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Si and C Isotopes in Presolar Silicon Carbide Grains From AGB Stars

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We compare the Si and C isotopic data of presolar SiC grains with predictions of AGB star models computed with a wide range of input parameters. The models confirm an AGB star origin for SiC grains of type mainstream, Y and Z. Cool bottom processing during the AGB phase is required to explain simultaneously the Si and C data for Z grains. The Z grain data together with the new models indicate that the interstellar $^{29}\text{Si}/^{28}\text{Si}$ ratio was high at low metallicity, relative to models of Galactic Chemical Evolution.

1. Introduction

Primitive meteorites contain preserved mineral grains which formed in the winds of dying stars and supernova explosions before the Sun formed 4.6 Gyr ago [1]. These presolar grains are identified as such by extreme variations in isotopic ratios, compared to anything of solar system origin. The best-studied presolar grain type is SiC and it is now well established that more than 90% of the presolar SiC grains originated in C-rich asymptotic giant branch (AGB) stars [1–3]. Many isotope ratios measured in the grains, e.g., C, N, Mg, Mo, Zr, Ba, and Ru, are mostly affected by internal nuclear burning processes and mixing in the parent stars. However, the Si isotopic ratios of the grains are believed to reflect both variations in initial compositions of the parent stars and dredge-up of s-processed Si into the AGB atmospheres. We are revisiting the issue of Si isotopes in AGB stars for a number of reasons: (1) Previous models spanned a relatively narrow range of parameter space. (2) Recent studies have greatly increased the amount of high precision SiC Si isotope data, especially for the rare Y and Z grains [4–7]. (3) New measurements of the Si isotope neutron capture cross-sections indicate that these have changed significantly from those used in previous AGB nucleosynthesis models [8]. Here, we present results of a large grid of AGB nucleosynthesis calculations and compare the results with the observational data for presolar SiC grains

2. SiC From AGB Stars

More than 7,000 individual presolar SiC grains ($\lesssim 2 \mu\text{m}$) from meteorites have been isotopically analyzed and assigned to one of several isotopic groups. Three SiC groups have been associated with an AGB star origin (Fig. 1): **Mainstream grains** make up $\sim 90\%$ of all SiC. These have $^{12}\text{C}/^{13}\text{C}$ ratios ranging from ~ 15 –100, $^{14}\text{N}/^{15}\text{N}$ ratios generally $>$ solar, ^{26}Mg excesses from ^{26}Al decay, and s -process isotope signatures of many trace elements (*e.g.*, Ba, Mo, Zr, Ru). It is well-established that these formed in low-mass, \sim solar metallicity AGB stars. However, their $^{29}\text{Si}/^{28}\text{Si}$ and $^{30}\text{Si}/^{28}\text{Si}$ ratios are aligned on a 3-isotope plot with a steeper slope than expected for mixing (third dredge-up) in AGB stars; these data are believed to reflect both Galactic Chemical Evolution and AGB mixing. **Y Grains** make up ~ 1 –2% of SiC grains. They have $^{12}\text{C}/^{13}\text{C} > 100$, N and Al-Mg isotopes similar to mainstream grains, and Si isotope compositions slightly more ^{30}Si rich than mainstream grains. They have been suggested to have formed in $\sim Z_{\odot}/2$ AGB stars of mass 1.5 – $5M_{\odot}$. **Z Grains** also make up ~ 1 –2% of SiC grains. They have $^{12}\text{C}/^{13}\text{C} = 4$ –100, N and Al-Mg isotopes similar to mainstream grains, and ^{29}Si depletions and ^{30}Si enrichments relative to mainstream and Y grains. They have been suggested to have formed in low-mass stars of even lower metallicity than the Y-grain parent stars.

3. Nucleosynthesis Calculations

Using a post-processing code [9], we have computed the evolution of Si and C isotopic ratios and C/O ratios in the envelopes of AGB stars. A total of 184 models were computed, encompassing stars with a range of mass (1.5 , 2 , 3 , and 5) $\times M_{\odot}$ and metallicity ($1, 1/2, 1/3$ and $1/6$) $\times Z_{\odot}$, as well as five different values of the Reimers mass-loss parameter η (ranging from 0.1 – 10 for different stellar masses) and two sets of nuclear cross sections [8,10]. Models were also computed for a range of ^{13}C pocket sizes, a free parameter which determines the amount of neutrons available via the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction. For AGB models of $< 3M_{\odot}$, stellar structural parameters were obtained from analytical formulae [11] derived from a set of stellar models previously evolved using the FRANEC code [12]. The $5M_{\odot}$ parameters were derived directly from FRANEC results. Initial Si isotopic ratios for stars of sub-solar metallicity were adjusted by increasing the ^{28}Si abundance for a given $[\text{Fe}/\text{H}]$ value based on observations of low-metallicity disk stars [13]. $^{12}\text{C}/^{13}\text{C}$ ratios at the start of the AGB phase were assumed to be 12 for the 1.5 and $2M_{\odot}$ stars and 24 for the higher-mass stars. The former assumes that some cool bottom processing (CBP) occurred prior to the AGB phase [14].

4. Results and Discussion

Fig. 1 overlays representative model results on Si and C isotope data for a large number of mainstream, Y and Z SiC grains. Some key characteristics of the models are: (1) The effect of 3rd dredge-up (shifts in Si isotopes, increased $^{12}\text{C}/^{13}\text{C}$) is larger for larger stellar masses and lower metallicities. (2) The cross sections of [8] yield lower slopes (*i.e.*, more ^{30}Si and less ^{29}Si) on the Si 3-isotope plot than those of [10]. (3) For a given mass and Z , increasing the mass-loss parameter η decreases the amount of 3rd dredge-up. (4) For a given mass, Z value, and η value, increasing the ^{13}C pocket increases the effect of

3rd dredge-up. Note that in all cases, the calculated $^{12}\text{C}/^{13}\text{C}$ ratio changes dramatically before any shift in the Si isotopic ratios is observed.

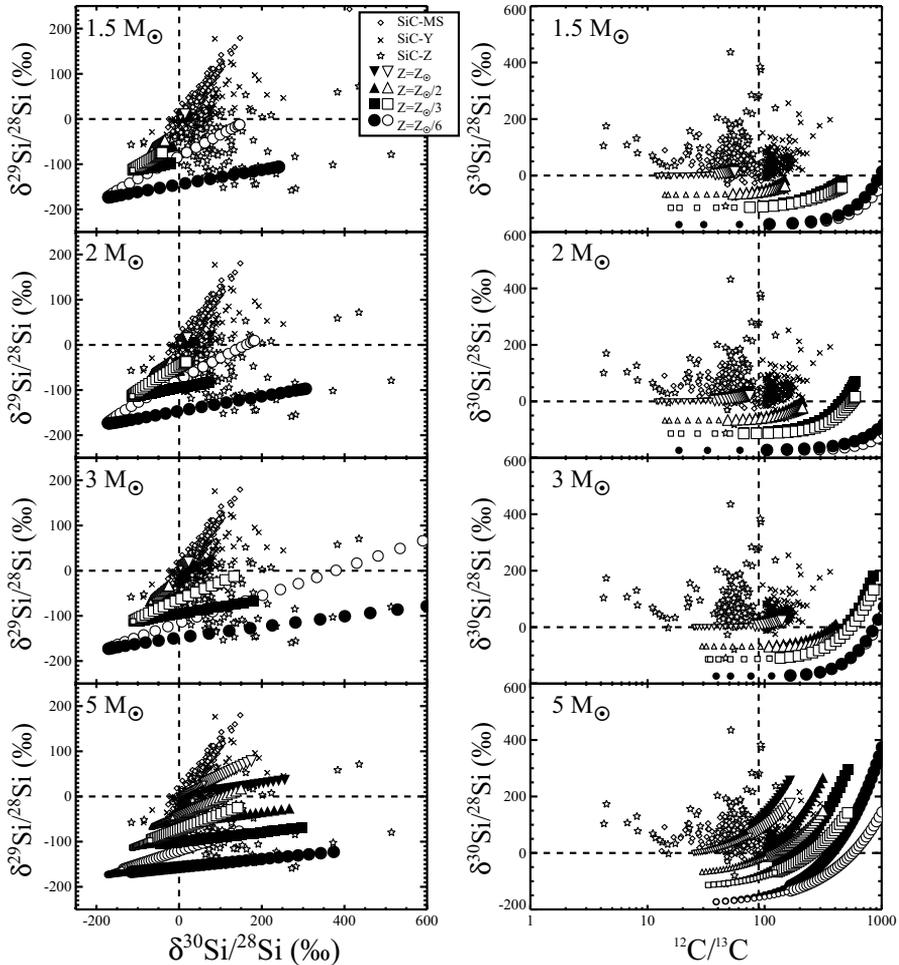


Figure 1. Si and C isotopic ratios in presolar SiC grains and predicted for AGB star envelopes by representative models. Si-isotope ratios are expressed as δ -values, permil deviations from a terrestrial isotope standard: $\delta R = [R_{\text{meas}}/R_{\text{standard}} - 1] \times 10^3$. Dashed lines indicate Solar ratios. Open model symbols represent calculations using cross-sections of [8]; filled symbols represent results using [10]. Small model symbols represent AGB envelopes with $\text{C} < \text{O}$; SiC will only form when $\text{C} > \text{O}$ (larger symbols). Data are from [3–7,15]

Detailed examination of the new models indicates that the Y grain data agree best with models of 3–5 M_{\odot} stars of $Z \sim Z_{\odot}/3$ – $Z_{\odot}/2$ [4]. However, no model comes close to reproducing the Si and C isotope data for Z grains: although low- Z AGB models have large shifts in $^{30}\text{Si}/^{28}\text{Si}$, they invariably have much higher $^{12}\text{C}/^{13}\text{C}$ ratios than are observed in the grains. This previously-recognized problem [15,5] most likely indicates that CBP occurred during the AGB phase of the parent stars. The few Z grains with $^{12}\text{C}/^{13}\text{C} < 10$ might indicate an origin in intermediate-mass AGB stars undergoing hot-bottom burning, but such stars are expected to have $\text{C} < \text{O}$. More likely, these grains formed in novae, like a few other grains [16,7].

Models of Galactic Chemical Evolution (GCE) indicate that $^{29,30}\text{Si}/^{28}\text{Si}$ ratios increase with increasing metallicity in the Galaxy [17]. Previous work has indicated that low metallicity stars have higher $^{29}\text{Si}/^{28}\text{Si}$ ratios than predicted by GCE theory [4]. Our new models allow us to address this issue somewhat more quantitatively. Assuming that all of the Z grains originated in 2 M_{\odot} stars and considering predicted shifts in $^{30}\text{Si}/^{28}\text{Si}$ with metallicity, we find a much earlier rise in $^{29}\text{Si}/^{28}\text{Si}$ with metallicity than predicted by GCE models, such that stars with $\sim 0.25Z_{\odot}$ have $\sim 80\%$ of solar $^{29}\text{Si}/^{28}\text{Si}$. Although this specific result is model-dependent, we have not yet identified any model parameters which would result in a GCE trend close to that of [17], perhaps indicating a low-metallicity nucleosynthetic source of ^{29}Si not accounted for by GCE models.

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