ZIRCONIUM ISOTOPE EVIDENCE FOR DUST PROCESSING IN THE EARLY SOLAR NEBULA

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1. Introduction

Isotopic Anomalies

- Isotopic variations (unrelated to mass-dependent fractionation, cosmic-ray induced spallation and radioactive decay) have been detected in different meteorite groups, relative to the Earth [1].
- These variations provide information about the chemical and physical nature of the early solar system and its subsequent evolution.
- For example, Mo isotope variations are reported for differentiated and primitive meteorites relative to the Earth and Moon [2-4].
- This large scale heterogeneity is attributed to different accretionary regions of the solar system that received variable contributions of s-process material, most likely from a low mass AGB star.

Open Questions

1. Did the solar system receive variable amounts of s-process material from only low mass AGB stars, or also from other s-process sources (e.g. intermediate mass AGB stars).
2. Which process(es) was(were) responsible for the heterogeneous distribution of this material?

Zr Isotopes

Zirconium isotopes ($^{90, 91, 92, 94, 96}Zr$) can address these issues, as:

- They are largely neutron capture isotopes.
- They receive variable contributions from different s-process sources.
- Different s-process sources produce unique Zr isotope compositions.

→ Zr is a key tracer in identifying different s-process sources in the solar system.

Zr Isotope Anomalies in Meteorites

- Resolvable excesses (~ 1ε) were reported for the neutron-rich isotope ^{96}Zr in carbonaceous chondrites (CC), relative to the Earth and Moon (Fig. 1) [5-7].
- The majority of Allende CAIs are characterised by enrichments (+2ε) in $^{96}Zr/^{90}Zr$ [8].

→ For the majority of CCs (excluding the CB/CR subgroup), the ^{96}Zr excesses scale with the CAI abundance.

- The rest of the bulk planetary material and CI, CB/CR subgroups show small ^{96}Zr enrichments (< 0.5ε), coupled with smaller depletions in ^{91}Zr (< 0.3ε) (Fig. 1., line A) [7].
- These bulk rock $\varepsilon^{96}Zr$ variations scale with Mo isotope variations.

→ The bulk rock Zr isotope heterogeneity may be related to the s-process.

Updated s-process model predictions for Zr isotopes can be used to constrain the origin of the mixing line A.

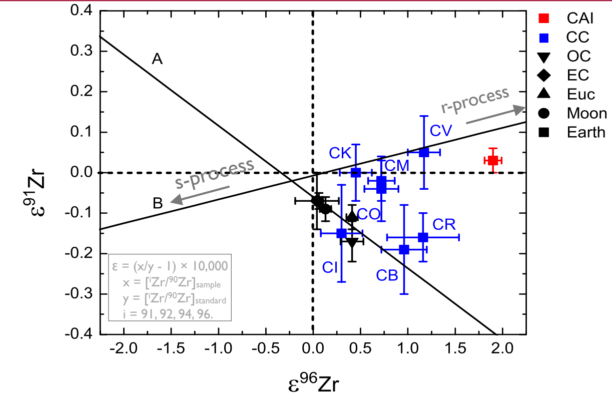

Fig. 1: Zr isotope data from [7] for carbonaceous (CC), ordinary (OC) and enstatite (EC) chondrites, eucrites (Euc), Earth and Moon. Data normalised to $^{94}Zr/^{90}Zr$. Best fit line (A) for Earth, Moon, OC, EC and Euc. Line B is defined by stepwise dissolution of CC (leachates) [9].

2. Methodology

Mixing Calculations

- We computed mixing lines between the Earth and the following s-process sources [(i) - (vii)]:
  - **Main s-process**
    - (i) Classical Model [LM AGB] [10]
    - (ii) Stellar Model (1999) [LM AGB] [10]
    - (iii) Stellar Model (2012) [LM AGB] [11]
    - (iv) Stellar Model (2012) [IM AGB] [11]
    - (v) Galactic Chemical Evolution [LM + IM AGB] [12]
  - **Weak s-process**
    - (vi) Core He exhaustion [MS] [13]
  - **Main s-process accompanying p-process**
    - (vii) White Dwarf [Type Ia SNe] [14]

LM: low mass (1 - 3 Msun), **IM**: intermediate mass (5 - 8 Msun), **MS**: massive stars (> 15 Msun).

Mixing lines are calculated relative to terrestrial samples ($\varepsilon^{91}Zr$, $\varepsilon^{96}Zr$ = 0).

3. Results

LM AGB Star

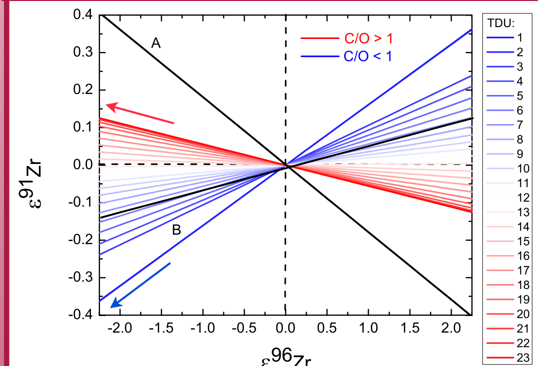

Fig. 2: Envelope composition of a single LM AGB star during sequential TDU episodes (characterised by increasing C/O ratios), with solar metallicity. Main neutron source: $^{13}C(\alpha,n)^{16}O$ reaction (kT ~ 8 KeV). Arrows indicate direction of s-process source. Lines A and B as in Fig. 1.

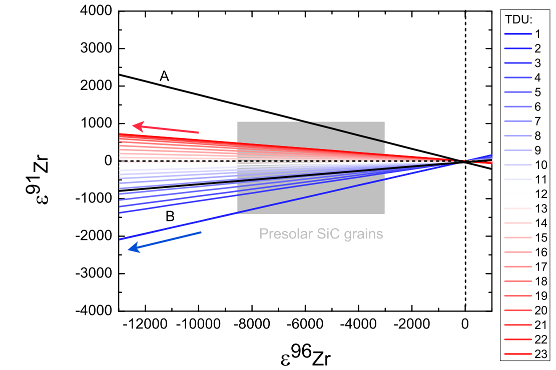

Fig. 3: Same as Fig. 2. but with an enlarged scale. Grey area shows the range of Zr isotope compositions measured for presolar SiC grains [15-17].

All s-process sources

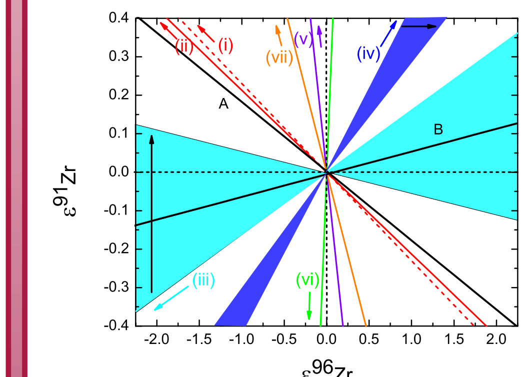

Fig. 4: Various mixing lines based on s-process predictions for Zr (see text). Stellar and classical models (1999) reproduce mixing line A well, unlike the recent model predictions [11].

4. Discussion

s-process Source

Leachate and SiC grain Zr data:

- Material condensing during the early TDU episodes (C/O < 1) of a LM AGB star admixed to terrestrial material, can explain the leachate data (Fig. 2).
- The Zr isotopic composition of presolar SiC grains matches the range of envelope compositions (for all C/O ratios) of LM AGB stars (Fig. 3).

→ LM AGB stars can account for Zr isotope variations in both acid leachates and SiC grains.

Bulk rock Zr data:

- The bulk rock Zr line (A) is not reproduced by any of the mixing lines generated by mixing material from a single LM AGB star, with terrestrial material (Fig. 2).
- Neither of the individual s-process sources (sites) reproduces the mixing line A (Fig. 4).

→ An n-component mixing between multiple s-process components (i.e. multiple stars) is needed to explain the bulk rock Zr isotope data.

s-process Heterogeneity

The heterogeneous distribution of material from multiple sources makes selective dust processing within the solar nebula a likely mechanism:

Injection of material from a single source:

- The injection of material from a single source can be excluded as the cause of bulk rock Zr isotope heterogeneities (line A).
- Thus the bulk rock heterogeneity is not caused by a late injection of supernovae material (or AGB material) that led to the collapse of the solar nebula.
- Sic grains fall on a different trend than the bulk rock heterogeneity. Hence, they are not the cause of the bulk rock heterogeneity.

Thermal processing:

- All bulk rock material fall on the s-deficit (i.e. depleted) side of the mixing line.

→ Multiple phases from different s-process sources were removed from regions in the solar nebula.
→ This can be explained by thermal processing of different s-process material within the solar nebula.

Bulk rock Zr, Mo and Ti isotope heterogeneity:

- Mo isotope variations attributed to a s-process deficit.
- Ti isotope variations attributed to thermal processing of dust [18].
- s-deficit material characterised by ^{50}Ti depletions [19].
  - Zr isotope variations ($\varepsilon^{96}Zr$) negatively correlate with Ti isotope variations ($\varepsilon^{50}Ti$).
  - Zr isotope variations ($\varepsilon^{96}Zr$) correlate with Mo isotope variations.

→ Bulk rock Zr, Mo and Ti isotope heterogeneity consistent with thermal processing of dust, with a multiple s-process component signatures.

Acknowledgements

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