{18}O and ^{17}O are products of quite different processes, this absence strongly constrains numerical models of the 'chemical' evolution of the Galaxy.

1. Introduction

Spectroscopy of stellar or interstellar gas in its atomic phase does not allow to discriminate between different isotopic species. If one has no direct access to the material (through cosmic rays or solar system samples), isotopic abundances can only be determined from spectroscopy of molecular isotopomers. This is why molecular spectroscopy is of fundamental importance to constrain stellar nucleosynthesis and the 'chemical' evolution of the Galaxy.

The isotopes of carbon, nitrogen, and oxygen are of particular interest, given their large abundances and the presence of seven stable nuclei, each of them being formed under specific physical conditions. Most known interstellar and circumstellar molecules contain at least one of these elements. $^{12}C/^{13}C$, $^{14}N/^{15}N$, $^{16}O/^{18}O$, and $^{18}O/^{17}O$ ratios are thus known not only for the solar system, but also for the galactic nuclear region and disk out to $R_{\rm GC} \sim 10$ kpc ($R_\odot$=8.5 kpc; see Table 1). Data from cosmic rays, extragalactic starburst nuclei, and interstellar dust grains have also been collected (e.g., Gibner et al. 1992; Amari et al. 1993; Henkel & Mauersberger 1993). While Table 1 displays the best presently available interstellar and solar system ratios, Fig. 1 illustrates the radial isotope gradients in the galactic disk.

2. Searching for internally consistent concepts

Over the last few decades, several approaches have been developed to interprete the data summarized in Table 1 and Fig. 1. These attempts are the following: (1) The solar system ratios are typical for the local interstellar medium $4.5\,10^9$ yrs ago; effects caused by radial inflow or infall of gas from outside the galactic plane can be neglected; (2) a large amount of radially inflowing gas or, equivalently, a substantial increase in the solar galactocentric distance has decoupled solar and interstellar isotope ratios; (3) ejecta from massive stars have enriched the presolar nebula, and (4) infall of gas onto the galactic disk has altered the ISM abundances after the formation of the solar system.

While a number of numerical studies exist, *a qualitative self-consistent picture is still missing.* The basic equations to describe the 'chemical' evolution, including infall and delayed mass return from evolving stars (see, e.g., Güsten & Mezger 1983), are

$$\frac{\mathrm{d}}{\mathrm{d}t}\,M_{\rm g} = A(t) - \Psi(t) + \int_{M_{\rm l}}^{M_{\rm u}} \Psi(t-\tau(m))\,\phi(m)\,b(m)\,\mathrm{d}m \qquad (1)$$

and

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}\,[Z_{\rm i}(t)M_{\rm g}(t)] \;&=\; Z_{\rm A,i}(t)\,A(t) - Z_{\rm i}(t)\Psi(t) + \\ &\int_{M_{\rm l}}^{M_{\rm u}} \Psi(t-\tau(m))\,\phi(m)\,b(m)\,\times \\ &[Z_{\rm i}(t-\tau(m)) + \Delta m(Z_{\rm i})]\,\mathrm{d}m. \qquad (2)\end{aligned}$$

$M_{\rm g}$ denotes the total gas mass. $A(t)$ is the time dependent infall rate, $\Psi(t)$ the star formation rate, $\phi(m)$ the initial mass function (IMF) normalized for the mass range $M_{\rm l}...M_{\rm u}$, $b(m)$ the mass returned back to the interstellar medium after a stellar lifetime $\tau(m)$, $Z_{\rm i}$ the total gas mass fraction of isotope i, and $Z_{\rm A,i}$ the corresponding fraction for the infalling gas. For a 'primary' nucleus i which is not a seed element for a 'secondary' isotope, the material returned to the ISM is enriched by $\int \delta_{\rm i}\,\mathrm{d}m = \int \Delta m(Z_{\rm i})\,b(m)\phi(m)\,\Psi(t-\tau(m))\,\mathrm{d}m$.

Table 1: Isotope ratios[a)]

Isotope ratio	Region	Observed ratios
$^{12}C/^{13}C$	Galactic disk	$(7.5\pm1.9)\,R_{GC} + (7.6\pm12.9)$
	Galactic center	25 ± 5
	Inner disk	40 ± 10
	Local ISM	70 ± 10
	Solar system	89
	Starburst nuclei	~50
$^{14}N/^{15}N$	Galactic disk	$(19.0\pm8.5)\,R_{GC} + (288.6\pm65.1)$
	Galactic center	900 ± 200
	Inner disk	375 ± 60
	Local ISM	450 ± 60
	Solar system	270
	Starburst nuclei	–
$^{16}O/^{18}O$	Galactic disk	$(58.8\pm11.8)\,R_{GC} + (37.1\pm82.6)$
	Galactic center	250 ± 30
	Inner disk	300 ± 30
	Local ISM	540 ± 30
	Solar system	490
	Starburst nuclei	$\sim150-200$
$^{16}O/^{17}O$	Galactic disk	$(206\pm41)\,R_{CG} + (130\pm289)$
	Galactic center	900 ± 150
	Inner Disk	1050 ± 200
	Local ISM	1900 ± 200
	Solar system	2700
	Starburst nuclei	>1200
$^{18}O/^{17}O$	Galactic disk	~3.5, no gradient
	Galactic center	3.5 ± 0.2
	Inner disk	3.6 ± 0.3
	Local ISM	3.6 ± 0.3
	Solar system	5.5
	Starburst nuclei	≥8

a) The data are taken from Wilson & Matteucci (1992), Henkel & Mauersberger (1993), and Wilson & Rood (1994); for the $^{16}O/^{17}O$ ratios, the non-solar $^{16}O/^{18}O$ values were multiplied by 3.5. Errors for the solar system ratios are negligible when compared with those for the interstellar medium (ISM). R_{GC} is the galactocentric distance in kpc. In those cases where there is a gradient, the inner disk values refer to R_{GC}=4.5 kpc, the local ISM values to R_{GC}=8.5 kpc.

Figure 1: $^{12}C/^{13}C$ (upper panel), $^{14}N/^{15}N$ (middle panel), and $^{16}O/^{18}O$ (lower panel) disk gradients as a function of radial distance from the galactic center (R_{GC}=8.5 kpc). The figure was taken from Wilson & Rood (1994).

For a secondary isotope, this quantity becomes $\int \delta_{\rm i}\, Z_{\rm j}(t-\tau(m))\,{\rm d}m$, with j being the seed nucleus.

Qualitatively, these equations allow us to differentiate between 'primary', 'secondary', and 'tertiary' nuclei, depending on the number of stellar generations required to synthesize a given nucleus. High mass stars need little time to eject their processed material into the ISM, while lower mass stars need more time. Depending on the number of stellar generations and on the mass and lifetime of the stars involved, the timescale of 'chemical' enrichment differs from nucleus to nucleus. This leads to characteristic nuclear abundance ratios which vary as a function of time and metallicity. To give an example: ^{13}C is a product of incomplete CNO burning and requires pre-existing ^{12}C. Thus ^{12}C/^{13}C isotope ratios tend to decrease with time and metallicity. Such considerations based on models of stellar evolution and a comparison with measured ratios provides fundamental insights into the progress of 'chemical' evolution in the galactic plane. Since stellar yields are highly uncertain, we will limit ourselves to the basic qualitative concepts, leaving numerical aspects to future articles.

2.1 The standard appraoch

In most studies, the solar CNO abundances were assumed to be representative for the local ISM $4.5\,10^9$ yrs ago (cf. Wilson & Rood 1994). While this is qualitatively consistent with the carbon isotope ratios, the nitrogen and oxygen ratios remain unexplained. The following problems arise:

(1) ^{14}N is in part a primary and in part a secondary product (e.g. Pagel 1985; Sneden 1985; Diaz & Tosi 1986; Matteucci 1986a,b). The relative amounts synthesized in stars with high ($>8\,{\rm M}_\odot$) and intermediate ($1-8\,{\rm M}_\odot$) masses are not well known. ^{15}N is believed to be produced in novae and perhaps also in Type II supernovae (e.g. Matteucci & d'Antona 1991). It is partially destroyed in stars of intermediate mass (for ^{14}N/^{15}N ratios in the circumstellar shells of late type stars, see e.g. Wannier et al. 1991). Since the local ISM value is larger than the solar system ratio, we can assume that interstellar ^{14}N/^{15}N ratios increase with time and metallicity, indicating that ^{14}N must be more secondary than ^{15}N. This is consistent with the galactic center ^{14}N/^{15}N ratio which is larger than the solar and galactic disk values. This difference is then explained as a consequence of more extensive nuclear processing in the central region of the Galaxy. However, the ^{14}N/^{15}N ratio systematically decreases with decreasing galactocentric radius along the galactic plane toward the inner disk. This is opposite to the expected behavior. An alternative view, taking a decreasing ^{14}N/^{15}N ratio with increasing degree of nuclear processing (cf. Matteucci & d'Antona 1991) leads to two major inconsistencies: First, the local interstellar ratio exceeds the solar value, in contradiction with this assumption of slowly decreasing interstellar ^{14}N/^{15}N ratios. Second, the large ^{14}N/^{15}N ratio in a highly processed region like the galactic center is also not compatible with our assumption.

(2) When analysing oxygen, similar problems arise. ^{16}O is a primary product of nucleosynthesis, mainly synthesized via $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ by He-burning in massive stars. If ^{18}O (synthesized by He-burning from ^{14}N) and ^{17}O (produced by H-burning) are secondary, the galactic disk $^{16}\mathrm{O}/^{17}\mathrm{O}$ and $^{18}\mathrm{O}/^{17}\mathrm{O}$ gradients are readily explained. Also, the galactic center ratios fit well into this scheme. There are, however, two basic problems: The solar system $^{18}\mathrm{O}/^{17}\mathrm{O}$ ratio is 5.5, significantly larger than the local interstellar value, $\sim$3.5 (Table 1). Explaining this by defining ^{18}O as a secondary and ^{17}O as a tertiary nucleus is in conflict with the absence of an $^{18}\mathrm{O}/^{17}\mathrm{O}$ gradient as a function of galactocentric radius. In addition, the $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratio of the local ISM is slightly larger than the solar value. This is in contradiction with the $^{16}\mathrm{O}/^{18}\mathrm{O}$ gradient, which requires decreasing $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios in time.

In summary, *the assumption of 'normal' solar isotope ratios*, excluding radial inflow or infall of gas onto the galactic plane, *fails to explain the nitrogen and oxygen data.*

2.2 Radial inflow

There are several mechanisms which may lead to a loss of orbital angular momentum in the gas phase, driving a radial inflow. Such a process (neglecting infall) may be caused by the viscosity of the gas layer, a gravitational interaction between the gas and a bar or by scattering of stellar objects in the gravitational field of giant molecular clouds (e.g. Mayor & Vigroux 1981; Lacey & Fall 1985; Russell & Dopita 1992). With a negative galactic disk O/H gradient (i.e. decreasing O/H with increasing galactocentric radius) and a solar oxygen abundance eventually surpassing local interstellar values (see Sect. 3.1.5) this appears to be an attractive scenario: the oxygen-rich gas out of which the solar system formed would now be located well inside the solar circle, while fresh oxygen-poor interstellar gas from outside the solar circle has reached the solar neighborhood. A less likely scenario, involving a gradual increase of the solar galactocentric distance, leads to an equivalent effect.

If the ISM or the solar system have been substantially affected by such radial motions, the galactic disk gradients imply that the interstellar $^{12}\mathrm{C}/^{13}\mathrm{C}$, $^{14}\mathrm{N}/^{15}\mathrm{N}$, and $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios of the local ISM should be larger than the solar values. For $^{12}\mathrm{C}/^{13}\mathrm{C}$, the contrary is observed. While the interstellar $^{16}\mathrm{O}/^{18}\mathrm{O}$ ratios may be consistent with this model, the $^{18}\mathrm{O}/^{17}\mathrm{O}$ ratios are also not explained: the interstellar ratio, 3.5, is independent of galactic radius, metallicity, and degree of nuclear processing and is inconsistent with the solar system ratio of 5.5.

We conclude that *radial motions cannot be the main cause for the differences between solar system and interstellar CNO isotope ratios.*

2.3 Peculiar solar system CNO isotope ratios

The problems with the standard approach and radial flows as well as the possibility that the solar system O/H abundance may be almost twice as large as that of the local ISM (see Sect. 3.1.5) provide motivation to relax the assumption of 'normal' solar isotope ratios. In order to avoid too many unknown parameters, we must estimate what anomalies are to be expected. A high oxygen abundance implies a significant enrichment by material from massive stars. Thus the assumption of a presolar nebula enriched not only in ^{16}O but also in other massive star constituents is a good first approximation.

Following Henkel & Mauersberger (1993), the interstellar CNO isotope ratios can be interpreted as follows: For the ^{12}C/^{13}C gradient, ^{13}C is synthesized from ^{12}C. ^{12}C may be more efficiently produced in high mass stars than ^{13}C (e.g. Weaver & Woosley 1993). A part of the solar ^{12}C/^{13}C enhancement over the local interstellar value may thus not be due to the fact that there has been ongoing ^{13}C enrichment of the ISM in the $4.5\,10^9$ years since the formation of the solar system, but may have been caused by an enrichment of the presolar nebula by massive stars. For first attempts to unravel the relative efficiencies of these effects, see Audouze (1985) and Henkel & Mauersberger (1993; their Sect. 6.4).

As mentioned in Sect. 2.1, ^{15}N is synthesized in novae and destroyed in late type stars of intermediate mass. Adding a significant primary contribution (cf. Audouze 1985; Güsten & Ungerechts 1985), the nitrogen ratios can also be explained: Compared to the ISM, the smaller solar system ratio is due to the peculiar environment of the protosolar nebula. If the initial mass function (IMF) shifts toward massive stars at smaller galactic radii and the equilibrium between ^{15}N destruction and production shifts more in favor of production, then the gradient with smallest ^{14}N/^{15}N ratios in the inner galactic disk can be reproduced. The large galactic center value indicates a lack of massive stars, consistent with the observations.

If ^{18}O is mainly produced by massive stars (cf. Audouze 1985) as a secondary or tertiary product from ^{14}N (which is itself primary or secondary; see Sect. 2.1) and if ^{17}O arises from stars of intermediate mass (e.g., Kahane et al. 1992), the peculiar solar system ^{16}O/^{18}O, ^{16}O/^{17}O, and ^{18}O/^{17}O ratios are immediately understood. Since ejecta from massive stars contribute extra amounts of ^{16}O and ^{18}O to the presolar nebula, the solar system ^{16}O/^{17}O and ^{18}O/^{17}O ratios are significantly enhanced, while ^{16}O/^{18}O remains close to the interstellar value. The ^{16}O/^{18}O and ^{16}O/^{17}O gradients can be understood in terms of the primary and non-primary nature of the nuclei. However, the almost constant ^{18}O/^{17}O ratio must be addressed separately. Here secondary and tertiary products from massive stars, being partially destroyed by lower mass stars, are compared with secondary products mainly synthesized by stars of intermediate mass. The apparently constant interstellar ^{18}O/^{17}O ratio over the entire galactic plane is remarkable and cannot be explained by the model.

Overall, *the assumption of peculiar solar system CNO ratios is consistent with the data.*

2.4 Infall scenarios

As an alternative to presolar nebula enrichment, it is also possible that the nucleosynthesis products in the ISM have been diluted by infalling gas from the halo or a captured dwarf galaxy with little ^{12}C, ^{15}N, ^{16}O, and ^{18}O (cf. de Freitas Pacheco 1993).

If the halo experienced massive star formation only very early in its history, it may contain a large fraction of gas processed in stars of intermediate mass. It is thus justified to assume that its isotopic properties are characterized by small ^{12}C/^{13}C, ^{18}O/^{17}O, and large ^{14}N/^{15}N ratios. These are the properties of the local ISM when compared with the solar system isotope ratios. With a total ISM of $\sim 5\,10^9$ M$_\odot$ and a star formation rate of a few M$_\odot$ yr^{-1}, the gas consumption time of the present ISM is only $1-2\,10^9$ yrs. While infall rates are not well known (e.g. Bregman 1980; Mirabel & Morras 1984), a gradual change in the composition of the local ISM due to halo gas is thus possible within a timescale of several 10^9 yrs. This implies that *a change of interstellar abundances caused by infall of gas onto the galactic plane is consistent with the data.* As before, the lack of an ^{18}O/^{17}O gradient as a function of galactocentric radius remains unexplained.

2.5 Starbursts in the nuclei of other galaxies

Starbursts are well known for their large numbers of massive luminous stars. A comparison of galactic isotope data with results from extragalactic starburst nuclei thus allows us to discriminate between nuclei synthesized in massive and less massive stars. Here we confine ourselves to oxygen.

Sage et al. (1991) and Henkel et al. (1994) find ^{18}O/^{17}O$\geq$8 in the nuclear starbursts of NGC 253, M 82, and NGC 4945. These results are based on three completely independent data sets. For the 'sub-burst' nucleus IC 342, Sage et al. (1991) tentatively reported ^{18}O/^{17}O$\geq$5.5. This was confirmed ($\sim$6.5) by later measurements (Sage, priv. comm.). These ratios might imply that also in the Galaxy, 10 billion years ago when the disk was forming, massive star and ^{18}O formation was high, yielding large ^{18}O/^{17}O ratios ($\gg$5.5). Later, almost five billion years ago and now, the ratios dropped to 5.5 and 3.5, respectively. There are, however, two problems: (1) ^{18}O is a product of He-burning from ^{14}N. Since ^{14}N must have had a low abundance at early epochs (e.g. Wheeler et al. 1989), ^{18}O should only become abundant in stars with metallicities similar to or higher than those of the local ISM. (2) If ^{18}O/^{17}O decreases with time, we should observe a galactic gradient with smallest values in the inner disk or near the galactic center, where 'chemical' processing is most advanced. (cf. Sect. 2.1). This is incompatible with the data (see Table 1). Assuming instead a peculiar solar system ^{18}O abundance from the ejecta of massive stars or from infall of ^{18}O-poor gas into the local ISM after the formation of the solar system, the data can be better explained. In the starbursts, the ISM is enriched by ejecta from massive stars, yielding high $^{18}O/^{17}O$ ratios. The $^{16}O/^{18}O$ ratios appear to be low (see Table 1 and Henkel et al. 1993, 1994), thus favoring *highly* enhanced ^{18}O production. This is consistent with a large ^{14}N abundance at the onset of the starburst. The $^{16}O/^{17}O$ limit for starbursts (see Table 1) requires ratios surpassing the galactic center ratio and supports ^{16}O synthesis in massive and ^{17}O production in less massive stars.

2.6 Two possible concepts

Testing several concepts of galactic chemical evolution, we find only two which are consistent with the measured CNO isotope ratios. These infer that either the solar system was substantially enriched by ejecta from massive stars at the time of its formation or that infall of large amounts of gas onto the galactic plane has later altered the composition of the ISM. Both scenarios do not explain the absence of an interstellar $^{18}O/^{17}O$ gradient in the galactic plane.

3. Discussion

In the following, we discuss observational and theoretical aspects which are crucial for a critical evaluation of the two successful scenarios. These include measured abundance inhomogeneities in the ISM, the influence of dust grains on gas phase abundances, the solar 'oxygen anomaly', isotope ratios from cosmic rays, and new results from models of massive stellar evolution.

3.1 Observational aspects

3.1.1 Abundance inhomogeneities in the ISM

The assumption of peculiar solar system abundances requires that small pockets of interstellar gas can be enriched by stellar ejecta of high metallicity. Whether this is a realistic approach can best be studied in a low metallicity environment, where the abundance contrast between normal and contaminated material becomes most pronounced.

O and N abundances in giant HII regions of metal poor dwarf irregular galaxies were modeled by Pilyugin (1992, 1993), who finds that a substantial fraction of the HII regions must be 'self-enriched' due to winds of the ionizing stars and supernovae. A more direct confirmation for this situation has been obtained by Rosa & Mathis (1985) for the LMC: Within 30 Dor, there is a region of only a few pc in size which exhibits a normal nitrogen abundance but shows overabundances in O, Ne, S, Cl, and Ar by a factor of $\sim$5. All these elements with enhanced abundances are believed to be synthesized by massive stars. In the Galaxy abundance contrasts tend to be smaller, but more accurate observational data can be obtained. Studying oxygen abundances in the Orion OB association, Cunha & Lambert (1992) find that the younger sub-associations have higher average O/H ratios. ¿From these examples it is clear that observational evidence favors the concept of metal enrichment within a limited volume of gas.

3.1.2 The role of the dust

Are there specific isotopes preferentially incorporated into dust grains, thus altering gas phase abundances in a way that true interstellar ratios cannot be determined? The influence of dust grains on oxygen abundances appears to be small when comparing results from HII regions and young stars. However, CNO isotope ratios are determined in dense cool molecular clouds where conditions might be different.

Dust grains arising from the winds of late type stars (e.g. Woitke et al. 1993) should be ^{13}C and ^{17}O-rich and ^{15}N and ^{18}O-poor (see, e.g., Kahane et al. 1988). If these stars are the main contributors to dust grain masses, we expect gas phase ^{13}C and ^{17}O abundances to be depleted and ^{15}N and ^{18}O abundances to be enhanced relative to the main species. Comparing interstellar with solar system ^{12}C/^{13}C, ^{14}N/^{15}N, and ^{16}O/^{18}O ratios, we find, however, the opposite behavior. Dust grains may also form out of the metal enriched ejecta of supernovae (e.g. Seab 1987) and may accrete dust grain mantles in dark clouds (Seab 1987; but see also Chokshi et al. 1993). If such grains are astrated in dense molecular clumps and if sticking probabilities do not strongly depend on isotopic substitution (see Williams 1993 for the case of deuterium), their CNO isotope ratios would be similar to that of the ambient gas. This is consistent with the lack of a significant difference between ^{12}C/^{13}C ratios from the dense molecular gas ($H_2^{12}CO/H_2^{13}CO$) and the diffuse ISM ($^{12}CH^+/^{13}CH^+$). Another argument in favor of gas phase data providing reliable abundance estimates for the entire ISM is related to data from 'processed' meteoritic inclusions. The observed variations in oxygen abundances (e.g. Clayton 1993) appear to be decoupled from those of other elements and can be interpreted in terms of a two-phase model, with a protosolar ^{16}O-enriched dust component and a ^{16}O- depleted gas component (^{18}O/^{17}O ratios are almost the same). In this case differences between oxygen abundances of the gas and dust components are only a few percent, well below the sensitivity limits of present interstellar data.

The analysis of small 'unprocessed' interstellar graphite, diamond, and silicon carbide dust grains is also possible (e.g., Amari et al. 1992, 1993; Hoppe et al. 1992; Ott 1993). Deviations from 'normal' isotope ratios can be quite large. Notable are the rare 'grains X' from SiC particles of the Murchison CM2 chondrite with isotopically very light carbon (^{12}C/^{13}C up to $\sim$2000) and very heavy nitrogen (^{14}N/^{15}N down to $\sim$10). Most interesting within this context are the graphite particles (Hoppe et al. 1992): About 25% of the analysed grains have large ^{18}O excesses. In the most extreme case,

$^{16}O/^{18}O$ is reduced to $\sim$50. Even more interesting, the grains with reduced $^{16}O/^{18}O$ ratios have also anomalously low $^{14}N/^{15}N$ and high $^{12}C/^{13}C$ ratios, thus yielding a good agreement with the peculiarities postulated in Sect. 2.3 for massive star ejecta. For the grains with $^{16}O/^{18}O\sim50$, it is found that $^{12}C/^{13}C=722$ and $^{14}N/^{15}N=134$. According to Hoppe et al. (1992), these grains contain material which must have been ejected from Wolf-Rayet stars.

3.1.3 Meteoritic inclusions and cosmic rays

In Sect. 3.1.2, we used already oxygen data from 'processed' meteoritic inclusions in primitive meteorites. Here we only add that contamination of the protosolar material by short-lived radioactive nuclei (e.g. ^{26}Al, ^{107}Pd, and ^{129}I with half lives of $\sim 10^6 - 10^7$ yrs) is commonly explained by explosions of nearby supernovae or by accretion of stellar wind material from giant stars of intermediate mass (e.g. Cameron 1988). Clayton et al. (1988) favor a supernova scenario to explain ^{48}Ca, ^{49}Ti, ^{50}Ti, ^{54}Cr, and ^{64}Ni anomalies.

Cosmic rays may arise from massive stars. Hence it is interesting to compare their isotope ratios with those in starbursts. To date, only a $^{16}O/^{18}O$ ratio has been determined from cosmic rays: $^{16}O/^{18}O\sim100$ (Gibner et al. 1992). This result is close to that obtained from starbursts (Table 1). The solar system ratio (490) is much larger. This and the relatively small solar system $^{18}O/^{17}O$ value when compared with that from starbursts (5.5 versus $\geq$8) indicates that the solar material is diluted if it was enriched by material from massive stars. With solar system $^{16}O/^{17}O\sim2700$ and $^{16}O/^{18}O\sim100$ from cosmic rays (i.e. high mass stars) we then find that $^{18}O/^{17}O\geq30$ should be typical for massive star ejecta (see also Sects. 3.1.2 and 3.2).

3.1.3 The 'oxygen anomaly'

As already mentioned in Sects. 2.2 and 2.3, the solar system oxygen abundance *might* be almost twice as large as that of the local ISM. This potential difference is fundamental for any realistic description of galactic 'chemical' evolution and thus requires a more detailed discussion. There are an impressive number of independent studies which favor a lower oxygen abundance in the ISM and young stellar objects. These are based on indirect evidence from radio recombination lines from HII regions (Shaver et al. 1983; Wink et al. 1983), more direct OI absorption from the diffuse ISM (de Boer 1981; York et al. 1983), early B stars, intermediate mass F-K supergiants, young planetary nebulae, and perhaps young F dwarfs (Luck & Lambert 1985; Peimbert 1987; Dufton et al. 1990; Fitzsimmons et al. 1990; Baldwin et al. 1991; Cunha & Lambert 1992; Gies & Lambert 1992; de Freitas Pacheco 1993; López et al. 1993). Sub-solar oxygen abundances are most thoroughly studied in Orion, where the influence of dust grains affecting the gas phase oxygen abundances is known to be small (e.g. Peimbert 1987; Gies & Cunha 1992). The difference between oxygen abundances from the solar photosphere, the local ISM, and young stellar objects in the solar neighborhood thus seems to be well established. However, metal rich ([Fe/H]> -0.3) F and G dwarfs not belonging to young open clusters have O/H ratios within 0.05 dex of the solar value (e.g. Nissen & Edvardsson 1992; Edvardsson et al. 1993). Compared to most local F and G dwarfs, the solar oxygen abundance thus appears to be normal.

The discrepancy between oxygen abundances from F and G dwarfs and 'chemically' younger interstellar and stellar sources can be reconciled with the infall scenario introduced in Sect. 2.4 (cf. de Freitas Pacheco 1993). An increase in the number of Type I relative to Type II supernovae (also suggested by de Freitas Pacheco 1993) cannot account for this effect: Type Ia supernovae are rare (e.g., Evans et al. 1989; van den Bergh 1990) and do not appear to destroy oxygen (e.g., Nomoto et al. 1984), while massive stars ending their life as Type Ib supernovae should synthesize large amounts of oxygen. A more exotic explanation of the oxygen data is the assumption that the photospheric O/H values of nearby F and G stars (including the sun) are not representative for the bulk of their mass. Following Peimbert (1987), deviations may be caused by two processes: (a) the solar surface might be enriched by capture of planetesimals or cometary material and (b) the solar surface oxygen may be enhanced by an oxygen poor solar wind.

The accretion of cometary material would increase oxygen and decrease helium abundances. This agrees with the photospheric anomalies as observed by Peimbert (1987). Note, however, that Baldwin et al. (1991) favor a high solar helium abundance. If the latter result is correct, the cometary accretion scenario has to be rejected.

The heavy element compositions of the solar corona and the solar wind differ from photospheric values according to their first ionization potential (FIP). H, C, N, and O all belong to the group of elements with 'high' ($>$11 eV) FIP, implying that CNO abundances relative to hydrogen are almost normal (e.g. Meyer 1985; McKenzie & Feldman 1992). This does not favor evolutionary modifications of CNO abundances in the solar photosphere due to the solar wind (since Si belongs to the elements with 'low' first ionization potential, the peculiar O/Si ratios discussed by Luck & Lambert (1985) are not relevant here). Since Fe has, unlike O, a low first ionization potential, its abundance may be enhanced in the solar wind (cf. Meyer 1985). If the wind can significantly alter photospheric abundances, one can expect that differences in the wind properties from star to star will introduce significant variations in [Fe/O]. However, [Fe/O] ratios in nearby F and G dwarfs vary by only ± 0.04 dex for [Fe/H]> -0.3 (Nissen & Edvardsson 1992).

To summarize: Alternative views exist, but it is likely that the solar oxygen abundance (and that of other F and G dwarfs) does not require significant systematic corrections.

3.2 Theoretical aspects

The three oxygen isotopes ^{16}O, ^{18}O, and ^{17}O are produced in quite different environments and provide a sensitive measure of stellar mass and stellar convection. As noted by Henkel & Mauersberger (1993), models of massive stars using the Schwarzschild criterion for convection, with or without overshooting (e.g. Maeder 1985; Schaller et al. 1992), do not provide ^{18}O enrichment of the ISM by massive stars; instead, enrichment by ^{17}O tends to be favored. In contrast, massive star models computed with the Ledoux criterion for convection and semiconvective mixing, including the effect of 'molecular' weight gradients on convection, allow for a significant production of ^{18}O.

Weaver & Woosley (1993) calculated the evolution of a variety of massive star models, varying the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate, the stellar mass, and the efficiency of semiconvective mixing. Deriving the integrated yields, there appears an interesting pattern for those intermediate mass isotopes (^{16}O...^{40}Ca) which are expected to be produced in massive stars. For a specific range of ^{12}C$(\alpha,\gamma)^{16}$O rates, the 'production factors' (see Weaver & Woosley 1993 for a definition) are $\sim$10. With $\sim$10% of the material cycled through a massive star, solar abundances for almost all these nuclei are thus reproduced. The exception is ^{18}O: The models with a fast semiconvective mixing rate do not show any peculiar behavior. However, the models with strongly reduced semiconvection predict an ^{18}O overproduction by roughly an order of magnitude, almost independent of the ^{12}C$(\alpha,\gamma)^{16}$O rate. Production factors $\sim$50 as predicted in these models could lead to a much higher ^{18}O abundance than what is typical for the ISM. Note, however, that ^{18}O is produced from ^{14}N which was underabundant relative to ^{16}O when metallicities were low. Also, much of the ^{18}O may be destroyed in late type stars of intermediate mass, where commonlly ^{16}O/^{18}O$\gg$500 (e.g., Kahane et al. 1992). While the grid of parameters in the Weaver & Woosley (1993) models may be somewhat coarse, the results obtained with a low efficiency of semiconvection fit nicely into our concept of ^{18}O production in massive stars.

Models of Wolf-Rayet stars including the effect of 'molecular' weight gradients on convection (Langer 1991; Woosley et al. 1993) predict the presence of an ^{18}O-rich transition layer between the He-burning core and the outer mantle. This leads to temporary surface abundance ratios of order ^{16}O/^{18}O$\sim$10, while ^{18}O/^{17}O$\sim$200, which is consistent with the cosmic ray and graphite data (see also Biermann & Cassinelli 1993).

Such a good agreement between theory and observations cannot be obtained for ^{17}O. The Weaver & Woosley (1993) ^{16}O production factors tend to be slightly smaller than those for ^{17}O. However, starburst ^{16}O/^{17}O ratios are larger than the corresponding value for the galactic center region (see Table 1). Furthermore, ^{17}O is known to be strongly enhanced in evolved stars of intermediate mass (e.g. Kahane et al. 1992). Finally, the solar system ^{16}O/^{17}O ratio is larger than the local ISM value. Since the observational data are clear, in this case it is the theory of stellar nucleosynthesis which has to be modified in order to account for the observational results. Within this context it is to be mentioned that the CNO-equilibrium abundance of ^{17}O is strongly affected by the highly uncertain nuclear reaction rates of ^{17}O(p,α)^{14}N and ^{17}O(p,γ)^{18}F (cf. Landré et al. 1990).

Almost independent of stellar mass, ^{12}C(α,γ)^{16}O rate, and the treatment of convection, about half of the ^{15}N is found to be destroyed in the ejecta of massive stars prior to the iron core collapse (Weaver & Woosley 1993). For explosive nuclear processing during the supernova event, Weaver & Woosley obtain ^{15}N enhancements by factors of 2$-$6. This is not sufficient to compensate for the ^{15}N losses in the outer shell prior to the supernova. Note, however, that calculations of explosive nucleosynthesis may give larger uncertainties. Even for hydrostatic burning, which should be easier to handle, computed massive stellar ^{17}O yields appeared to be too large to be consistent with the observations.

3.3 Summary

As we have seen, there is compelling evidence for small interstellar regions with peculiar abundances. Dust grains appear not to distort gas phase CNO isotope ratios. There is theoretical evidence for enhanced ^{18}O production in massive stars. Graphite grains have been found which show all the CNO isotope anomalies required for the idea of peculiar solar abundances (Sect. 2.3). While all this is consistent with the view that the presolar nebula has been enriched by ejecta from massive stars, stellar and interstellar oxygen data seem to favor the alternative scenario: a variation of ISM abundances due to infall of gas from outside the galactic plane. To discriminate between both concepts, it is thus mandatory to study the 'oxygen anomaly' in even greater detail and to establish the isotopic composition of the solar wind.

4. Improving the molecular database

4.1 Extragalactic sources

The amount and precision of the extragalactic CNO isotope data does not match those from the galactic ISM and the solar system. However, extragalactic data are of high importance, because they allow to discriminate between products of massive and less massive stars. We have some approximate estimates for the ^{12}C/^{13}C ratios from two galactic nuclei, the molecular 'goldmines' NGC 253 and NGC 4945 (Henkel et al. 1993, 1994). Two or three more nearby ($D \leq 5$ Mpc) sources are still within reach of the most sensitive cm- and mm-wave instruments. For ^{12}C/^{13}C studies of nearby galaxies, perhaps the most important molecular species is CN. ^{12}CN emission is relatively strong and almost always optically thin (thus providing a linear correlation between abundance and line intensity). The hyperfine structure of the rotational lines allows a direct estimate of the main isotope's opacity. However,

$^{12}C/^{13}C$ ratios from CN have never been determined for the central region of the Galaxy. While fractionation or selective photoionization may not be significant, an observational test is clearly required before taking extragalactic CN based $^{12}C/^{13}C$ ratios seriously.

A very important experiment could be made with nitrogen. If $^{14}N/^{15}N$ disk gradients are a common phenomenon in spirals (elemental abundance gradients in spirals appear to be similar to those observed in the galactic disk; e.g. Shields 1990) and if starbursts are triggered by infall of disk gas toward the nuclear regions (due to bars; e.g. Henkel et al. 1991), the pre-burst $^{14}N/^{15}N$ ratio should be of order 350−400 (the inner galactic disk value; see Table 1). If ^{15}N is synthesized in significant quantities by massive stars, the $^{14}N/^{15}N$ ratio should thus become <350. With a J=1−0 HCN line opacity of order 2.5 (Henkel et al. 1993) and $^{14}N/^{15}N \sim 100$, the HCN/HC^{15}N intensity ratio is ~40 and HC^{15}N should be detectable.

The determination of $^{16}O/^{18}O$ and $^{16}O/^{17}O$ ratios from extragalactic systems will remain very difficult in the foreseeible future. However, there is a chance to further confirm that $^{18}O/^{17}O$ ratios are substantially enhanced in starbursts: If ratios of 3−4 are found in quiescent extragalactic nuclear regions, this would provide the needed evidence.

4.2 The Galactic ISM

Interstellar $^{12}C/^{13}C$ ratios from the galactic disk and center are approximately known. Radio data from at least two molecular species, C^{18}O and H_2CO, are available which appear to bracket the actual ratios (e.g. Langer et al. 1984; Wilson & Rood 1994). Perhaps most urgent are good optical CH^+ data from the local ISM, since $^{12}CH^+/^{13}CH^+$ abundance ratios are believed to be free of fractionation effects. There appears to be a convergence to ratios ~70 (e.g. Stahl et al. 1989; Stahl & Wilson 1992), but recent results by Vladilo et al. (1993) underline the need for more and better spectroscopic data.

Most $^{14}N/^{15}N$ measurements have been collected from HCN. Including more results from other molecules (NH_3, HNC or CN) would be desirable, although the few $^{14}N/^{15}N$ ratios obtained from NH_3 seem to be consistent with those from HCN (Wilson & Rood 1994)

Almost all $^{16}O/^{18}O$ and $^{18}O/^{17}O$ ratios are based on only H_2CO and CO, respectively. Only toward the galactic center sources Sgr A and Sgr B2, $^{16}O/^{18}O$ was also estimated from OH (e.g. Whiteoak & Gardner 1981). For Sgr B2, $^{18}O/^{17}O$ was also obtained from HCO^+ (Guélin et al. 1982). These ratios are consistent with those derived from H_2CO and CO. While this is encouraging and while fractionation is not expected to affect the results (e.g., Langer et al. 1984), more data from OH, HCO^+, and other species are needed.

5. Conclusions

The determination of CNO isotope gradients as a function of galactocentric radius (e.g. Wilson et al. 1976; Gardner & Whiteoak 1979; Henkel et al. 1982; Tosi 1982) has deeply altered our view of chemical processing and evolution in the Galaxy. The recently obtained data from extragalactic starbursts have triggered a similarly fundamental change of perspective: Somehow, *the solar system CNO ratios must have decoupled from those of the ISM.*

The two concepts which can explain the measured data in a self-consistent way are related: They associate a specific CNO isotope with the same stellar cooking site. Even without the use of a numerical code, many features of these models are clear. The following points are of particular interest:

(1) To explain the measured $^{16}O/^{18}O$ and $^{18}O/^{17}O$ ratios, massive star models computed with the Ledoux criterion for convection and semiconvective mixing should be preferred. Low efficiencies of semiconvection seem to provide the best agreement with observational data. Consistent with these models, evidence from cosmic rays and interstellar graphite grains indicates that $^{18}O/^{17}O$ should temporarily reach values $\geq$30 in the ejecta of massive stars.

(2) Measured $^{16}O/^{17}O$ and $^{18}O/^{17}O$ ratios indicate that ^{17}O abundances are inconsistent with the values predicted from models of stellar evolution. The calculated ^{17}O yields from massive stars are too large.

(3) A significant part of the ^{15}N nuclei must arise from massive stars.

(4) The lack of a $^{18}O/^{17}O$ gradient in the galactic plane is not explained by any model. ^{18}O appears to be a secondary and tertiary product from massive stars. Some ^{18}O must be destroyed in stars of intermediate mass. ^{17}O is predominantly a secondary product from stars of intermediate mass. The lack of a gradient will thus provide an important input for the fine-tuning of numerical models simulating the 'chemical' evolution of the Galaxy.

Acknowledgements. N. Langer acknowledges partial support through DFG grant La 587/8–1; Y.-N. Chin was supported by the DAAD.

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