THE EVOLUTION OF THE PROTOPLANETARY DISK RECORDED BY NUCLEOSYNTHETIC ISOTOPE VARIATIONS OF VARIABLE STELLAR ORIGIN IN REFRACTORY INCLUSIONS.

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Introduction: The oldest known solar system material, calcium-aluminum-rich inclusions (CAIs), formed during the earliest stages of solar system formation in a hot area of the cooling protoplanetary disk. Numerous CAIs experienced re-heating and melting before they were brought to cooler disk regions and accreted onto their chondritic parent bodies. They carry characteristic nucleosynthetic isotope compositions, which they acquired in the part of the disk where they originally condensed. Hence, CAIs provide important constraints on the conditions prevailing in the hot disk region where they formed and evolved.

Our previous studies revealed that normal CAIs (non-FUN) can be divided into two groups based on their nucleosynthetic composition of Zr, Ti, Ni and Hf isotopes [1, 2]. The majority of the analyzed CAIs (main group) show correlated excesses in the neutron-rich isotopes ^{96}Zr and ^{50}Ti, and unexpectedly, in s-process Hf isotopes. The other rarer group of CAIs shows smaller ^{96}Zr and ^{50}Ti excesses coupled with s-process depletions in Hf isotopes [1]. Our preferred scenario to explain these data is a decoupling of the nucleosynthetic sources that produced the heavy and light ($A < 110$) neutron-rich isotopes. A similar conclusion was obtained by [3]. In our model [1], however, the light isotopes (e.g. ^{96}Zr) were mainly produced in Type II supernovae by charged-particle reactions. These reactions occurred in a high entropy wind environment, in which the heavier Hf isotopes cannot form. Here, we have extended the database to 17 new CAIs from the CV chondrites Allende and Mokoia to further evaluate the extent of nucleosynthetic heterogeneities recorded by CAIs.

Results and discussion: The analyzed CAIs (fine-grained and coarse-grained) were classified as type A, B or C. Furthermore, we obtained rare earth element (REE) concentrations, Nb/Zr ratios and high precision Zr, Sr and Ti isotope data. The new data for CAIs with non-group II REE patterns are in agreement with previous results [1, 2], which showed a relatively limited spread in isotopic composition. For example, ε^{96}Zr scatters around 0.8 for the rare group and 2.0 for the main group. This suggests that these CAIs condensed from a relatively well-mixed reservoir in the protoplanetary disk. Moreover, ^{92}Zr/^{90}Zr ratios correlate with Nb/Zr ratios and indicate an initial ^{92}Nb/^{93}Nb ratio of 1.6 (±1.5) x 10^{-5} for our solar system. In combination with previous work [4, 5, 6], this demonstrates the homogeneous distribution of the p-process isotope ^{92}Nb in the region sampled by these CAIs, chondrites, mesosiderites and achondrites and enables the use of the Nb-Zr chronometer (half-life = 36 Myr) to date early silicate differentiation.

However, we also analyzed inclusions with group II REE patterns. The Zr isotope compositions of these CAIs display a larger and more variable spread (ε^{96}Zr from -0.3 to + 5.0). The ^{92}Zr/^{90}Zr and Nb/Zr ratios are again correlated, but indicate a higher initial ^{92}Nb/^{93}Nb ratio on the order of 3 x 10^{-5}. This provides evidence for a p-process heterogeneity that was only sampled by group II CAIs. It suggests that these inclusions formed from a less well homogenized reservoir that was separated from the reservoir of the other CAIs either in time and/or space. We propose that these CAIs formed as condensates to explain their REE pattern [6], but also entrained some refractory dust grains. These dust grains were never fully evaporated and preserved their original nucleosynthetic signature, carrying an ^{92}Nb excess probably produced in a supernova environment. Hence, CAIs can be divided into subgroups that likely sampled an evolving gas-dominated reservoir in the protoplanetary disk close to the Sun. They are condensates and may have re-melted at some point, but likely also record the survival of extremely refractory dust in a hot nebular environment.

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