

# Condensation of Trace Elements into Presolar SiC Stardust Grains

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## Introduction

Inferring the condensation behavior of major and trace elements into SiC stardust grains in stellar environments is important for two reasons: (1) to understand the basic chemical processes that govern condensation and how they relate to the stellar environment and (2) to interpret (and predict) laboratory studies of stardust and observations of stars.

Trace elements can condense in one of two ways (or some combination of them): (1) by forming grains of their own phases that are later incorporated into a major element grain or (2) by forming a solid solution with the major element phase. Even though subgrains of trace-element carbides have been observed inside graphite grains [1], our results indicate that the main condensation mechanism for trace elements is the formation of a solid solution.

## Methods and Materials

We measured 34 individual micrometer-sized presolar SiC grains (Murchison meteorite size fraction KJF, average grain diameter of  $\sim 1.5 \mu\text{m}$  [2]) by nondestructive synchrotron x-ray fluorescence [3]. The measurements were done at the APS Synchrotron Research Institute Collaborative Access Team (SRI-CAT) beamline 2-ID-D. The grains were mounted on 7- $\mu\text{m}$ -thick Kapton<sup>®</sup> film. Three beam energies of 18, 22.5, and 24.5 keV were used in order to explore the full hard x-ray range relevant to the grains (each grain was measured at one of the energies). The beam spot cross section at the target plain was  $\sim 0.5 \mu\text{m}$ . Data analysis was done at the GeoSoilEnviro Consortium for Advanced Radiation Studies (GSECARS)-CAT sector.

## Results

The following trace elements were detected in the grains (not every element in every grain): Ti, V, Mn, Fe, Ni, Sr, Y, Zr, Nb, Mo, and Ru. Table 1 summarizes the results. It also gives related data and results of calculations. The elements are divided into four groups on the basis of whether they are s-process (i.e., slow process) elements and their abundance in the grains. The measured grains are assumed to be mainstream grains that condense in AGB stars. The s-process neutron capture can highly

enrich s-process—mainly heavy elements in these stars while only slightly affecting the abundance of other elements. An abundance enrichment factor is given by the ratio of the element to Si and is normalized to the same ratio in C1 chondrites [abundance enrichment factor =  $(\text{element}/\text{Si})_{\text{SiC}} / (\text{element}/\text{Si})_{\text{C1}}$ ]. The four groups are (1) non-s-process elements that have an abundance enrichment factor of  $\sim 1$  (C1) in the grains: Ti and V; (2) non-s-process elements that are highly depleted in the grains: Mn, Fe, and Ni; (3) an s-process element that is depleted in the grains: Sr; and (4) s-process elements that are enriched in the grains: Y, Zr, Nb, Mo, and Ru.

*Table 1. The four groups of trace elements. The range of enrichment factors (see text for definition) is from this study. The range of results is from a previous study by Amari et al. [4] (only Fe from Group 2; only Y, Zr, and Nb from Group 4). The range of calculated values, from Gallino et al. [5], is for 1.5 and 3 solar mass AGB stars.*

	Group 1	Group 2	Group 3	Group 4
Character	Non-s, C1 ratios	Non-s, depleted	s, depleted	s, enriched
Elements	Ti, V	Mn, Fe, Ni	Sr	Y, Zr, Nb, Mo, Ru
Enrichment factor in SiC	0.15-3.47	$5 \cdot 10^{-5}$ - $4 \cdot 10^{-2}$	0.07-0.46	0.4-67
Prev. study Amari et al. 1995	0.04-3.71	$6 \cdot 10^{-5}$ -0.39	--	0.05-35
Calculated Gallino et al. 1998	1	1	1-40	1-40

## Discussion

### Group 1

Since both Ti and V are not s-process elements, their abundance in the stellar atmosphere, where SiC grains condense, is predicted to be C1 (Table 1). (This is due mainly to the fact that only a small fraction of the stellar envelope is being convected down to the He burning shell to be processed in the s-process). On the other hand, there

is a big difference in the condensation temperature ( $T_C$ ) of their first phases to condense: 100% of Ti is calculated to condense as TiC from 150-200K above the  $T_C$  of SiC [6]. V is calculated to condense as VC<sub>0.88</sub> at the  $T_C$  from 60K below the  $T_C$  of SiC to 20K above it. Each phase condenses over a range of ~100K. If this were the main condensation process, by the time SiC would start to condense, the gas would have been completely depleted in Ti, and V may or may not have started to condense. In this case, a small negative correlation between Ti and V is expected: The first SiC grains to condense can incorporate TiC into them (depleting the environment in TiC grains) while V is only starting to condense. Later SiC grains to condense will have more VC<sub>0.88</sub> grains and fewer TiC grains available to them.

As can be seen in Fig. 1, this is not the observed pattern in the grains. The two elements are positively correlated. Lodders and Fegley [6] calculated the 50%  $T_C$  of both elements in solid solution with SiC and found it to be equal to the  $T_C$  of SiC (in this way, fewer refractory elements condense into a major element host phase at a higher temperature than the  $T_C$  of their own phase). It seems that the simple way of explaining the Ti-V pattern is that both elements condensed in solid solution with SiC.

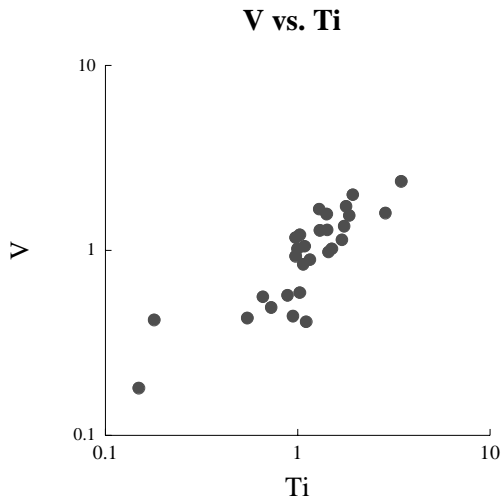


FIG. 1. Vanadium vs. titanium.

### Group 2

This group contains Mn, Fe, and Ni. All are non-s-process elements and are calculated (Table 1) to have enrichment factors of ~1 in the stellar atmospheres. On the other hand, they are highly depleted in the grains, with enrichment factors of  $\sim 10^{-5}$  to  $10^{-2}$ . At present, we

have the results of the condensation calculation only for Fe. In this case, both the  $T_C$  of its first condensing phases, Fe and Fe<sub>3</sub>C, and the 50% solid solution  $T_C$  are at least 200K below the  $T_C$  of SiC. The fact that Mn and Ni are also depleted may indicate that they have similar condensation chemistries under these conditions (both elements have higher enrichment factors than does Fe), although we do not see any correlations among these elements.

### Group 3

Sr was detected in only five grains. Despite the fact that it is an s-process element with stellar enrichment factors of up to 40, it is depleted in the grains (Table 1). Again, like Fe, the calculated  $T_C$  of the first Sr phase to condense, SrS, and its 50% solid solution  $T_C$  are at least 270K below the  $T_C$  of SiC. Both mechanisms can explain the depletion despite the s-process enrichment in the stellar source.

### Group 4

This group has five s-process elements — Y, Zr, Nb, Mo, and Ru — that are enriched in both the stars and grains (Table 1). The fact that the enrichment factors of this group's elements in both stars and grains are comparable suggests that these elements fully condense into the grains. Hence their ratios in the grains represent their ratios in the stellar source rather than a chemical enrichment. But again, as with the Group 1 elements, there are big differences in the  $T_C$ 's of their first phases to condense. However the differences among the elements of this group are much greater. The biggest gap in  $T_C$  is between Nb (NbC) and Zr (ZrC) on one hand, which condense at ~350K above SiC, and Y (YC<sub>2</sub>, YS) on the other hand, which condenses at 250-90K below SiC (i.e., Y starts to condense only after SiC is finished). If these elements were to condense into grains of their own phases (and later be incorporated into SiC), then Nb and Zr would be enriched in the grains and Y would be highly depleted.

As can be seen in Fig. 2, this is not the case. Y actually has slightly higher enrichment factors than Zr. And as was the case for the Group 1 elements, the 50% solid solution  $T_C$  for Nb, Zr, and Y is the same and is equal to the  $T_C$  of SiC.

### Acknowledgments

Use of the APS was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38. This work was also supported by SRI-CAT and GSECARS-CAT.

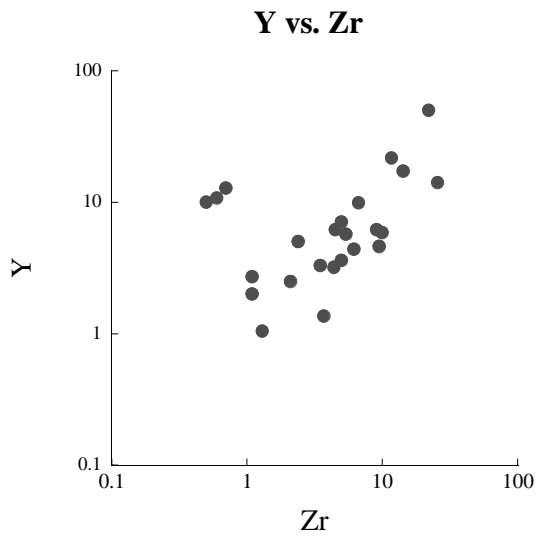


FIG. 2. Yttrium vs. zirconium.

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