A New Astrophysical Interpretation of the Si and Ti Isotopic Compositions of Mainstream SiC Grains from Primitive Meteorites

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Abstract. Mainstream presolar SiC grains from primitive meteorites show a clear s-process signature in the isotopic composition of heavy trace elements. These grains most likely condensed in the winds of a variety of AGB stars. However, the non-solar and correlated Si and Ti isotopic compositions measured in these grains are inconsistent with a pure s-signature. We present a possible solution to this much-discussed problem by assuming a spread in the original composition of parent AGB stars due to small chemical inhomogeneities in the interstellar medium at the time of their birth. These inhomogeneities may naturally arise from variations in the contributions of each nuclide to the interstellar medium by the relevant stellar nucleosynthetic sites, SNII and different subtypes of SNIa.

1 AGB envelope prediction for Si and Ti

Predictions from the AGB models discussed in [3, 9] for the Si isotopic compositions in the envelope of AGB stars of solar metallicity and different initial mass are shown in Fig. 1. They result from a mixture of s-processed material from the He shell and the envelope as a consequence of recurrent third dredge-ups [3], and are given for six different choices of the amount of $^{13}$C in the He intershell (case ST refers to Fig. 1 of reference [3]). Open symbols are for envelopes with C/O > 1, the condition for SiC condensation. Whereas predictions from the same models match the measured compositions of heavy trace elements in bulk SiC grains (Kr, Sr, Xe, Ba, Nd and Sm) [4], and in single SiC grains (Zr and Mo) [5], they cannot account for the Si and Ti isotopic compositions of mainstream SiC grains [6, 7]. As for Si, the measured isotopic ratios show a much larger spread than AGB envelope predictions. Indeed, the s-process occurring in the He shell of AGB stars only slightly affects the Si isotopic abundance (as well as most other light neutron poisons), owing to their low neutron capture cross sections. The resulting composition in the dredged-up material essentially depends on the marginal activation of the $^{22}$Ne neutron source during thermal pulses.

Analogous considerations hold for the Ti isotopic composition: $\delta(^{46,47}{\text{Ti}}/^{48}{\text{Ti}})$ values of individual SiC grains range from -50 to +150 and from -50 to +70, respectively [6], whereas AGB envelope predictions cover a much smaller range, of up to +50 and +10. Note that $\delta(^{46,47}{\text{Ti}}/^{48}{\text{Ti}})$ are linearly correlated with $\delta(^{29,30}{\text{Si}}/^{28}{\text{Si}})$ [6]. In contrast, the neutron-rich isotopes $^{49,50}$Ti are more easily produced by neutron capture. Their $\delta$-values measured in SiC reach +150 and +300 [6], in agreement with
Figure 1: s-process model predictions for $\delta^{30}\text{Si}/^{28}\text{Si}$ and $\delta^{30}\text{Si}/^{28}\text{Si}$ in the envelope of AGB stars of solar metallicity and different initial mass, for six different choices of the amount of $^{13}\text{C}$ supplied in the He intershell. The $\delta$-values are permil deviations from the solar ratio: e.g. $\delta^{30}\text{Si}/^{28}\text{Si} = \left(\frac{^{30}\text{Si}}{^{28}\text{Si}} / \left(\frac{^{30}\text{Si}}{^{28}\text{Si}}\right)_{\odot} - 1\right) \times 1000$. Open symbols are for C/O > 1 in the envelope. Note that the SiC mainstream isotopic compositions cover a much larger range [from (-50,-100) to (+150,+250) permil in the Si three isotope plot, see Fig. 2] than the predicted values, and the correlation line has a slope of $\sim 1.34$.

2 Galactic local inhomogeneities of Si and Ti

A current interpretation of silicon isotopic ratios in SiC relates them to the Galactic chemical evolution (GCE), taking into account that the nucleosynthesis of $^{29,30}\text{Si}$ is of secondary nature, while $^{28}\text{Si}$ is a primary isotope [1]. In this view the mainstream correlation line reflects the evolution of silicon isotopes with metallicity and leads to the conclusion that the majority of presolar SiC grains should have been originated in the outflows of AGB stars with higher than solar metallicity. To overcome this contradiction, the hypothesis of a general diffusion of stars from their birthplace towards higher galactocentric distances has been advanced [1].

Without discarding the GCE interpretation, we propose that the interstellar medium (ISM) is affected by small local heterogeneities and that this assumption may help to reach a better understanding of the Si and Ti isotopic compositions observed in the
According to Woosley et al. [15], three major stellar sources in the Galaxy contribute in different ways to the Si isotopes: (i) Supernovae of Type II (SNII) [13], (ii) Supernovae of Type Ia according to the standard model [10] and (iii) Supernovae of Type Ia originating from sub-Chandrasekhar white dwarfs accreting He from a binary companion [12]. As a test exercise, we started from an ISM of solar composition and then perturbed it with small (positive and negative) contributions by each of these three stellar sources. In this way, the mainstream SiC grain parent stars, born in different molecular clouds, are expected to show a spread of initial compositions, reflecting local heterogeneity in the ISM. We calculated the resulting perturbed mass fractions in the ISM as $X^i = X^i_0 + \sum_{j=1}^3 a_j M^j_i$, where $M^j_i$ is the ejected mass (in solar masses) of isotope $i$ by the stellar source $j$, and $a_j$ represents the level of contribution from each source. A plausible range for the $a_j$ parameters has been assumed, from $-0.0004 M_{\odot}^{-1}$ to $+0.0004 M_{\odot}^{-1}$.

The resulting $\delta$-values are shown in Fig. 2 as open symbols and are compared with
the δ-values measured in single SiC grains (filled circles); the latter have errors (not shown in the figure) ranging from 10 to 50 permil [6, 7]. The mainstream correlation line is also shown in Fig. 2. Since the heavy elements, in particular Fe, are produced in the sources involved, the parent star metallicities will be perturbed too: we obtain metallicities ranging from 0.013 to 0.023. This is roughly in accord with the variation by a factor of two in [Fe/H] for stars of the same age observed by Edvardsson et al. [2].

Work is in progress in order to apply a similar model to the Ti isotopic composition of SiC grains. A preliminary solution has already been obtained by including, beside the three major stellar sources mentioned above, the rare type of SNIa described in [14] and [8], i.e., a massive white dwarf approaching the Chandrasekhar mass and exploding while accreting mass in a binary system, which is likely to contribute almost all galactic 50Ti. Moreover, it has to be noted here that a complete astrophysical interpretation of Si and Ti anomalies in SiC grains from AGB stars must include also the small subpopulations of SiC grains (up to a few percent of the total), such as SiC-Y and SiC-Z, which show isotopic compositions different from those of the mainstream grains.

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References
[1] Clayton, D. D. 1997, ApJ, 484, L67
[2] Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
[3] Gallino, R., Arlandini, C., Busso, M., Lugano, M., Travaglio, C., Straniero, O., Chieffi, A., & Limongi, M., 1998, ApJ, 497, 388
[4] Gallino, R., Busso, M., & Lugano, M. 1997, inAstrophysical Implications of the Laboratory Study of Presolar Materials, ed. T. Bernatowicz & E. Zinner, (New York: AIP), 115
[5] Gallino, R., Lugano, M., Arlandini, C., Busso, M., & Straniero, O. 1998, Meteoritics & Planetary Science, 33, A54
[6] Hoppe, P., Amari, S., Zinner, E., Ireland, T., & Lewis, R. S. 1994, ApJ, 430, 870
[7] Hoppe, P., Strebel, R., Pungitore, B., Amari, S., and Lewis, R.S., 1996 Geochim. Cosmochim. Acta, 60, 883
[8] Meyer, B.S., Krishnan, T.D., & Clayton, D.D., 1998 ApJ, 462, L462
[9] Straniero, O., Chieffi, A., Limongi, M., Busso, M., Gallino, R., & Arlandini, C. 1997, ApJ, 478, 332
[10] Thielemann, F.-K., Nomoto, K., & Yokoi, Y. 1986, A&A, 158, 17
[11] Timmes, F. X., & Clayton, D. D. 1990, ApJ, 472, 723
[12] Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371
[13] Woosley, S. E., & Weaver, T. A. 1995, ApJS, 101, 181
[14] Woosley, S. E. 1997, ApJ, 476, 801
[15] Woosley, S. E., Hoffman, R. D., Timmes, F. X., Weaver, T. A., & Thielemann, F.-K. 1997, Nucl. Phys. A, 621, 445c