

# コンドライト隕石の Sr 同位体異常に見られる初期太陽系の同位体二分性

深井 稜汰<sup>1</sup>、横山 哲也<sup>1</sup>、杉本 圭<sup>1</sup>

<sup>1</sup>東京工業大学 地球惑星科学系

## Isotopic dichotomy in the early Solar System inferred from nucleosynthetic Sr isotope anomalies in bulk chondrites

Ryota FUKAI<sup>1</sup>, Tetsuya YOKOYAMA<sup>1</sup>, and Kei SUGIMOTO<sup>1</sup>

<sup>1</sup>Department of Earth and Planetary Sciences, Tokyo Institute of Technology

### Introduction:

The Solar System has formed by the collapse of molecular cloud core composed of gas and presolar dust grains that originated from various stellar environments (e.g., AGB stars and supernovae). The early Solar System has been considered to be isotopically homogeneous as a result of destruction of presolar dust grains via multiple physical processes occurred in the molecular cloud and the solar nebula. However, the finding of planetary-scale isotopic variability for refractory heavy elements in bulk meteorites revealed that the Solar System was not isotopically homogeneous as was previously thought. The observed isotopic heterogeneity in bulk meteorites is most likely nucleosynthetic in origin, which would provide useful information regarding the physical condition of the early Solar System.

Recently, Warren [1] proposed a new taxonomy of meteorites based on the stable isotopic compositions of O, Ti and Cr, by which stony meteorites can be divided into carbonaceous chondrites and the other meteorites (non-carbonaceous meteorites: ordinary chondrites, enstatite chondrites, and achondrites). Such an "isotopic dichotomy" between carbonaceous chondrites (CCs) and non-carbonaceous meteorites (NCs) have been reported for the other isotopic systems including Cr–Sr [2] and Mo [3–4]. The observation implies the presence of two isotopically distinct reservoirs in the solar nebula, which could be generated by the input of supernova-ejected materials into the region where carbonaceous chondrites have formed [4]. In addition, the other physical processes (e.g., size sorting and nebular thermal processing) were proposed to account for the isotopic heterogeneity between CCs and NCs [5].

Sr is an intriguing element for revealing the origin of isotopic dichotomy observed in meteorites. Sr has four isotopes synthesized by the *p*-process (<sup>84</sup>Sr) and *s*-process (<sup>86</sup>Sr, <sup>87</sup>Sr, <sup>88</sup>Sr), while a small portion of <sup>88</sup>Sr is produced by the *r*-process. Sr isotopic compositions in meteorites are susceptible to the input of supernova materials because Type II supernovae dominantly synthesize light *r*-process nuclides (*A* < 110–130) [6]. In addition, a previous study found an isotopic variation of <sup>84</sup>Sr/<sup>86</sup>Sr ratios among different classes of CCs and NCs [2] that cannot be explained by a single process. However, the extent of Sr isotope heterogeneities across entire classes of chondrites remains unclear due to the limited number of Sr isotope data with sufficiently high precision. In this study, we revisited high precision Sr isotope analysis of bulk chondrites coupled with a robust sample digestion technique that confirmed complete dissolution of presolar grains.

### Experimental:

We investigated two terrestrial basalts (JB-3 and JB-1a), one enstatite chondrite (Y-691, EH3), two ordinary chondrites (Forest City, H5; Saratov, L4), and four types of carbonaceous chondrites (Dho 1432, CR2; Murchison, CM2; DaG 190, CO3; and Allende, CV3). The meteorite chips were cleaned with acetone and H<sub>2</sub>O, then powdered using either an agate mortar and pestle or a sample homogenizer. The enstatite and ordinary chondrites with a petrologic grade greater than 3.6 were dissolved by a conventional acid digestion method using HNO<sub>3</sub> + HF + HClO<sub>4</sub>. For carbonaceous chondrites, each sample was digested using a high-pressure digestion system (DAB-2, Berghof) with HF + HNO<sub>3</sub> + H<sub>2</sub>SO<sub>4</sub> to completely dissolve acid resistant presolar grains (e.g., SiC, graphite). Sr isotope measurements were performed using TIMS (Triton *plus*, Thermo Fisher Scientific) installed at the Tokyo Institute of Technology. Sr isotopes were collected with a two-jump cup configuration within a single measurement run, in which <sup>84</sup>Sr/<sup>86</sup>Sr and <sup>87</sup>Sr/<sup>86</sup>Sr ratios were obtained using multistatic method. The reproducibilities for NIST 987 standard obtained by the multistatic method were ±18 ppm and ±9.2 ppm for <sup>84</sup>Sr/<sup>86</sup>Sr and <sup>87</sup>Sr/<sup>86</sup>Sr ratios (*n* = 18, 2 SD), which are approximately two times superior to those in previous studies [2,7–8]. The Sr isotope ratios for terrestrial and meteorite samples are reported in the  $\mu$ Sr notation that is parts per 10<sup>6</sup> relative deviation from the standard (NIST 987).

### Results and discussion:

All types of chondrites including the enstatite chondrite exhibited positive isotope anomalies in  $\mu^{84}\text{Sr}$  compared with the terrestrial basalts. The enstatite and ordinary chondrites possessed uniform  $\mu^{84}\text{Sr}$  isotopic compositions within each group. In contrast, different classes of carbonaceous chondrites showed variable  $\mu^{84}\text{Sr}$  isotope anomalies, which extended from –5.4 ppm (CR2) to 62 ppm (CV3). To assess the cause of variable  $\mu^{84}\text{Sr}$  values across different types of chondrites, we compared the results with Nd isotopic data from the same aliquots reported in [9]. The enstatite and ordinary chondrites (non-carbonaceous meteorites) and terrestrial basalts present a positive correlation in the  $\mu^{84}\text{Sr}$  versus  $\mu^{148}\text{Nd}$  and  $\mu^{84}\text{Sr}$  versus  $\mu^{150}\text{Nd}$  diagrams (Fig. 1). In addition, non-carbonaceous meteorites are plotted on the mixing line of *s*-process components [10] and terrestrial

composition. This suggests that *s*-process components have been heterogeneously distributed within the inner Solar System, which is consistent with the results of Mo–Nd isotope measurements [11].

In contrast to the non-carbonaceous meteorites, different types of carbonaceous chondrites show a positive shift from the mixing line of *s*-nuclide and terrestrial material (Fig. 1). CAIs (Calcium- and Aluminum-rich inclusions), the additional anomalous carriers of refractory heavy elements in bulk carbonaceous chondrites, could induce the offset observed in the results of carbonaceous chondrites. To assess this hypothesis, we conducted a mass-balance calculation in which the contribution of CAIs was subtracted from the bulk carbonaceous chondrites. Consequently, carbonaceous chondrites without CAIs are generally plotted on the mixing line of *s*-nuclides and terrestrial materials in the  $\mu^{84}\text{Sr}$  versus  $\mu^{148}\text{Nd}$  and  $\mu^{84}\text{Sr}$  versus  $\mu^{150}\text{Nd}$  diagrams (Fig. 2). This result implies that the isotope heterogeneities for Sr and Nd in carbonaceous chondrites were caused by the two main processes; (i) heterogeneous distribution of *s*-process components in the solar nebula and (ii) incorporation of CAIs into the location where parental bodies of carbonaceous chondrites have formed.

The positive correlation observed in non-carbonaceous meteorites and CAI-free carbonaceous chondrites suggests that a single carrier exhibiting *s*-excess signatures both in Sr and Nd isotopes, which is most likely mainstream SiC grains, has been heterogeneously distributed throughout the early Solar System. The positive correlation within non-carbonaceous meteorites and terrestrial basalts is interpreted that nebular thermal processing selectively destroyed thermally weak dust grains that were depleted in *s*-process components. The CAI-free carbonaceous chondrites show a similar positive trend, however, simple thermal processing model do not account for Sr and Nd isotope variations within different types of carbonaceous chondrites. For instance, CR chondrites, which are considered to have formed in the outer Solar System [12], represent the Sr isotopic composition close to the non-carbonaceous meteorites. These results suggest that physical processes that induced the heterogeneous distribution of presolar dust grains would be distinct between non-carbonaceous and carbonaceous meteorites.

**Figures:**

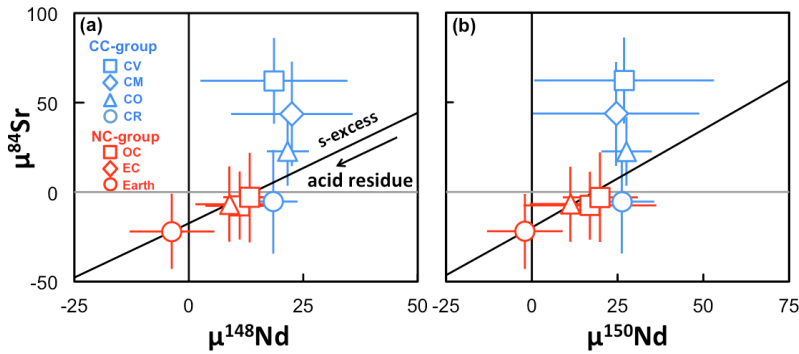


Figure 1. Sr and Nd isotope compositions of chondrites plotted on the  $\mu^{84}\text{Sr}$ – $\mu^{148}\text{Nd}$  and  $\mu^{150}\text{Nd}$  diagrams (Errors: 2SD).

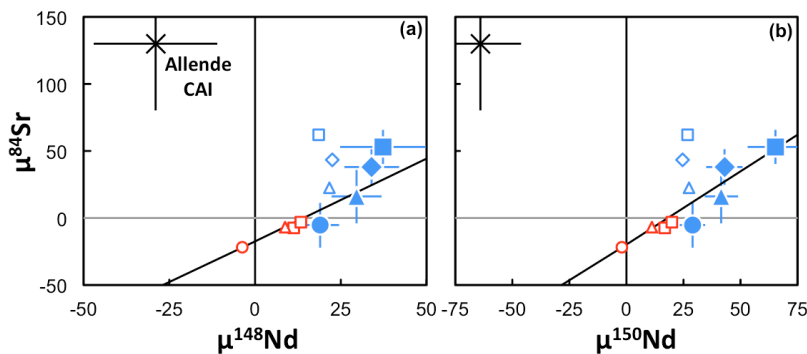


Figure 2. Sr and Nd isotope compositions of CAI-free CC plotted on the  $\mu^{84}\text{Sr}$ – $\mu^{148}\text{Nd}$  and  $\mu^{150}\text{Nd}$  diagrams (Errors: 2SE). Open symbols are the same as in figure 1. CAI data are from [13].

**References:**

[1] Warren, P. H. *EPSL*, **311**, 93, 2011. [2] Yokoyama, T. et al. *EPSL*, **416**, 46, 2015. [3] Budde, G. et al. *EPSL*, **454**, 293, 2016. [4] Worsham, E. A. et al. *EPSL*, **467**, 157, 2017. [5] Poole, G. M. et al. *EPSL*, **473**, 215, 2017. [6] Akram, W. et al. *ApJ*, **777**, 169, 2013. [7] Moynier, F. et al. *ApJ*, **758**, 45, 2012. [8] Paton, C. et al. *ApJL*, **763 (L40)**, 2013. [9] Fukai, R. and Yokoyama, T. *EPSL*, **474**, 206, 2017. [10] Qin, L. et al. *GCA*, **75**, 7806, 2011. [11] Render, J. et al. *GPL*, **3**, 170, 2017. [12] Van Kooten, E. M. M. E. et al. *PNAS*, **113 (8)**, 2011, 2017. [13] Brennecka, G. A. et al. *PNAS*, **110 (43)**, 17241, 2013.