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Titanium isotopic compositions of rare presolar SiC grain types from the Murchison meteorite

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Abstract

We report the Ti isotopic compositions of 8 mainstream, 22 Y, 9 Z, and 26 AB presolar SiC grains from two SiC-rich residues of the Murchison CM2 meteorite together with Si, C and some Mg-Al isotopic data for the same grains. Mainstream, Y and Z grains are believed to originate in asymptotic giant branch (AGB) stars of varying metallicities, but the stellar sources of AB grains are poorly understood. We find that the ^{46,47,49}Ti/^{48}Ti ratios are correlated with ^{29}Si/^{28}Si for all of the grain types, indicating that these ratios are mainly dominated by Galactic chemical evolution (GCE). The mainstream, Y and Z grains all show enrichments in ^{50}Ti from neutron capture nucleosynthesis. However, AGB models predict smaller excesses in ^{50}Ti (and ^{49}Ti) than are observed in these grains. For Z grains and especially for Y grains, the enhancement of ^{50}Ti is greater than the enhancement in ^{30}Si, indicating that the ^{13}C neutron source produced a greater total fluence of neutrons than the ^{22}Ne source in the low metallicity parent AGB stars. The Z grains plot below the mainstream correlation lines at more ^{48}Ti- and ^{28}Si-rich compositions in plots of ^{46,47,49}Ti/^{48}Ti vs. ^{29}Si/^{28}Si. On the other hand, the Y grains plot close to the mainstream correlation line. This could imply that the Ti isotopes evolved non-linearly at metallicities below ~1/3 solar. The AB grains in this study have Ti isotopic compositions that fall along correlation lines defined by the mainstream grains, suggesting origins in close to solar metallicity stars. However, these grains fall below the mainstream correlation lines in plots of ^{46,49,50}Ti/^{48}Ti vs. ^{29}Si/^{28}Si and do not show enhancements in ^{50}Ti, indicating that their parent stars did not undergo significant *s*-process nucleosynthesis. These data support origins of AB grains in J-type C stars rather than born-again AGB stars that undergo *s*-process nucleosynthesis. AB grains that do not have ^{50}Ti excesses may provide the best measure of Si and Ti isotope GCE since their parent stars were less affected by *s*-process nucleosynthesis than the mainstream grains.

Keywords: Circumstellar grains; Galactic chemical evolution; Nucleosynthesis; Stars

1. INTRODUCTION

Presolar grains originating from the outflows and ejecta of evolved stars, such as asymptotic giant branch (AGB) stars, supernovae (SNe), and novae, are found in primitive meteorites, interplanetary dust particles (IDPs), and cometary dust returned by NASA's Stardust mission (Floss et al., 2013; Zinner, 2014). These grains are identified by their highly anomalous isotopic compositions relative to any solar system material. These isotopic compositions are the products of nucleosynthetic and mixing processes that occurred deep within their parent stars. The study of presolar grains in the laboratory has provided unprecedented insight into various astrophysical phenomena, such as Galactic chemical evolution (GCE), stellar nucleosynthesis and mixing, dust condensation in circumstellar environments, and dust processing in the interstellar medium (ISM) and the solar system.

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The first presolar grains to be isolated in the laboratory were the carbonaceous phases diamond, SiC, and graphite that have anomalous noble gas components (Bernatowicz et al., 1987; Lewis et al., 1987; Amari et al., 1990). Ion microprobe studies later identified highly anomalous isotopic compositions associated with several oxide and silicate phases, and Si_3N_4 (Hutcheon et al., 1994; Nittler et al., 1994, 1995, 1997; Messenger et al., 2003; Nguyen and Zinner, 2004). The analysis of individual roughly micron-sized grains was made possible by the development of the ion microprobe, and led to the identification of different sub-types of presolar grains having distinct stellar origins.

Presolar SiC grains are the best characterized presolar phase and have been the focus of many detailed presolar grain studies for multiple reasons. Unlike O-rich phases, all SiC grains in primitive meteorites have presolar origins and concentrated samples of SiC can be produced in the laboratory by acid dissolution techniques and gentle separation methods (Amari et al., 1994; Bernatowicz et al., 2003; Nittler and Alexander, 2003; Tizard et al., 2005). Moreover, presolar SiC grains can have diameters of several microns, with some unusually large grains exceeding 25 μm (Virag et al., 1992; Zinner et al., 2011). This makes it easier to analyze multiple isotopic systems in single grains. As such, the database of Si, C, and N isotopic compositions is very well established and several sub-types of presolar SiC have been classified based upon their Si, C, and N isotopic signatures (Hoppe et al., 1994; Zinner, 2014).

The most widely studied SiC grain sub-type, termed mainstream, makes up ~90% of all presolar SiC and has $^{12}C/^{13}C$ ratios in the range of 10–100 (terrestrial ~89). These grains are typically enriched in ^{29}Si and ^{30}Si by up to ~20% relative to the solar composition. They most likely condensed in low-mass C-rich AGB stars of approximately solar metallicity (Hoppe and Ott, 1997; Lugaro et al., 2003). Type Y grains have $^{12}C/^{13}C > 100$, are ^{30}Si-rich and ^{29}Si-poor relative to mainstream grains, and are believed to have originated in C-rich AGB stars of about one-half solar metallicity with masses up to 5 $M_{\odot}$ (Amari et al., 2001b). Z grains have $^{12}C/^{13}C$ between 10 and 100, similar to mainstream grains, are more ^{30}Si-rich and ^{29}Si-poor than Y grains, and likely condensed in AGB stars of about one-third solar metallicity (Alexander, 1993; Hoppe et al., 1997; Zinner et al., 2007). SiC X grains have compositions (e.g., enrichments in ^{28}Si and ^{15}N and a wide range of $^{12}C/^{13}C$ ratios) pointing to Type II supernova (SN) sources (Nittler et al., 1996). The latter three grain types each make up ~1–2% of all presolar SiC. Z grains are predominantly found among submicrometer-sized grains. Type C SiC grains are extremely rare (~0.1%) and likely have SN origins as well (Hoppe et al., 2012; Xu et al., 2015; Liu et al., 2016). However, while X grains are enriched in ^{28}Si, C grains show excesses in ^{29}Si and ^{30}Si (Amari et al., 1999; Hoppe et al., 2010, 2012). A few grains with marked excesses in ^{13}C and ^{15}N could have nova origins (Amari et al., 2001a), though additional isotopic analyses of some putative nova grains indicate SN origins instead (Nittler and Hoppe, 2005; Liu et al., 2016). Type A and B grains are more abundant (~5%), but their parent stellar sources are ambiguous. These grains are enriched in ^{13}C with $^{12}C/^{13}C < 10$, show both enrichments and depletions in ^{15}N, and have Si isotopic distributions similar to mainstream grains. The N and Si isotopic compositions of AB grains are distinct from the putative nova grains. Proposed stellar sources include born-again AGB stars or J-type carbon stars (Alexander, 1993; Hoppe et al., 1994; Amari et al., 2001c). Excess ^{32}S in three AB grains support born-again AGB stars as the source of some of these grains (Fujiya et al., 2013). One AB grain shows enhancements in *r*-process and *p*-process isotopes of Mo and Ru, suggesting material transfer from a Type II SN in a binary system (Savina et al., 2003, 2007), though the *p*-process likely occurs in multiple astrophysical settings. Recent multi-element isotopic analyses of some ^{15}N-rich AB grains also suggest possible origins in Type II SNe (Nittler et al., 2016). In all cases, the isotopic compositions of the AB grains are not well understood within the context of existing nucleosynthesis models.

The isotopic compositions of many trace elements, including Mg-Al, S, Ti, Fe, Ni, Mo, Zr, Ru, and Ba, have been measured in presolar SiC grains owing to their relatively high concentrations (Amari et al., 1995). Of the tens of thousands of presolar SiC identified, there are only ~250 published analyses of Ti isotopic ratios, with most being mainstream and X grains (Hoppe et al., 1994; Nittler et al., 1996; Alexander and Nittler, 1999; Amari et al., 2001b, 2001c; Hoppe and Besmehn, 2002; Nittler and Hoppe, 2005; Gyngard et al., 2006; Huss and Smith, 2007; Zinner et al., 2007; Lin et al., 2010; Fujiya et al., 2013). X grains typically have excesses in ^{49}Ti attributed to the decay of ^{49}V (half-life = 330 d) and n-capture nucleosynthesis, and excesses in ^{44}Ca from the decay of ^{44}Ti (half-life = 60 yr), which is only produced in SN explosions (Amari et al., 1992; Hoppe et al., 1996, 2000; Nittler et al., 1996; Hoppe and Besmehn, 2002; Lin et al., 2010). In AGB stars, the C and N isotopic compositions are affected by core and shell H- and He-burning, whereas the Si and Ti isotopes are affected by slow neutron capture (*s*-process) nucleosynthesis. Most of the Si and Ti isotopic ratios of SiC grains from AGB stars are more strongly affected by the initial stellar compositions, reflecting GCE (Hoppe et al., 1994; Gallino et al., 1997, 1998; Alexander and Nittler, 1999; Amari et al., 2001b). However, the effects of *s*-process nucleosynthesis on Ti isotopes are stronger in lower-metallicity stars, making Ti data for the Y and Z grains highly desirable to test models of both GCE and AGB nucleosynthesis. For example, the Ti isotopic compositions of some Z grains confirmed a low-metallicity origin for the grains but some discrepancies with *s*-process nucleosynthesis models were found (Zinner et al., 2007). The number of grains in this study was limited, however.

Although the Ti isotope systematics of mainstream and X-type SiC grains are reasonably well understood, there are far fewer data for the rare Y, Z, and AB types. We report here C, Si, and Ti isotopic data for 8 mainstream, 22 Y, 9 Z, and 26 AB SiC grains from the Murchison meteorite. We also discuss the Mg-Al isotopic data for 5 AB grains that were previously reported by Zinner et al. (2007). These

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