Si and Mg isotopes in Enstatite chondrites and the evolution of inner solar nebula

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Introduction: Compared to ordinary and carbonaceous chondrites (OC/CC), Enstatite chondrites (EC) are known to have formed in inner regions of the solar system with higher C/O ratio (~0.83) relative to solar value (~0.5) [1]. A characteristic feature of EC is that they display the least nucleosynthetic/stable isotope anomaly relative to terrestrial rock samples (BSE) for a number of elements such as O, S, N, Mo, Ru, Ni, Cr, Ti, Fe, Os, Nd, Ca, Zn and Sr, which is suggested to indicate a genetic link between EC and the Earth [2]. Si isotopes have remained an odd to this observation and the relatively larger $\delta^{30}Si$ offset between bulk EC and BSE has been used to suggest a negligible contribution of EC like planetary bodies in the accretion of Earth [3]. This is further supported by the unique chemical composition of EC and its lower Mg/Si ratio compared to BSE. Si and Mg are amongst the most abundant elements in the solar system that are involved in almost all major geo- and cosmo-chemical processes. Being formed under highly reduced conditions, EC displays a bimodal distribution of Si among metal and silicates whereas Mg in distributed in its respective silicate and sulfide phases [4]. EC are nebular condensates and an understanding of the extent of Si and Mg isotope fractionation among different components of EC should provide unique insights into the evolution of the inner reduced solar nebula where Earth and other terrestrial planets had accreted.

Samples and Methods: Mineralogically pre-characterized metals, silicates and matrices (metal-silicate-sulfide mixed phases) were carefully micromilled from three un-equilibrated enstatite chondrites (EH3): PCA 91461, LAR 06252, MIL 07028. Additionally, non-magnetic and magnetic separates of two more EH3 chondrites: Y 691 and Parsa were also analyzed. Following NaOH digestion in Teflon vial, simultaneous purification of Si and Mg from same aliquot of the samples was carried out using a newly developed chromatographic protocol [5]. The Si and Mg isotopic analysis were performed using Thermo Neptune MC-ICPMS at PRL, India.

Results: We found extreme Si isotope heterogeneity within different fractions of EC that varies according to the variable proportions of metal to silicate in the target phases. The metals of EC possess extremely light $\delta^{30}Si$, going as low as –6.94±0.09‰. Interestingly, the silicate phases were found to be substantially heavier with average $\delta^{30}Si$ of –0.33±0.11‰, which is remarkably similar to BSE (–0.29±0.08‰). In contrast to Si isotopes, Mg isotopes were found to be homogeneously distributed in the silicate and matrix fractions of EC and the average $\delta^{26}Mg_{silicate/matrices}$ (–0.29±0.12‰, 2SD) was found to be indistinguishable from $\delta^{26}Mg_{BSE}$.

Discussion: According to condensation sequence of minerals at high C/O ratio, metals of reduced nebula (an alloy of Fe, Ni and Si) become increasingly more refractory leading to its earlier condensation followed by silicates and oxides [1]. Therefore, based on thermodynamic constraints on condensation sequence of minerals in oxygen deficient region and Si-Mg isotope data from micro-phases of EC, it can be suggested that the preferential alloying of extremely light Si isotopes in early-condensed metals of reduced nebula is a likely mechanism that had enriched the residual silicate-dominated gaseous reservoir in heavier isotopes of Si relative to unfractionated $\delta^{30}Si_{OC/CC}$. As the inner nebula cooled further, the silicates condensed with its characteristic heavy $\delta^{30}Si$ signature and accreted with early formed metals to form EC parent bodies. Unlike Si isotopes, Mg isotopes were not fractionated by its partitioning between silicates and sulfides. The similarity in $\delta^{30}Si$ and $\delta^{26}Mg$ between silicate reservoir of Earth, *i.e.,* BSE and silicate fractions of EH3 chondrites provides a strong evidence for similar sequence of isotope evolution in both the planetary bodies.

Incorporation of ~1-3 wt% nebular Si in the huge metallic inventory of Earth forming embryos (similar to EC) is a probable mechanism for the gradual enhancement of FeO content in the residual (otherwise reduced) silicate gaseous reservoir through the reaction $2Fe_{metal} + SiO_{2silicate} = 2FeO_{silicate} + Si_{metal}$ [2]. One important consequence of such gradual oxygenation event in the Earth accretion region is that the formation of enstatite ($MgSiO_3$) through reaction between forsterite (Mg_2SiO_4) and SiO gas could not go to completion. As a result of the significant incorporation of forsterite (Mg/Si=2 for olivine) along with partitioning of Si in the core, the Mg/Si of BSE was elevated to higher values compared to silicate fractions of EC (Mg/Si=1 for Enstatite ($MgSiO_3$)). Thus, the chemical evolution pathway of Earth was eventually modified relative to EC although both the planetary bodies evolved in isotopically similar way from initially reduced nebular gas.

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