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Simultaneous iron and nickel isotopic analyses of presolar silicon carbide grains

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Abstract

Aside from recording stellar nucleosynthesis, a few elements in presolar grains can also provide insights into the galactic chemical evolution (GCE) of nuclides. We have studied the carbon, silicon, iron, and nickel isotopic compositions of presolar silicon carbide (SiC) grains from asymptotic giant branch (AGB) stars to better understand GCE. Since only the neutron-rich nuclides in these grains have been heavily influenced by the parent star, the neutron-poor nuclides serve as GCE proxies. Using CHILI, a new resonance ionization mass spectrometry (RIMS) instrument, we measured 74 presolar SiC grains for all iron and nickel isotopes. With the CHARISMA instrument, 13 presolar SiC grains were analyzed for iron isotopes. All grains were also measured by NanoSIMS for their carbon and silicon isotopic compositions. A comparison of the measured neutron-rich isotopes with models for AGB star nucleosynthesis shows that our measurements are consistent with AGB star predictions for low-mass stars between half-solar and solar metallicity. Furthermore, our measurements give an indication on the $^{22}Ne(\alpha,n)^{25}Mg$ reaction rate. In terms of GCE, we find that the GCE-dominated iron and nickel isotope ratios, $^{54}Fe/^{56}Fe$ and $^{60}Ni/^{58}Ni$, correlate with their GCE-dominated counterpart in silicon, $^{29}Si/^{28}Si$. The measured GCE trends include the Solar System composition, showing that the Solar System is not a special case. However, as seen in silicon and titanium, many presolar SiC grains are more evolved for iron and nickel than the Solar System. This confirms prior findings and agrees with observations of large stellar samples that a simple age-metallicity relationship for GCE cannot explain the composition of the solar neighborhood.

Keywords: Presolar grains; *S*-process; Stellar nucleosynthesis; Galactic chemical evolution; Isotope anomalies

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1. INTRODUCTION

After the Big Bang, the universe contained mainly hydrogen, helium, and small amounts of lithium. Heavier elements were subsequently synthesized in stars and mixed into the interstellar medium (ISM) when those stars exploded or lost their outer shells through stellar winds. Stars with initial masses larger than about 10 solar masses ($M_\odot$) end their lives as core-collapse supernovae (CCSNe). These stars have shorter lifetimes than stars with initial mass $\leq 10 M_\odot$, and played a proportionally greater role in enriching the ISM with heavy elements early on. Type Ia supernovae form in binaries where both stars have initial masses of $\leq 10 M_\odot$. The larger of the two stars lives its life and forms a white dwarf. When the companion star reaches the red giant stage, it transfers mass to the white dwarf until the latter grows beyond the Chandrasekhar mass and explodes. This requires that one star with a mass $\lesssim 10 M_\odot$ undergoes its full stellar evolution and become a white dwarf. Heavier stars would not have resulted in a white dwarf (see, e.g., Herwig, 2013). Type Ia SNe therefore could not have contributed to the interstellar medium right after the Big Bang. The same is true for asymptotic giant branch (AGB) stars – their low mass results in a longer lifetime and hence in a later return of synthesized material compared to massive stars. A recent review on GCE was given by Nomoto et al. (2013).

Presolar grains, recovered from meteorites, are mineral condensates that formed in the outflows of dying stars, survived their journey through the ISM, and were incorporated into meteorite parent bodies at the time the Solar System formed. They represent a unique opportunity to study stellar nucleosynthesis as well as GCE in the laboratory. For recent reviews, see Davis (2011) and Zinner (2014). Various types of presolar grains are known, among which silicon carbide (SiC) grains, which can only condense from gases with a carbon-to-oxygen ratio >1, are the best studied. Presolar SiC occurs in sizes from tens of nanometers to tens of micrometers and can contain relatively high levels of trace elements (Amari et al., 1995). Silicon carbide grains can be divided into several groups based on their nitrogen, carbon, and silicon isotopic compositions (Zinner, 2014). The composition of each group along with other chemical, structural, and isotopic data, is indicative of the type of parent star the grains came from. While mainstream, Y, and Z SiC grains came from AGB stars, X and C grains originated in CCSNe. The origin of AB grains is ambiguous, and several possibilities including novae have been discussed in the literature (e.g., Amari et al., 2001a; Amari et al., 2001c).

Most presolar SiC grains carry the isotopic signature of AGB stars. Most of the variation in isotopic compositions for elements heavier than iron can be attributed to a range of masses and/or metallicities resulting in a variety of neutron exposures and neutron-to-seed ratios in their parent AGB stars. However, certain elements in mainstream presolar SiC grains, like silicon and titanium, vary in isotopic composition in ways different from that expected from AGB stars (e.g., Nittler, 2005; Huss and Smith, 2007). Isotopic anomalies in silicon and titanium are of larger magnitude and correlate with one another in ways not expected for AGB star nucleosynthesis, which can have only relatively small effects on silicon and titanium isotopes. These isotopic variations could be due to GCE. Clayton and Timmes (1997) showed that silicon isotopes in presolar SiC grains vary with metallicity of the parent star. In a standard GCE picture where age and metallicity correlate, higher ^{29}Si and ^{30}Si relative to ^{28}Si would indicate a later formation. This, however, would mean that the Solar System is a special case, since it looks isotopically less evolved than most presolar mainstream grains, i.e., it looks older than presolar SiC grains in the standard GCE model. A different explanation was introduced by Lugaro et al. (1999). They argued that the silicon isotopic composition represents heterogenous GCE. Nittler (2005) followed up on this idea and showed that such a heterogenous evolution could not fully explain the silicon-to-titanium correlation. A third explanation was introduced by Clayton (2003): a dwarf galaxy merged with the Milky Way and subsequently, the Solar System and the parent stars of the presolar SiC mainstream grains formed from material that originated from mixing the materials from both galaxies. A galactic merger could trigger star formation in this region and add an isotopic composition different from the composition of the Milky Way prior to the merger. The isotopic composition of presolar grains and the Solar System in this scenario would be on a mixing line between the metal-poor and the metal-rich component, i.e., between the merging galaxy and the Milky Way. The Solar System composition would not be special and is simply one possible mixture. Focusing on analyses of Y and Z grains, Zinner et al. (2006) showed that the silicon isotopic composition of presolar grains with respect to the Solar System could be explained by GCE; however, a low-metallicity source, i.e., a CCSN, for ^{29}Si and ^{30}Si needs to be included into GCE models in order to explain the observed correlation between δ^{29}Si and δ^{30}Si. Note that observations of stars in the solar neighborhood do not confirm the existence of an age-metallicity relationship (e.g., Holmberg et al., 2007). Lewis et al. (2013) explored the ability of chemodynamical models (e.g., Kobayashi and Nakasato, 2011) to explain the silicon isotopic composition of presolar SiC grains. Lewis et al. (2013) proposed that the enrichment in ^{29}Si and ^{30}Si of presolar SiC grains is a bias effect, due to high-metallicity stars producing dust more efficiently than low-metallicity stars.

Models of *s*-process nucleosynthesis in AGB stars (e.g., Gallino et al., 1998; Cristallo et al., 2011) predict that, similar to silicon isotopes, most of the iron and nickel isotopes (except for ^{58}Fe and ^{64}Ni) are little-affected by AGB nucleosynthesis. Furthermore, iron and nickel are abundant enough in presolar SiC grains that these elements are suitable to be measured and used as GCE proxies. Previous measurements of iron and nickel in presolar SiC grains were performed by Marhas et al. (2008) using a CAMECA NanoSIMS 50. In addition, Ong and Floss (2015) measured iron isotopic ratios in presolar silicates using the same instrument. Iron-58 and ^{58}Ni could not be resolved with the NanoSIMS, and the peak at mass 58 u was dominated by ^{58}Ni. Iron-58 was therefore not reported, and the

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