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Lawrence E. Brown
*Clemson University*

Donald D. Clayton
*Clemson University*, claydonald@gmail.com

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# SiC PARTICLES FROM ASYMPTOTIC GIANT BRANCH STARS: Mg BURNING AND THE *s*-PROCESS

LAWRENCE E. BROWN AND DONALD D. CLAYTON
Department of Physics and Astronomy, Clemson University, Clemson, SC 29634-1911
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## ABSTRACT

We address whether isotopically anomalous SiC particles found in meteorites originate in AGB stars. We show that if the peak helium shell flash temperatures of massive (6–9 $M_\odot$) AGB stars are about 10% larger than they are normally assumed to be, alpha particle reactions with the magnesium will become significant. Then the $^{26}$Mg($\alpha$, $n$)$^{29}$Si reaction produces a large excess of $^{29}$Si. With a light element nuclear reaction network, we calculate the evolution of the silicon isotopic composition during AGB evolution and find that the experimentally determined (slope = 1.4) correlation between excess $^{29}$Si and excess $^{30}$Si in SiC particles from carbonaceous chondrites can indeed be naturally produced in this way. This demonstration contrasts with previous negative conclusions for temperatures too low for magnesium burning to contribute. We are therefore led to suggest that if the large isotopically anomalous SiC particles carrying nearly pure *s*-process krypton and xenon do indeed originate in AGB stars, those stars were massive and have peak shell flash temperatures near 450 MK. We also demonstrate that this suggestion may answer some interesting questions related to the sizes of the meteoritic SiC particles.

*Subject headings:* dust, extinction — meteoroids — nuclear reactions, nucleosynthesis, abundances — stars: giant

## 1. INTRODUCTION

The first hint of the presence of interstellar SiC particles in meteorites came from the discovery (Srinivasan & Anders 1978) of carriers of *s*-process xenon. Subsequent isolation, purification, and characterization of that residue identified it as SiC particles (Tang & Anders 1988). Subsequent work has left little doubt of the identity of SiC particles as carriers of *s*-process xenon in carbonaceous meteorites. This scenario was made more specific by Lewis, Amari, & Anders (1990) and by Gallino et al. (1990), who argued that the winds from asymptotic giant branch (AGB) carbon stars were the specific site of SiC condensation. These noble-gas abundances have been very suggestive of the correctness of that basic belief. Further, Lewis et al. (1990) also found a strong correlation between particle size and $^{86}$Kr abundance. This implies that the *s*-process krypton in large particles formed at higher neutron densities than that in small particles (Beer 1991). We will return to this.

A big step forward was the isotopic analysis of individual SiC grains using the sputtering ion microprobe (Zinner, Tang, & Anders 1989; Stone et al. 1990). By this method, the carbon and silicon of individual particles were shown to be isotopically anomalous. That the structural stuff of SiC is also anomalous confirms that these particles have indeed condensed in stellar outflows before those flows could mix with the interstellar medium. These particles were shown (Zinner et al. 1989; Stone et al. 1990, 1991) to be isotopically heavy in both major constituents (C and Si). When compared with solar isotopic composition the $^{29}$Si deviation in parts per thousand defined by

$$\delta\,^{29}\mathrm{Si} = [(^{29}\mathrm{Si}/^{28}\mathrm{Si})/(^{29}\mathrm{Si}/^{28}\mathrm{Si})_\odot - 1] \times 1000 \qquad (1)$$

is correlated with the analogous $^{30}$Si deviation, but along a line of slope near 1.4 having a positive $\delta\,^{30}$Si ($x$-axis) intercept of $\sim$17. Simple *s*-processing of silicon alone is incapable of producing compositions in this region of the $\delta\,^{29}$Si-$\delta\,^{30}$Si plane (starting from roughly solar abundances). The large $^{33}$S($n$, $\alpha$)$^{30}$Si cross section ensures that $\delta\,^{30}$Si exceeds $\delta\,^{29}$Si by a factor of 2 in a "pulse and mix" model. We will show that of the nuclear processes operating in low- or intermediate-mass stars, only reprocessing in a hot ($T > 400$ MK), helium-rich environment, can yield silicon isotope compositions like those seen in large pristine SiC particles. The key will be interactions of not only neon with alpha particles but of magnesium as well. We will refer to this as magnesium burning.

## 2. NUCLEAR REPROCESSING OF Si IN AGB STARS

We have evolved nuclear reaction networks for a variety of conditions and compositions to determine all of the processes which could occur in stellar environments. Our *s*-process network consists of a single *s*-process path from $^{12}$C to $^{33}$S. Neutrons produced by ($\alpha$, $n$) reactions with $^{22}$Ne or $^{13}$C are assumed to be immediately absorbed. The fraction of neutrons ($f_i$) caught by a given species is determined by $f_i = \sigma_i Y_i/\Sigma_i \sigma_i Y_i$, where $Y_i$ is the abundance of $i$ and $\sigma_i$ is its neutron capture cross section. For this survey we take $\Sigma_{(A<56)}\sigma_i Y_i/\Sigma_{\mathrm{all}}\sigma_i Y_i = 0.4$ because this is the asymptotic value given by Truran & Iben (1977). We include all of the light-element reactions with alphas which operate at less than $10^9$ K, taking rates from Caughlan & Fowler (1988). $^{22}$Ne, $^{13}$C, and magnesium reactions with alphas provide the neutron sources. The whole network is evolved explicitly with a Runge-Kutta stepper routine (Press et al. 1988). For hydrogen burning at the base of a convective envelope (or any other similar environment), we have used a standard, implicitly differenced network incorporating all elements with $Z < 15$ and alpha and proton capture reactions for $T \lesssim 500$ MK.

Five nuclear processes operate in AGB stars of $< 10\ M_\odot$. Each of their effects on silicon can be associated with a characteristic vector in the $\delta\,^{29}$Si-$\delta\,^{30}$Si plane (see Fig. 1, which shows the directions, but not the magnitudes, of the isotopic

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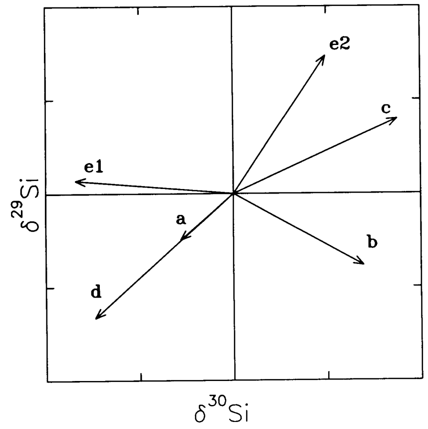

FIG. 1.—The vectors representing possible nuclear reprocessing of silicon. a: mild hydrogen burning; b: strong hydrogen burning; c: *s*-process neutron capture; d: helium burning; e1: early magnesium burning; e2: late magnesium burning.

shifts). More than one process operating concurrently (or successively) will add the respective vectors.

### 2.1. *Mild Hydrogen Burning*

Proton capture at temperatures in the range 80–100 million degrees (K) will turn $^{27}$Al into $^{28}$Si, increasing the denominator of both $\delta\,^{29}$Si and $\delta\,^{30}$Si equally. When the initial $^{27}$Al is consumed, this process terminates at $\delta\,^{29}\mathrm{Si} \approx \delta\,^{30}\mathrm{Si} \approx -40$ for these low temperatures. This hot bottom burning occurs at the base of convective envelopes of stars $> 5\ M_\odot$ in some models.

### 2.2. *Strong Hydrogen Burning*

$^{29}$Si is more easily destroyed by protons than are $^{28}$Si and $^{30}$Si. Proton capture at $T > 100$ MK will thus favor $^{28}$Si and $^{30}$Si at the expense of $^{29}$Si. This will occur at the base of convective envelopes of stars $\lesssim 7\ M_\odot$ in some models.

### 2.3. *s-Process Neutron Capture*

$^{29}$Si captures neutrons at roughly twice the rate of $^{28}$Si (Bao & Käppeler 1987). The $^{33}$S($n$, $\alpha$) cross section is very large. These two effects ensure that any composition with roughly solar sulfur will produce $\delta\,^{29}$Si-$\delta\,^{30}$Si evolution along a line of slope 0.46, whatever the neutron source. This sharp contrast to the observed slope 1.4 line in the SiC particles has raised serious doubts (Obradovic et al. 1991) about the correctness of the AGB origin paradigm. The *s*-process can occur in the helium-burning shell of thermally pulsing AGB (TP-AGB) stars, but the source of the neutrons has been disputed. $^{13}$C($\alpha$, $n$) may operate in low-mass stars (Iben & Renzini 1982; Hollowell & Iben 1988; Gallino et al. 1988). $^{22}$Ne($\alpha$, $n$) operates only in more massive stars and produces a higher neutron density than does $^{13}$C (Bazan 1991; Truran & Iben 1977). Whether real stars of intermediate mass can even reach an AGB phase has been an open question. We will show that the SiC particles argue strongly that they can in come cases.

### 2.4. *Helium-Burning Chain*

At temperatures greater than $\sim$400 MK the main line of helium burning will proceed along the path, $3\,^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} \rightarrow {}^{20}\mathrm{Ne} \rightarrow {}^{24}\mathrm{Mg} \rightarrow {}^{28}\mathrm{Si}$. This can make $^{28}$Si a significant fraction of the mass density if the process is allowed to continue long enough. Although this process operates at some small level in all TP-AGB stars, production of a significant amount of new $^{28}$Si in the helium-burning shell during a pulse depends sensitively on stellar conditions.

### 2.5. *Magnesium Burning*

Conversion of $^{25}$Mg and $^{26}$Mg into $^{29}$Si and $^{30}$Si occurs by ($\alpha$, $n$) reactions. [$^{24}$Mg($\alpha$, $\gamma$) is, for our purposes, more clearly considered as part of helium burning.] The helium will have developed from hydrogen-rich material through the CNO cycle, during which carbon, nitrogen, and oxygen are transmuted to $^{14}$N. At relatively low temperatures ($\sim$100 MK) in the resulting helium rich gas, $^{14}$N captures two alphas to become $^{22}$Ne. At temperatures above $\sim$300 MK $^{22}$Ne($\alpha$, $n$) $^{25}$Mg causes an *s* process with the associated effect on silicon described above. As the *s*-process continues, up to half of the generated $^{25}$Mg can become $^{26}$Mg by associated neutron capture. If the temperature is hot enough, or if the process continues long enough, the $^{22}$Ne will burn completely, and the magnesium will itself ($\alpha$, $n$) to $^{28}$Si and $^{29}$Si. As a conceptual aid, in Figure 2 we show the track in the $\delta\,^{29}$Si-$\delta\,^{30}$Si plane for the artificial situation of a hot helium gas with the helium burning reactions "turned off." This clarifies the evolution in the absence of new $^{12}$C (and new $^{28}$Si from it). The starting composition is helium 90% by mass, solar C, N, and O all entered as $^{22}$Ne, and all other elements with solar abundance. The main features are clear: first, the silicon follows its standard *s*-process track of slope 0.46; then $^{28}$Si and $^{29}$Si are produced from magnesium with little $^{30}$Si production (vector e1 in Fig. 1), until the $^{25}$Mg is exhausted (1 yr at 450 MK); then finally the remaining $^{26}$Mg undergoes ($\alpha$, $n$) to both $^{29}$Si and $^{30}$Si (vector e2 in Fig. 1). We will return to the realistic case with helium burning "turned on" below. [We also show a track with the $^{26}$Mg($\alpha$, $n$) rate doubled to illustrate the effect of a change in the ratio of the $^{26}$Mg($\alpha$, $n$) rate to the $^{25}$Mg($\alpha$, $n$)

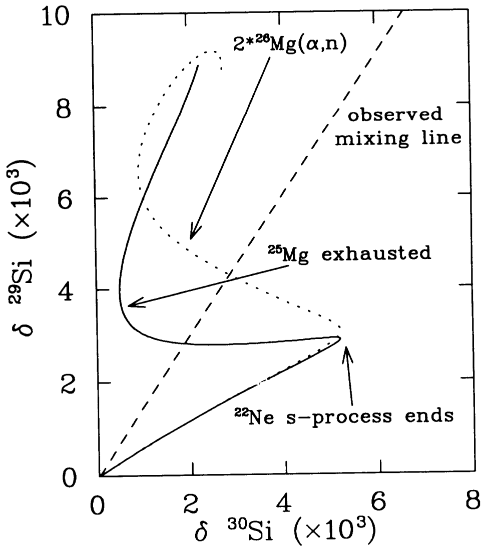

FIG. 2.—The evolution of silicon isotopes in helium burning at constant temperature $T = 450$ MK for a network that excludes new $^{28}$Si synthesized from new $^{12}$C via the alpha chain. The three separate epochs are then $^{22}$Ne burning, $^{25}$Mg and $^{26}$Mg combined burning, and $^{26}$Mg only burning. These have slope 0.46, slope 0, and slope 1.3, respectively. Although the *s*-process cannot yield the observed particle mixing (*dashed*), magnesium burning does move the composition "leftward" to regions where $\delta\,^{29}\mathrm{Si} > \delta\,^{30}\mathrm{Si}$. A sense of cross section dependence is shown by repeating the track with a doubled value for $^{26}$Mg($\alpha$, $n$).

rate]. This magnesium burning may occur in AGB stars (although current models predict temperatures ~10% too low), but only in those with core masses very near the Chandrasekhar mass. Stars ($\gtrsim 7\ M_\odot$) can undergo this process.

Of the above processes, only magnesium burning can produce a composition near or above the slope 1.4 line (displayed dashed in Figs. 2 and 3) in the $\delta\,^{29}$Si-$\delta\,^{30}$Si plane. It appears that only such helium shell silicon is appropriate for growing large ($>1\ \mu$m) SiC grains. We therefore propose that the bulk silicon of the SiC particles must have been enriched by a mixing endmember that has undergone magnesium burning. Further, since this can only occur following $^{22}$Ne burning, a $^{22}$Ne *s*-process must also have already occurred in this component. This does not imply that a $^{22}$Ne *s*-process is responsible for the bulk solar abundance of *s*-process elements, but it strongly suggests that nature is capable of producing a $^{22}$Ne *s*-process in some massive AGB stars.

## 3. A SIMPLE ASTROPHYSICAL MODEL

In any star, more than one and perhaps all of these processes will be operating at once. The helium shell and the evolving envelope constitute two "reservoirs" with different compositions. The particles will be a mixture of the two. In AGB stars, dredge-up episodes at the end of each thermal pulse (separated by 100–$10^6$ yr) mix the two reservoirs. For a very simple picture of an AGB star, we can plot the composition of the helium shell and the composition of the envelope and assume that the SiC particles should have compositions lying on the line connecting these two (a rigorous three-isotope theorem for binary mixtures).

Although hot bottom burning in the envelope may alter its composition through processes a and b, we will for our immediate purpose assume a solar composition for the envelope. We calculate the helium shell composition for a series of pulses with a fraction $r$ of previously burnt material remaining from each previous pulse. Using $r = 0.3$ (appropriate for core masses of $>1\ M_\odot$) we obtain a saturated (stationary) composition after about 10 pulses. For this model, we have derived an approximate temperature and density versus time profile from the intermediate-mass star models of Iben (1977):

$$T_6 = T_{6\,\max} - 100t/\Delta t\ , \quad \rho = \rho_{\max} e^{-2t/\Delta t}\ , \tag{2}$$

$$\begin{aligned} T_{6\,\max} &= 310 + 285(M_c - 0.96)\ , \\ \rho_{\max} &= -711.48 + 4649.1M_c - 1249.6M_c^2\ , \end{aligned} \tag{3}$$

where $T_6$ is the temperature in $10^6$ K, $t$ is time, $\rho$ is density in g cm$^{-3}$, $\Delta t$ is the duration of the shell flash, and $M_c$ is the stellar core mass. These temperatures and densities apply to the base of the convective helium burning shell. To average the nuclear rates over the whole shell, we simply divide by 10. According to Iben (1977) this is valid for the $^{22}$Ne alpha capture rate and should be reasonably valid for the other single alpha captures but perhaps not for the $3\alpha$ rate. More realistic models must eventually be investigated, but with this simple prescription we have explored the range of maximum density, maximum temperature, and flash duration allowed by the parameterized formulas of Bazan (1991) (eq. [3]) and have found that magnesium burning will not quite occur for these standard values. However, increasing the maximum temperature by 10% in a 7 $M_\odot$ star (to 450 MK) generated the saturation point shown in Figure 3. This point is very close to the observed particle mixing line (also shown dashed). The silicon evolution track in Figure 3 shows our full helium-burning model. This is qualitatively just the track of Figure 2 with all of the post-$^{22}$Ne burning development of silicon isotopes shifted toward the origin by including the helium burning chain production of $^{28}$Si, which dilutes $\delta\,^{29}$Si and $\delta\,^{30}$Si equally. This dilution introduces a systematic trend toward the origin and is

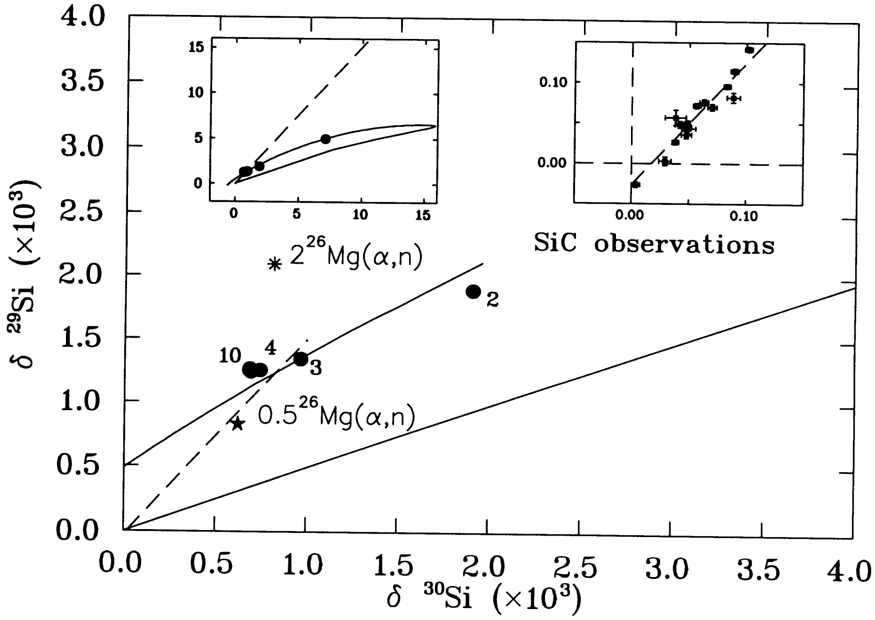

FIG. 3.—The track shown represents the evolution of $^{29,30}$Si enhancements during helium burning starting from a solar composition with all NCO elements turned into $^{22}$Ne (see text). The points are individual numbered pulses for a model with $T_{\max} = 450$ MK, $\rho_{\max} = 3200$ g cm$^{-3}$, $\Delta t = 1$ yr, and $r = 0.3$. The inset boxes show the same silicon isotopic ratios on both large and small scale: (*left*) the entire track and all 10 pulses shown; (*right*) single SiC particle measurements (Zinner 1991; Stone et al. 1991). The observed anomalies are much smaller, presumably because of dilution of shell silicon with envelope silicon. The dashed slope 1.4 line is shown in each view. Asterisk and star show shell saturation compositions with the rate of $^{26}$Mg($\alpha$, $n$) altered by factors of 2.

actually helpful, because without it the $\delta^{29,30}$Si values are so much larger than for the particles found in meteorites that mixing with the envelope might not reduce them to observed levels. Importantly, the absolute silicon concentration increases markedly along this track.

We should also note that hot bottom burning in the envelopes of very massive AGB stars ($M_\odot > 7$) can produce the small shift of the "envelope" endmember away from solar composition found by Stone et al. (1991) (vectors a plus b).

## 4. DISCUSSION

We have shown at the level of a simplified model that AGB stars can produce the silicon isotopic composition observed in SiC particles by a small extension of standard conditions. This exciting new result seems called for by the meteoritic particles. It may therefore be valid new astronomical information. We have also argued that only a $^{22}$Ne *s*-process followed by magnesium burning can produce these particles in stars of $< 10\ M_\odot$. In the absence of isotopic evidence for a supernova origin for these particles, this is a strong argument that the $^{22}$Ne *s*-process can operate in some stars.

We must now address the question of why measurements on large grains do not yield some values consistent with less extreme processing of silicon (i.e., simple *s*-process silicon). We see three possible explanations:

1. Perhaps large SiC particles cannot form in AGB stars of $\lesssim 7\ M_\odot$ and do not form in these massive stars until the core mass is large enough to cause magnesium burning. Possible reasons exist. The first is enhanced silicon concentration. Magnesium burning and alpha chain burning produce shell silicon in amounts two orders of magnitude above their solar mass fractions. This high silicon abundance clearly enhances SiC growth. A carbon (not oxygen) rich environment is also necessary for SiC formation, and evolution along the AGB to carbon star formation could preclude SiC formation in large stars before they develop a large core mass, but this is a speculation for more detailed modeling. The lower silicon concentration in low-mass C stars may cause carbon to condense as elemental carbon rather than as SiC.

Measurements on aggregates of *smaller* SiC grains (as opposed to single large grains) do fall below the slope 1 line, but they fall so near the shifted slope 1.4 line of the large particles (Fig. 3, *inset*) that it is unclear whether they should be attributed to *s*-processing in lower mass carbon stars. Alternatively, they could result from the same processes which produced the large grain mixing line. If the smaller grains are indeed *s*-process products of lower mass carbon stars, the implication of the $^{86}$Kr measurements, namely, that increasing grain size correlates with increasing core mass of an AGB star (Lewis et al. 1990), is supported. We await further measurements of this type. Since, unlike krypton, all *s*-process silicon is roughly the same, regardless of neutron density, we would expect all of the SiC below a certain grain size (stellar core mass) to have a similar silicon isotopic composition. Large variations should occur only for conditions of magnesium burning which only occur in stars with the most massive cores. This is the actual behavior of the SiC particles as noticed by Amari, Zinner, & Lewis (1991).

We also note that a few individual particles (called "Y" particles) do have silicon compositions compatible with a simple *s*-process (Amari et al. 1992).

2. A single AGB star near the forming Sun may have contributed essentially all (with the exception of the "Y" and "X" particles; Amari et al. 1992) of the observed SiC particles, which it formed only at the end of its life. This removes any problem of "fine tuning" since the observed shell endmember of a single star is not required to have a naturally preferred position (see also Stone et al. 1991). A single star origin would strongly favor models in which an AGB star triggers the formation of the solar system (Cameron 1992). Zinner et al. (1989), argued for at least six independent components in the SiC particles, but Stone et al. (1991) find only two components in the large platy hexagonal SiC grains. If further measurements on smaller grains show that they belong on the same mixing line as the larger grains, this option may become more strongly favored.

3. The measured SiC particles have not formed in AGB stars but in some astrophysical site where no reservoir of simple *s*-process silicon had evolved. In addition, this would also require that AGB stars with *s*-process silicon do not produce large SiC particles.

So far, we feel that the most likely origin for the large SiC particles is in an AGB star or stars of mass $\gtrsim 6\ M_\odot$. "Y"-type grains and smaller grains come from either smaller stars or early epochs in the evolution of the large stars. More detailed models are clearly necessary and this work is underway. More accurate predictions will require more thorough modeling of helium shell flashes in AGB stars with extremely large core masses and accurate determination of the $(\alpha, n)$ [and, to a lesser degree, $(n, \gamma)$] rates on the isotopes of magnesium. To encourage work on both of these points by members of the appropriate communities we submit our present calculations.

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