SILICON ISOTOPE EVIDENCE FOR AN ENSTATITE CHONDRITIC COMPOSITION FOR BULK SILICATE EARTH. V. K. Rai[1,2*] and J. Sikdar[1,3], [1]Physical Research Laboratory, Ahmedabad, India, [2]Center for Meteorite Studies, School of Earth and Space Exploration, Arizona State University, Tempe, USA, [3]Institut für Geologische Wissenschaften, Freie Universität Berlin, (*vkrai@asu.edu).

Introduction: Enstatite chondrites (EC) are a highly reduced group of meteorites that shows a bimodal distribution of Si between silicates and metals [1]. Compared to carbonaceous and ordinary chondrites, EC displays more similarity to bulk silicate Earth (BSE) for mass-dependent and mass-indepentent fractionations for a variety of elements such as O, S, N, Mo, Ru, Ni, Cr, Ti, Fe, Os, Nd, Ca, Zn and Sr with the exception of Si [2 and references therein]. Being one of the most abundant elements in the Solar System, the isotopic distribution of Si between chondrites and BSE places important constraints on identifying the building blocks of the terrestrial planets. The heavier silicon isotope of BSE and its higher Mg/Si ratio compared to chondrites have been used to argue for the presence of Si in Earth's core with a lighter isotopic composition, which also explains the core's density deficit relative to pure Fe-Ni alloy [3-4]. Although a number of studies have been carried out to estimate the Si content of Earth's core based on the $\delta^{30}Si$ offset between BSE and chondrites, such estimates depend on the choice of chondrites taken as proxy for bulk Earth composition and are based on the assumption of high temperature equilibrium Si isotope fractionation at the core-mantle boundary of the Earth [4-7]. The $\delta^{30}Si$ $[=\{(^{30}Si/^{28}Si_{sample})/(^{30}Si/^{28}Si_{NBS28})-1\}\times1000]$ offset between BSE and ordinary/carbonaceous chondrites ($\Delta^{30}Si_{BSE\text{-}OC/CC}$ = ~0.15‰) provides an estimation of ~6-12 wt% Si in Earth's core, which is consistent with most geophysical models. On the other hand, the relatively larger $\delta^{30}Si$ offset between BSE and EC ($\Delta^{30}Si_{BSE\text{-}EC}$ = ~0.30‰) demands the presence of ~28 wt% Si in Earth's core for an enstatite chondrite Earth model, which is significantly higher than that predicted by geophysical models. This led researchers to argue for a negligible contribution of EC like planetesimals to the accretion of Earth [7].

However, a recent study has shown that the non-magnetic fractions of EC possess heavier $\delta^{30}Si$ compared to bulk enstatite chondrite, suggesting heterogeneous Si isotope distribution within different components of EC [8]. Therefore, it is important to constrain the extent of Si isotope heterogeneity within different components within EC since it could have implications for whether EC may be a suitable precursor material for Earth.

Samples and Methods: Since the presence of finely disseminated metals throughout EC makes it difficult to effectively separate metals and silicates using hand magnets, we carefully micro-milled the purest possible components of EC that were pre-characterized using EPMA. The Si isotopic analysis was performed using Thermo Neptune MC-ICPMS at PRL. Following NaOH digestion in Teflon vial and column chromatography of the micromilled phases using a protocol described in [9], Si isotope analyses were carried out in several pure silicate and metal grains from three EH3 chondrites: PCA 91461, LAR 06252, MIL 07028. Additionally, non-magnetic and magnetic separates of two more EH3 chondrites: Y 691 and Parsa were also analyzed in this study. Samples were also analyzed from the fine grained component where grains were too small to get pure phases, these phases are defined a matrices.

Results: Our Si isotope measurements in micromilled phases of EC reveal the presence of extremely light $\delta^{30}Si$ in metals of enstatite chondrites with $\delta^{30}Si$ values as low as -6.94±0.09‰. Interestingly, the silicate phases were found to possess heavier $\delta^{30}Si$ composition (with an average value of -0.33±0.11‰), which is strikingly similar to BSE (–0.29±0.08‰ [10]). The $\delta^{30}Si$ values of matrices were found to vary, depending on the proportion of metal and silicate in these fractions (Fig. 1).

Discussion: The highly reduced nature of EC is indicative of their formation in inner regions of solar system with higher C/O ratio (~0.83) compared to solar C/O ratio of 0.42-0.5 [11]. One of the major differences in the condensation sequence of solar nebula at high C/O ratio (compared to solar C/O ratio) is the marked depression of condensation temperature (T_c) by ~400°C of the silicates and oxide phases. Unlike in an oxidized environment, the Fe-Ni metals become increasingly more refractory under reducing conditions, leading to earlier condensation relative to silicates. Under this scenario, the condensed metal is not only enriched in Si (1-3 wt%) but also prefers lighter isotopes as evidenced in EC metal. The isolation of a significant fraction of lighter Si in early condensed metal might have left the residual Si reservoir heavy. The silicates of EC are most likely condensed from this residul gas reservoir.

The similarity in Si isotope composition of BSE and silicate fractions of EH3 chondrite provides a strong evidence that the Earth had followed a similar sequence of heterogeneous accretion as that of enstatite chondrite, wherein the Si rich metallic embryos (Fe,Ni) had accreted preferentially earlier than silicates from a reduced nebula. Earth might have resulted from acretion of several such embryos where metal and silicates has already segregated. Upon partial melting, these metals segregated towards center and form the core.

Even in reduced solar nebula, Forsterite (Mg/Si~2) was the first silicate phase condensed. As the temperature cools down further, forsterite react with residual nebular SiO and converted to enstatite (Mg/Si~1). It is likely that Earth forming embryo might have sampled more of forsterite thereby showing high Mg/Si. Enstatite chondrite parent body which might have formed chemically evolved nebula after the major acretion of Earth, might have sampled enstatite rich silicate components.

Apart from enstatite chondritic silicates, lunar rocks [5] and angrites [12] are the only planetary bodies of solar system that carries nearly identical silicon isotope signature as that of BSE. The δ^{30}Si similarity between lunar rocks and BSE suggests either similar evolutionary sequence of Moon as that of Earth or the derivation of a major fraction of Moon from BSE after core formation in Earth had seized completely. A significant partitioning of light Si isotopes in metallic core of angrite would be an unlikely explanation of angrite's heavy δ^{30}Si composition due to its formation under oxygenated environment [12]. The accretion of angrites in a region where oxygen fugacity was spiked up due to localized accumulation of water vapor and SiO like migrators diffused out from adjacent reduced EC-Earth forming region could be a likely explanation for its similar δ^{30}Si as BSE and silicate fractions of EC.

Conclusion: The results of this work demonstrate that the lighter bulk δ^{30}Si of enstatite chondrites compared to ordinary and carbonaceous chondrites is a result of the incorporation of extremely light isotopes of Si in metallic fractions of EC. The fact that the silicate phases of EC have remarkably heavier δ^{30}Si, similar to BSE provides a very strong evidence for the formation of Earth and EC in a narrow region of solar nebula that had similar isotopic composition. The elevated δ^{30}Si of BSE compared to chondrites is best explained by the inheritance of the isotopic signature of Earth from a reduced nebular setting where fractionation was dominated by the partitioning of Si between metal and silicates rather than high temperature equilibrium Si isotope fractionation at the core-mantle boundary of Earth.

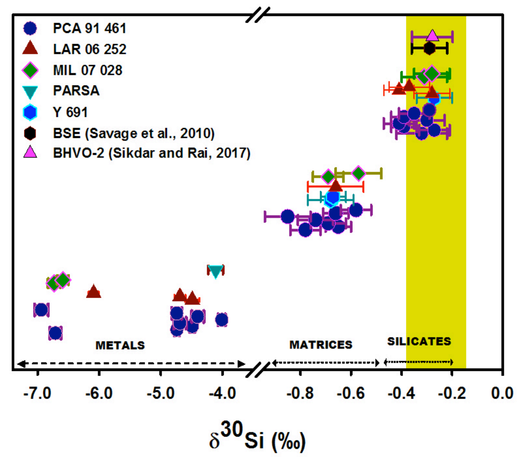

Fig 1. Variation in Si isotopic composition among different micro-phases of EH3 chondrites. The metals of EH3 chondrites are enriched in lighter isotopes of Si and silicates are isotopically similar to terrestrial rock samples. The yellow band represents the range of Si isotope composition for BSE by [6].

References: [1] Ringwood, A.E. (1961) *GCA* 25, 1–13. [2] Dauphas N., *Nature*, **541**, 521-524 (2017 [3] Allègre et al., (2001) *EPSL* 185(1), 49-69. [4] Georg et al., (2007) *Nature* 447 (7148), 1102-1106. [5] Armytage et al., (2011) *GCA* 75(13), 3662-3676. [6] Zambardi et al., (2013) *GCA* 121, 67-83. [7] Fitoussi, C. and Bourdon, B. (2012) *Science* 335, 1477–1480. [8] Savage, PS. and Moynier, F. (2013) *GCA* 361, 487-496. [9] Sikdar, J. and Rai, V.K. (2017) *JAAS* 32, 822-833. [10] Savage et al., (2010) *EPSL* 295, 139–146. [11] Larimer, J. and Bartholomay, M. (1979) *GCA* 43, 1455-1466. [12] Dauphas et al., (2015) *EPSL* 427, 236-248.