ZIRCONIUM ISOTOPE EVIDENCE FOR DUST PROCESSING IN THE EARLY SOLAR NEBULA.

W. M. Akram[1] and M. Schönbächler[1], [1]Institut für Geochemie & Petrologie, ETH Zürich, 8092 Zürich, Switzerland (waheed.akram@erdw.ethz.ch).

Introduction: Mass independent, nucleosynthetic isotope variations can be used to place constraints on early solar system processes and evolution [1]. For example, Mo isotope variations are reported for differentiated and primitive meteorites relative to the Earth and Moon [2-5]. This large scale heterogeneity was attributed to different accretionary regions of the solar system that received variable contributions of s-process materials, most likely from a low mass (LM) AGB star [3]. The process(es) responsible for the heterogeneous distribution of s-process material, and the type of s-process material affected, requires further understanding. Zirconium isotopes are a powerful tool to address this issue because they are largely neutron capture isotopes, on the first s-process peak. As such, they receive contributions from multiple s-process sources, including the main (low (LM) and intermediate (IM) mass AGB stars) and the weak s-process (massive stars).

In recent studies, resolvable excesses (~ +1ε) were reported for the neutron-rich isotope ^{96}Zr in carbonaceous chondrites (CC) relative to terrestrial and lunar samples [7, 8, 9], while the bulk of CAIs are characterized by enrichments of ~ +2ε [10, 7]. For the majority of CCs, the ^{96}Zr/^{90}Zr excesses scale with the CAI abundance. However, the two-component mixing model (between (i) average solar system material represented by CI chondrites and (ii) CAIs) is unable to account for the observed ^{96}Zr/^{90}Zr enrichments in CR and CB meteorites, which are almost void of CAIs (< 0.1%) – see Fig. 1. Furthermore, ^{96}Zr/^{90}Zr excesses (up to 0.4ε) were identified for eucrites, enstatite and ordinary chondrites, accompanied by small variations in ^{91}Zr/^{90}Zr (< 0.3ε). In the ε^{96}Zr-ε^{91}Zr diagram, the ordinary and enstatite chondrites along with samples from differentiated bodies such as eucrites, terrestrial and lunar samples define a mixing line (A - see Fig. 1; slope = 0.18 ± 0.09;), which implies that the ^{96}Zr/^{90}Zr excesses are associated with ^{91}Zr/^{90}Zr depletions in the solar nebula. Here, we use updated stellar model predictions for the s-process to further constrain the origin of this mixing line (A).

Method: Using the Zr data from [9] and the two-component mixing model presented in [3], we computed mixing lines between different s-process sources and CI chondrites (Fig. 2). This approach allows us to compare isotopic stellar yields to measured, instrumental mass bias corrected values (ε). The following models were considered: (i) the classical and (ii) stellar model predictions of [6], which characterize the main s-process component for LM AGB stars (1-3 $M_\odot$); (iii) the updated stellar model of [11], which predicts the composition of the mass-losing envelope of LM (2$M_\odot$) AGB stars during sequential Third Dredge Up (TDU) episodes (characterized by progressively increasing C/O ratios); (iv) the same model as (iii) but for IM (5$M_\odot$) AGB stars; (v) a galactic chemical evolution model of both LM and IM AGB stars [12]; (vi) contributions from the weak s-process, during core He exhaustion (and/or the C burning shell) of a 25 $M_\odot$ star [13]; (vii) a Type Ia supernova model [14], where small amounts of Zr exist in the progenitor white dwarf – AGB star companion.

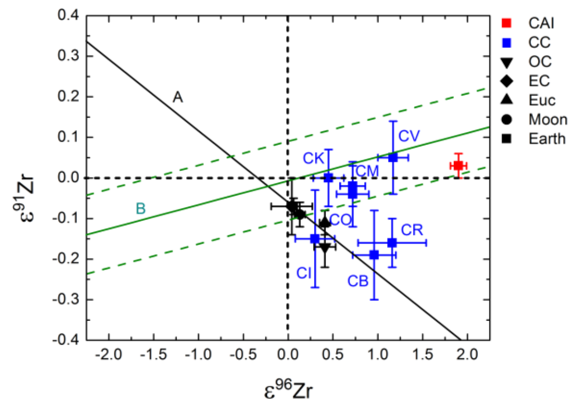

Figure 1: Zr isotope data from [9], for CCs, ordinary (OC) and enstatite (EC) chondrites, eucrites (Euc), Earth and Moon, and CAIs. Bulk rock mixing line (A), and leachate line (B) defined by stepwise dissolutions of CC [19] are also shown.

Results and Discussion: The considered models define various mixing lines (Fig. 2) characterized by s-process sources that are depleted in ε^{96}Zr (relative to the Earth) and depleted or enriched in ε^{91}Zr.

Models (i) and (ii) reproduce the mixing line A defined by bulk rock measurements closely, whereas the more recent model predictions (iii) and (iv) do not match the data. The latter predict a range of Zr isotope compositions, which gradually change with each successive TDU. In particular, for case (iii), the slope of the mixing line changes sign when C/O > 1, yielding positive ε^{91}Zr values (Fig. 2). For the higher mass AGB stars (iv), the range of Zr isotope compositions produced is more restricted (characterized by positive ε^{96}Zr and ε^{91}Zr). This is most likely due to the increased activation of the ^{22}Ne(α,n)^{25}Mg source. In both cases (iii) and (iv), a single AGB star is capable of producing grains with a range of Zr isotope compositions. The integrated isotopic yields from low and intermediate stellar masses (case v), averaged over different ^{13}C pocket efficiencies, metallicities and time falls between the mass specific models (iii) and (iv) for $2M_{\odot}$ and $5M_{\odot}$ AGB stars, respectively.

Mixing of an s-process component produced by a single star with average solar system material is incapable of explaining the $\varepsilon^{96}Zr$ - $\varepsilon^{91}Zr$ correlation defined by bulk rock samples (Fig. 2, line A). Rather, an n-component mixing between multiple s-process components (i.e. multiple stars) is needed (e.g. case (i) and (ii)) to explain the Zr isotope data.

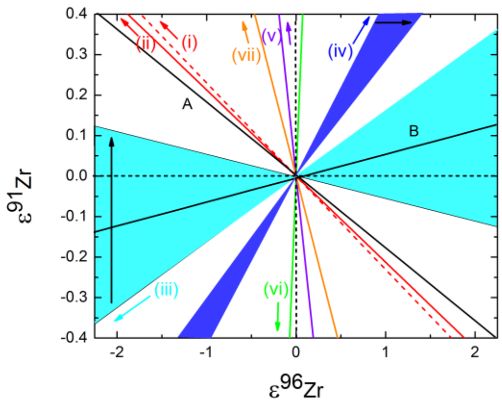

Figure 2: Various mixing lines based on s-process predictions for Zr, as defined in text, alongside the slopes defined by bulk rock Zr isotope data (A) and CC leachates (B). Black arrows for (iii) and (iv) show direction of increasing TDUs (i.e. C/O ratio).

Large Zr isotope variations also exist in acid leachates of CCs (from +50ε to -380ε for $^{96}Zr/^{90}Zr$) [15] and individual presolar SiC grains ($\varepsilon^{96}Zr \geq -9{,}000$) [16-18]. The leachates define a mixing line in $\varepsilon^{96}Zr$-$\varepsilon^{91}Zr$ space (Fig. 1, 2; line B; slope = 0.059 ± 0.003), which goes through the SiC data [15]. This slope is almost normal to the bulk rock line (A) and the predictions of the classical and stellar models [6]. The leachate line (B) is described well by LM AGB stars (case (iii)). Material dredged up can condense as SiC, which is then resolved by the leaching experiments. The leaching experiments, therefore, are influenced by SiC grains from LM AGB stars, while the bulk rock line indicates a mixture of dust produced in various types of s-process sources as an end member. Hence, materials from various s-process sources were heterogeneously distributed in the solar nebula resulting in the bulk rock heterogeneity. This is at odds with Mo isotope data [2–5], which points to a heterogeneous distribution of material restricted to LM AGB stars – cases (i) and (ii). This difference likely reflects the sensitivity of Zr isotopes to different s-process components, relative to Mo isotopes. Zr isotope provides evidence for multiple s-process sources and this excludes the heterogeneous distribution of material from an injection of a single star to the solar system. Rather, selective dust sorting within the solar nebula is the more likely mechanism that caused the heterogeneities. Two possible sorting mechanisms are:

Grain sorting: In this scenario [19], disk processes discriminate against grain size. This requires different s-process environments to produce similar sized grains, which survived the passage through the interstellar medium into our solar nebula.

Thermal processing: The Zr isotope variability (line A) indicates a deficit of s-process material from AGB stars. These stars also produce SiC grains that are enhanced in ^{50}Ti [21]. In line with this, the $\varepsilon^{96}Zr$ excesses of bulk rock samples are correlated with depletions in ^{50}Ti [20]. Thermal processing of dust within the solar nebula was proposed to account for the Ti isotope variability in the solar system [22], which by extension, may also apply to Zr isotopes.

Conclusions: Zr isotope data of bulk rock materials is compared to s-process model yields. The results indicate that the bulk rock heterogeneity reflects an s-process deficit, in agreement with Mo data [2-5]. A single source e.g., deficiency of LM AGB star material cannot explain the Zr data and mixing between multiple s-process sources is required. Since multiple sources are involved, an injection of material from a single star is not adequate, and selective sorting of dust grains within the solar nebula is the most likely process that caused the bulk heterogeneity. This can involve thermal processing, i.e. selective evaporation of dust in the hot region of the solar nebula or gain size sorting.

References: [1] Birck, J.-L. (2004) *In Geochemistry of non-traditional stable isotopes*, pp 25-64. [2] Dauphas N. et al. (2002) *ApJ.*, 565, 640-644. [3] Dauphas N. et al. (2004) *EPSL.*, 226, 465-475. [4] Burkhardt C. et al. (2011) *EPSL.*, 312, 390-400. [5] Burkhardt C. et al. (2012) *EPSL.*, 357, 298-307. [6] Arlandini C. et al. (1999) *ApJ.*, 525, 886-900. [7] Schönbächler M. et al. (2003) *EPSL.*, 216, 467-481. [8] Akram W. et al. (2011) *LPSC XXXXII*, [9] Akram W. et al. (2012) *PhD Thesis, The University of Manchester*. [10] Akram W. et al. (2011) 74th *MetSoc*. [11] Gallino R. (2012) *Priv. Comm.* [12] Travaglio C. et al. (2004) *ApJ.*, 601, 864-884. [13] Pignatari M. et al. (2010) *ApJ.*, 710, 1557-1577. [14] Travaglio C. et al. (2011) *ApJ.*, 739, 93-112. [15] Schönbächler M. et al. (2005) *GCA.*, 69, 5113-5122. [16] Nicolussi G. K. et al. (1997) *Science*, 277, 1281-1283. [17] Nicolussi G. K. et al. (1998) *ApJ.*, 504, 492-499. [18] Davis A. M. et al. (1999) *In Nuclei in the Cosmos V, eds. Prantzos N and Harissopulos S., Editions Frontières*, pp563-566. [19] Dauphas et al. (2010) *ApJ.*, 720, 1577-1591. [20] Schönbächler M. et al. (2011) *Formation of First Solids Workshop*, Hawaii. [21] Hoppe P. et al. (1994) *ApJ.*, 430, 870-890. [22] Trinquier A. et al. (2009) *Science*, 324, 374-376.