A COMBINED SILICON AND MAGNESIUM ISOTOPIC STUDY OF BULK METEORITES AND THE EARTH

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Introduction: Variations in the isotopic compositions between Earth and other Solar System bodies has been well documented. Isotopic differences between Earth and bulk meteorites can broadly be attributed to the following processes: (1) Fractionation and incomplete mixing in the solar nebula prior to accretion (2) Late injection of pre-solar material and its inhomogeneous distribution and (3) Terrestrial fractionation – from partial melting of the mantle and core formation. The extent of isotopic differences between Earth and meteorites vary. While there are large variations in Oxygen isotopes between Earth and meteorites and their components [1], smaller variations are observed in ^{26}Mg, ^{53}Cr, ^{129}Xe, ^{182}W and ^{142}Nd, due to decay of extinct radionuclides. Extremely small isotopic differences, as low as a few ppm, have been discovered between bulk meteorites and the Earth for ^{54}Cr [2], ^{50}Ti [3], ^{95,97}Mo [4], ^{96}Zr [5], $^{135,\ 138}$Ba [6,7], ^{142}Nd [8] and ^{144}Sm [9].

Even in major element compositions, differences exist between the Earth and meteorites. The primitive upper mantle of the Earth has a distinctly higher Mg/Si compared to chondrites and Mars [10-13]. A popular explanation of the superchondritic Mg/Si of the Earth's primitive upper mantle (PUM) is incorporation of Si in the Earth's core, consistent with the density constraints of the outer core.

Si and Mg isotopic variations: Very recently, it has been shown that the Silicon isotopic compositions (δ^{30}Si) of bulk meteorites (both differentiated and undifferentiated) are lighter (by ~0.3‰) than the Bulk Silicate Earth (BSE) and the Moon [14]. The heavier Si-isotopic composition of the Earth compared to bulk meteorites has been attributed to core formation on Earth. There is, however, a very limited dataset available for the Si-isotopic composition of terrestrial samples and meteorites owing to the analytical difficulties in measuring Si isotopes.

Mg isotopic compositions of most meteorites do not show much variability and it is debatable whether the BSE has a slightly heavier isotopic composition compared to chondrites [15] or is chondritic [16].

Goals of the present study: We have undertaken a study to perform Si and Mg isotopic measurements in the same samples of chondritic meteorites and silicate terrestrial samples. Si and Mg isotopes are analyzed by MC-ICPMS. Measurement of standards have yielded an external reproducibility of less than 0.1‰ ($\pm$ 1 standard deviation, s.d.) for δ^{30}Si and ~ 0.07 ‰ (1s.d.) for δ^{26}Mg. By analyzing the isotopes of Si and Mg, which are major chemical constituents of meteorites and the bulk silicate Earth, we wish to investigate whether there are any variations in the Si and Mg isotopic compositions of meteorites and the Earth, given the superchondritic Mg/Si of the PUM of the Earth.

Results: We have analyzed 14 meteorites, terrestrial and lunar samples for their Si-isotopic compositions using high-resolution MC-ICPMS. Si-isotopic variability in differentiated and undifferentiated meteorites, lunar rocks and terrestrial mantle-derived samples is small, follows mass-dependent isotopic fractionation and does not show any resolvable nucleosynthetic isotopic anomalies. Chondrites show a relatively wider range in δ^{30}Si and cover the entire range of values observed in all the samples of the present study. Average δ^{30}Si of the six chondrites analyzed is -0.41 $\pm$ 0.08 ‰. (1 s.d.). There is no discernible difference in the Si-isotopic composition of carbonaceous chondrites and ordinary chondrites. Average δ^{30}Si of achondrites derived from differentiated bodies Mars and Vesta as well as olivines from the Brenham pallasite is 0.42 $\pm$ 0.07 ‰. (1s.d.). Four representative terrestrial mantle-derived samples, including olivines from mantle peridotites and whole-rock basalts, show an average δ^{30}Si of 0.41 $\pm$ 0.07 ‰. (1 s.d.) whereas, a lunar breccia sample shows δ^{30}Si of -0.48 ‰. Our data suggests that Si-isotopic composition of the solar nebula was homogeneous and no later processes like accretion, planetary differentiation (partial melting or core formation) or giant impacts have fractionated Si-isotopes. Si isotopic variability in CAIs are due to kinetic evaporation-condensation effects [1].

We have also measured Mg-isotopes using MC-ICPMS in several terrestrial mantle-derived rocks and meteorites. All samples of the present study follow mass-dependent isotopic fractionation. δ^{26}Mg of chondrites (CHUR) (average = -0.5 $\pm$ 0.15‰) strongly overlap with terrestrial peridotites and basalts (BSE) (average = -0.6 $\pm$ 0.15‰).

Discussion: Our data suggests that the solar nebula was homogeneous with respect to Si isotopes. PUM of the Earth and chondrites are also homogeneous in Mg isotopes. While our data do not rule out incorporation of silicon in the Earth's core, no associated Si isotopic fractionation is observed. An alternate way to explain the superchondritic Mg/Si in the primitive upper mantle (PUM) is by heterogeneous accretion from the solar nebula. Mg/Si of chondrules are similar to those observed in mantle peridotites suggesting that the Earth possibly accreted from a more chondrule rich source in the proto-planetary disc compared to CI chondrites [12] and superchondritic Mg/Si of the PUM reflects source heterogeneity rather than later processes related to the core formation.

Experimental studies of partitioning of V, Cr and Si between metal and silicate in a wide range of pressures (1bar- 250kbar), temperatures (1260-2300^{0}C) and redox states (IW to IW-5) indicate that V and Cr are always more siderophile than Si [17-18]. If Si was partitioned into liquid metal during core formation, the abundances of V and Cr in the Earth's mantle would have been much lower than observed. At even higher pressures (>25 GPa) and temperatures (~ 2800K), equivalent to conditions at the base of a deep (>700 km) magma ocean, 2-7 wt% Si can dissolve into metal Fe [19]. Even though the siderophile nature of V, Cr and Mn increases only weakly with increasing pressures, at such high temperatures, V, Cr and Mn are extremely siderophile and their concentrations in the Earth's mantle would be negligible if such a condition existed [20]. However, this is not observed. Hence, in accordance with the heterogeneous accretion scenario mentioned above, the superchondritic Mg/Si of the Earth's upper mantle could have been an intrinsic property. It follows that the Si isotopic composition of the silicate Earth or the Moon should not be any different from chondrites as shown in the present study.

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