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The evolution of the C, N, and O isotope ratios from an improved comparison of the interstellar medium with the Sun

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Abstract. We present an improved comparison of the C, N, and O isotope ratios between the Sun and the interstellar medium, in which the birth-place of the Sun is taken into account. Such a comparison gives empirical information about the time evolution of the isotope ratios in the interstellar medium over the last $4.5 \cdot 10^9$ years. Wielen et al. (1996) have found that the Sun was born at a galactocentric distance $R_{i,\odot}$ which is 1.9 kpc (± 0.9 kpc) smaller than the present galactocentric distance R_0 of the Sun. Therefore, we use the values of the present-day isotope ratios of the interstellar medium at this galactocentric distance $R_{i,\odot}$, instead of the conventional approach using local values at R_0 for the comparison with the solar system. For three isotope ratios, the improved comparison produces results which are in better agreement with theoretical predictions than the results of a conventional comparison. The most important improvement is found for ^{16}O/^{18}O: This isotope ratio is found to decrease with time if the birth-place of the Sun is taken into account. The better agreement of the evolution in time of isotope ratios derived from our improved comparison with the theoretical expectations provides supporting evidence that the birth-place of the Sun is closer to the galactic center than R_0, as found by Wielen et al.

Key words: interstellar medium: abundances – Sun : abundances – Galaxy: abundances – Galaxy: evolution

1. Introduction

Studies of isotope ratios in stars and in the interstellar medium give important clues on the production of heavier elements in stars. The elements C, N, and O are especially important, since they are the most abundant ones besides the primordial elements H and He and since the measurements of their isotope ratios are most accurate.

Elements and their isotopes can be divided into ‘primary’ products and ‘secondary’ ones: (1) The production of primary isotopes does not require the presence of other elements besides the primordial ones. (2) Genuine secondary isotopes are produced only in the presence of elements formed in an earlier phase of stellar nucleosynthesis. In some cases, however, those primary isotopes which are mainly formed in long-living stars of lower mass, are also called secondary products, since their abundances increase with time in a similar fashion as for genuine secondary isotopes.

The ratio between two primary isotopes should be rather constant in time. In contrast, the ratio between a primary isotope and a secondary one should decrease with time, due to the increasing production rate of the secondary isotopes from the presence of an increasing amount of primary products. Hence the change in time of isotope ratios gives important empirical information on whether or not the production of some isotopes is of primary or secondary nature. Such empirical results can then be confronted with theoretical predictions on the sources and on the formation processes of the elements and their isotopes.

For some recent reviews on element production and isotope ratios we refer to Trimble 1991, 1996, Wheeler and Sneden 1989, Wilson and Matteucci 1992, and Wilson and Rood 1994, and to the literature cited in these reviews.

2. Basic procedure

Empirically the change in time of an isotope ratio can be obtained by comparing the isotope ratio of the Sun or of the solar system with the same isotope ratio of the interstellar medium. The solar value represents the composition of the interstellar medium at the time of birth of the Sun, about $4.5 \cdot 10^9$ years ago. By comparing this ‘ancient’ value with the present isotope ratio of the interstellar medium, the change of the isotope ratio of the interstellar medium over the last 4.5 billion years is obtained.

Until now, the *local* interstellar medium has been used for such a comparison with the Sun (We refer to this as the ‘conventional’ comparison). It was implicitly assumed that the Sun had been formed at the same galactocentric distance R_0 which the Sun has today.

In a recent paper, Wielen, Fuchs, and Dettbarn (1996) have found that the birth-place of the Sun was in the inner part of our Galaxy. From the solar anomaly in metallicity of $(\Delta[\mathrm{Fe/H}])_\odot = +0.17$ dex with respect to the mean metallicity of nearby stars

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of solar age, and from a galactic gradient in [Fe/H] of –0.09 dex/kpc, they found that the Sun was formed at a galactocentric distance $R_{i,\odot}$ = R_0 – 1.9 kpc. Such a migration of the Sun in galactocentric distance of about 2 kpc in net during 4.5 billion years is in good agreement with the predictions of the theory of the diffusion of stellar orbits (Wielen 1977) and with the observed increase of the dispersion in stellar metallicities with age (Wielen et al. 1996).

If the Sun was actually formed at $R_{i,\odot}$ = R_0 – 1.9 kpc, then the isotope ratio of the Sun should not be compared with the local interstellar medium (R = R_0), but with the present interstellar medium at the place of birth of the Sun at R = $R_{i,\odot}$ = R_0 – 1.9 kpc ('improved' comparison). Since the isotope ratios show often significant galactic gradients, this correction can be important for obtaining the time evolution of the isotope ratios.

In our procedure we assume that the interstellar medium at any given galactocentric distance R is well-mixed with respect to the metallicities and isotope ratios, i.e. that spatial fluctuations in isotope ratios are small, except for a smooth galactic gradient in R. In this case, the solar-system isotope ratios of C, N, and O are not expected to show any 'anomalies', e.g. due to a supernova explosion near to the birth-place of the Sun, shortly before or after formation. An argument in favor of a well-mixed interstellar medium is the small dispersion in the metallicities of stars of zero age, about ± 0.06 dex or less in [Fe/H], derived by Wielen et al. (1996).

We neglect here the problem of radial streaming motions of the interstellar medium, which are discussed by some authors (e.g. Mayor and Vigroux 1981, Lacey and Fall 1985, Köppen 1994) and which would represent an additional complication.

The improved comparison of the isotope ratios of the Sun and the interstellar medium is one of the many possible applications of the birth-place of the Sun found by Wielen et al. (1996).

3. An improved comparison of isotope ratios of C, N, and O

Here, we study in detail the following isotope ratios r_{iso}: ^{12}C/^{13}C, ^{14}N/^{15}N, ^{16}O/^{18}O, and ^{18}O/^{17}O. The values of these isotope ratios for the solar system, $r_{iso,\odot}$, are taken from Anders and Grevesse (1989). The mean errors of these solar isotope ratios are negligibly small with respect to those of the interstellar medium.

For the isotope ratios $r_{iso,ISM}(R_0)$ of the local interstellar medium, we have used the values given by Wilson and Rood (1994). The isotope ratio of the present interstellar medium *at the birth-place of the Sun*, i.e. at $R = R_{i,\odot}$, can be derived from the *local* value by

$$r_{iso,ISM}(R_{i,\odot}) = r_{iso,ISM}(R_0) + \alpha_{iso}(R_{i,\odot} - R_0) \ , \quad (1)$$

where

$$\alpha_{iso} = dr_{iso,ISM}(R)/dR \quad (2)$$

is the galactic gradient of the isotope ratio $r_{iso,ISM}$. For $R_{i,\odot} - R_0$, we use the value derived by Wielen et al. (1996):

$$\Delta R_{i,\odot} = R_{i,\odot} - R_0 = -1.9\,\mathrm{kpc} \pm 0.9\,\mathrm{kpc} \ . \quad (3)$$

The required galactic gradients α_{iso} for ^{12}C/^{13}C and ^{14}N/^{15}N are taken from Dahmen, Wilson, and Matteucci (1995), after being multipied by a factor of 8.2/8.5 to reduce their values of α_{iso} to R_0 = 8.5 kpc. For the gradient of ^{16}O/^{18}O we used the results of Wilson and Rood (1994). The isotope ratio ^{18}O/^{17}O is treated here for completeness also. Its galactic gradient is negligible,

$$\alpha_{iso}(^{18}\mathrm{O}/^{17}\mathrm{O}) = 0.0 \pm 0.1\,\mathrm{kpc}^{-1} \ , \quad (4)$$

from the CO survey of Penzias (1981).

The mean errors of $r_{iso,ISM}(R_{i,\odot})$ are calculated from the mean errors of $r_{iso,ISM}(R_0)$, of α_{iso}, and of $\Delta R_{i,\odot}$ by assuming that the local value of $r_{iso,ISM}(R_0)$ and α_{iso} are independent. This assumption is not strictly true, since α_{iso} and $r_{iso,ISM}(R_0)$ are obtained from a linear fit of data which are spread typically over an interval of R between 3 kpc and 10 kpc, and hence are asymmetrical with respect to R_0 = 8.5 kpc. A visual inspection of the corresponding diagrams (e.g. Fig. 1), however, essentially confirms that the mean errors of $r_{iso,ISM}(R_{i,\odot})$ are correctly given by our simplified procedure.

4. Results

The results of our improved comparison of isotope ratios of C, N, and O are presented in Table 1 and Fig. 1. The basic sources of the data are quoted in Sect. 3.

For illustration, Table 1 and Fig. 1 show both the results of a conventional comparison in which the Sun is compared to the local interstellar medium, and our new results which take the birth-place of the Sun into account.

The change in time of an isotope ratio is indicated in Table 1 by the difference

$$\Delta r_{iso} = r_{iso,ISM}(R) - r_{iso,\odot} \ , \quad (5)$$

by which Δr_{iso} has changed over the last 4.5 billion years, with $R = R_0$ (conventional comparison) or $R = R_{i,\odot}$ (improved comparison).

4.1. Carbon isotope ratio ^{12}C/^{13}C

The improved comparison indicates a stronger evolution in time of ^{12}C/^{13}C than the conventional comparison. This more rapid evolution is in better agreement with the theoretical predictions (e.g. Wilson and Matteucci 1992, Prantzos et al. 1996), according to which ^{12}C is a primary isotope, while ^{13}C is, at least partially, a secondary isotope.

4.2. Nitrogen isotope ratio ^{14}N/^{15}N

The improved comparison gives a slightly smaller increase of ^{14}N/^{15}N in time than the conventional comparison, but the increase by 53% ± 12% is still significant. The nitrogen isotopes are mainly secondary products, although some primary production may contribute. The interpretation of the change in time and of the galactic gradient of N^{14}/N^{15} is difficult (see e.g. Wilson and Matteucci 1992, Dahmen et al. 1995).

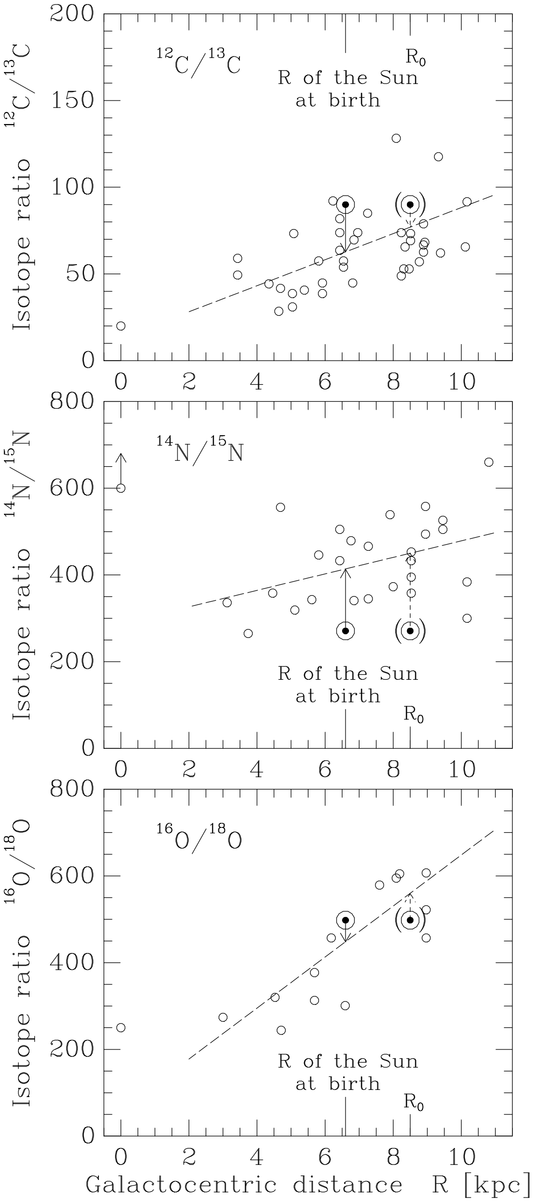

Fig. 1a–c. The isotope ratios **a** ^{12}C/^{13}C, **b** ^{14}N/^{15}N, and **c** ^{16}O/^{18}O of the interstellar medium (open circles) as a function of the galactocentric distance R. The data points and the linear fits are adapted from Wilson and Rood (1994) and Dahmen, Wilson, and Matteucci (1995); see Sect. 3. The time evolution of the isotope ratios is shown by a comparison with the solar system value, indicated by $\odot$. In the conventional comparison, the Sun is compared with the local interstellar medium at R_0 = 8.5 kpc. In the improved comparison, we compare the solar value of the isotope ratio with that of the interstellar medium at the birth-place of the Sun at $R_{i,\odot}$ = 6.6 kpc.

Table 1. Comparison of isotope ratios r_{iso} of C, N, O of the interstellar medium (ISM) and of the Sun

Isotope ratio	^{12}C/^{13}C	^{14}N/^{15}N	^{16}O/^{18}O	^{18}O/^{17}O
Conventional comparison using the local interstellar medium:				
Local ISM: $r_{iso,ISM}(R_0)$	77	450	560	3.2
	±7	±22	±25	±0.2
Solar system: $r_{iso,\odot}$	90	271	498	5.3
$\Delta r_{iso} = r_{iso,ISM}(R_0) - r_{iso,\odot}$	–13	+179	+62	–2.1
(Local ISM minus $\odot$)	±7	±22	±25	±0.2
Time evolution: $\Delta r_{iso}/r_{iso,\odot}$	–14%	+66%	+12%	–40%
	±8%	±8%	±5%	±4%
Improved comparison taking the birth-place of the Sun into account:				
Local ISM: $r_{iso,ISM}(R_0)$	77	450	560	3.2
	±7	±22	±25	±0.2
Galactic gradient: α_{iso} [kpc^{-1}]	+7.52	+19.0	+58.8	0.0
	±1.13	±8.6	±11.8	±0.1
$\alpha_{iso}(R_{i,\odot} - R_0)$	–14	–36	–112	0
ISM: $r_{iso,ISM}(R_{i,\odot})$	63	414	448	3.2
at $R_{i,\odot} = R_0 - 1.9$ kpc				
Solar system: $r_{iso,\odot}$	90	271	498	5.3
$\Delta r_{iso} = r_{iso,ISM}(R_{i,\odot}) - r_{iso,\odot}$	–27	+143	–50	–2.1
(ISM at $R_{i,\odot}$ minus $\odot$)	±10	±32	±62	±0.3
Time evolution: $\Delta r_{iso}/r_{iso,\odot}$	–30%	+53%	–10%	–40%
	±11%	±12%	±12%	±6%
Error budget of the improved comparison:				
Mean error of Δr_{iso}				
due to the error of $(R_{i,\odot} - R_0)$	±7	±17	±53	±0.0
due to the error of α_{iso}	±2	±16	±22	±0.2
due to the error of $r_{iso,ISM}(R_0)$	±7	±22	±25	±0.2
Total mean error of Δr_{iso}	±10	±32	±62	±0.3
Total mean error of $\Delta r_{iso}/r_{iso,\odot}$	±11%	±12%	±12%	±6%

4.3. Oxygen isotope ratios ^{16}O/^{18}O

The most significant change between the improved comparison and the conventional one occurs for ^{16}O/^{18}O: While the conventional comparison gave a rather significant *increase* with time of ^{16}O/^{18}O by +12% ± 5%, the improved comparison shows now a small *decrease* in time of ^{16}O/^{18}O by –10% ± 12%. Since ^{16}O/^{18}O is typical for a ratio of primary/secondary products, which is expected to decrease in time, the result of the improved comparison is in better agreement with the theoretical expectation than that of the conventional comparison. Formerly, rather special explanations have been proposed for the apparent increase of ^{16}O/^{18}O (e.g. Reeves 1978, Schramm 1978, Olive and Schramm 1982, Tosi 1982, Henkel and Mauersberger 1993). Prantzos et al. (1996) have recently discussed the problem of ^{16}O/^{18}O in great detail. A large part of the puzzle of ^{16}O/^{18}O is now solved by the improved comparison, which indicates a decrease in time, or at least a constant value, of ^{16}O/^{18}O. It still remains true, however, that most theories predict a stronger decrease in time of ^{16}O/^{18}O than it is observed even in the improved comparison.

The run of the isotope ratio ^{16}O/^{18}O as a function of the galactocentric distance R is illustrated in Fig. 1c. The difference between the conventional comparison at R_0 and the improved comparison at the birth-place of the Sun, $R_{i,\odot}$, especially the change in the sign of the time evolution of ^{16}O/^{18}O, is obvious. If we would not adopt the linear fit provided by Wilson and Rood (1994), but would use for the comparison the data points close to $R_{i,\odot}$ only, then the time evolution of ^{16}O/^{18}O would be even stronger, perhaps twice as large as given in Table 1.

4.4. Oxygen isotope ratios ^{18}O/^{17}O *and* ^{16}O/^{17}O

Since there is no significant galactic gradient α_{iso} of ^{18}O/^{17}O, the birth-place of the Sun has no direct influence on the comparison with the interstellar medium. However, the mean error of $r_{iso,ISM}(R_{i,\odot})$ may be somewhat larger than that of the local interstellar medium. In Table 1, we have included the uncertainty of α_{iso} in the determination of the mean error of $r_{iso,ISM}(R_{i,\odot})$. The effect is small, however. Both ^{18}O and ^{17}O are expected to be secondary products. The observed strong decrease in time of ^{18}O/^{17}O is difficult to explain theoretically (e.g. Wilson and Matteucci 1992, Wilson and Rood 1994, Prantzos et al. 1996).

The time evolution of ^{16}O/^{17}O follows directly from that of ^{16}O/^{18}O and ^{18}O/^{17}O. We obtain for $\Delta r_{iso}/r_{iso,\odot}$ of ^{16}O/^{17}O –32%±5% in the conventional comparison and –45%±10% in the improved comparison. The negative sign is qualitatively in accordance with theoretical expectations. The quantitative agreement between the observed time evolution of ^{16}O/^{17}O and the prediction of a specific model, obtained by Prantzos et al. (1996) in an conventional comparison, is also maintained, within the statistical uncertainties, in the improved comparison.

5. Conclusions

We have improved the empirical determination of the change in time of the isotope ratios of C, N, and O from a comparison of the solar system with the interstellar medium by taking the birth-place of the Sun into account. The empirical results on the change in time of the isotope ratios agree in general better with theoretical expectations if we use the data of the interstellar medium at a smaller galactocentric distance, $R_{i,\odot} = R_0 - 1.9$ kpc, where the Sun has been formed according to Wielen et al. (1996), rather than the data of the local interstellar medium. The most remarkable result is that the improved comparison leads to a *decrease* in time of the isotope ratio ^{16}O/^{18}O. Such a behavior is theoretically expected for an isotope ratio of primary/secondary products of element synthesis, such as ^{16}O and ^{18}O. The conventional comparison of the Sun with the local interstellar medium indicated an *increase* in time of ^{16}O/^{18}O, in contradiction to theoretical expectations.

The fact that the comparison of the Sun with the interstellar medium at $R_{i,\odot} = R_0 - 1.9$ kpc gives more plausible results than with the local interstellar medium, is also an additional argument in favor of the birth-place of the Sun proposed by Wielen et al. (1996).

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