

AN ISOTOPICALLY HOMOGENEOUS REGION OF THE INNER TERRESTRIAL PLANET REGION (MERCURY TO EARTH): EVIDENCE FROM E CHONDRITES AND IMPLICATIONS FOR GIANT MOON-FORMING IMPACT SCENARIOS.

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Introduction: A considerable variability in isotopic compositions and water contents among various planetary materials in the inner Solar System (Fig. 1) is now well established. This means that mixing of bulk of the material during accretion, at least in some regions of the inner Solar System, was limited. This evidence has been used to argue that planetary objects forming in the inner Solar System received the overwhelming majority of their masses from narrow annuli around the Sun [1].

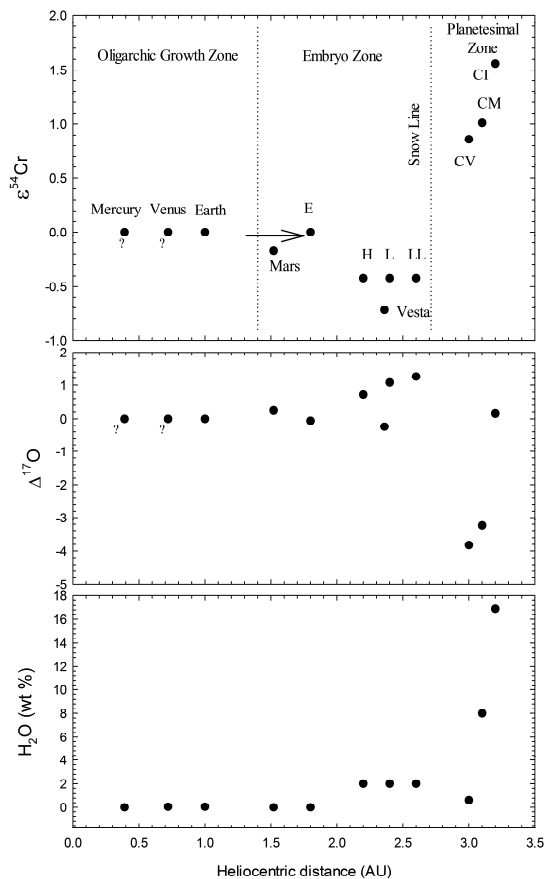


Fig.1. Variations in isotopic ratios and water content in the inner Solar System.

If so, the exact O isotope match between Earth and Moon suggests that the proto-Earth and the Moon-forming impactor were formed in the same source region. However, current dynamical models invoke three planet-forming stages: i) coagulation of dust in the protoplanetary disk into km-sized planetesimals, ii) runaway growth of these planetesimals to lunar- to Mars-sized planetary embryos, and iii) the main mass accre-

tion of planets via giant impacts. During stage 2 embryos rapidly accrete all of the material in their feeding zones that are typically only ~ 0.01 AU wide over $\sim 10^5$ – 10^6 yr. Thus, planetesimals and planetary embryos up to about Mars size tend to record the local isotope composition in the disk. In contrast, the $\sim 10^7$ – 10^8 yr oligarchic growth stage of Venus and Earth is thought to involve giant impacts. During this stage, the planets are thought to acquire materials from a broad region of the proto-planetary disk. As a result, their compositions do not represent the local disk. In such a scenario isotopic identity of the Moon-forming giant impactor and the Earth is unlikely. Two mechanisms have been proposed to resolve the fact that the Earth and Moon are isotopically identical: a magma disk equilibration model [2] or an impact onto a fast-spinning Earth [3].

A New Model for the Inner Solar System: Here we use the evidence from enstatite chondrites (ECs) to explore a different model for the early development of the inner Solar System. In this model, (i) the material that forms the Earth has significant contributions only from regions at heliocentric distance interior to Mars (Oligarchic Growth Zone) and (ii) this material is isotopically homogeneous and identical to Earth and ECs. Only the regions beyond ~ 1.8 AU form with significant isotopic heterogeneity. There are two such zones: one inside the snowline with moderate heterogeneity and another outside the snowline with much larger isotopic heterogeneity. Both regions form in a low-mass gap in the disk and could therefore never develop larger planets formed by the oligarchic growth. In this model the planets in the oligarchic growth zone forms essentially dry. The Earth has received its water as a late veneer via very minor contributions from the outer regions (1.8 – 3.5 AU), consistent with observed isotopic compositions and water contents (Fig. 1).

Isotopic and Chemical Compositions of Earth and ECs: The O isotopic compositions of ECs and Earth's mantle are nearly identical. This fact was used to argue that the ECs provide the best Solar System material for estimating the chemical composition of the Earth [4], with the Earth being made from essentially pure EH chondrite material. A possible link between the ECs and Earth is supported by recent observations that ECs and Earth have the same isotopic compositions for both major and minor elements (O, Ca, Ti, Cr, Ni, Ba, Nd) which exhibit substantial variations among

different chondrite groups. Si isotopes are the only known exception as $\delta^{30}\text{Si}$ in bulk ECs is different from the Earth. However, ECs have 2-3 wt.% Si in the metal and the Si in the metal of ECs has $\delta^{30}\text{Si} = -6$ [5]. We argue that the difference is due to the secondary processing of EH chondrites that produced the Si-rich metal. On the contrary, [6] argued that Si can be used as evidence against an EC Earth. In contrast to isotopes, there is a huge chemical difference between Earth and ECs (Fig. 2). The ECs have much too high Rb/Sr (present $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.8$) and K/U ratios and are depleted in FeO and refractory lithophile elements compared to the composition of Earth's mantle deduced from terrestrial rocks.

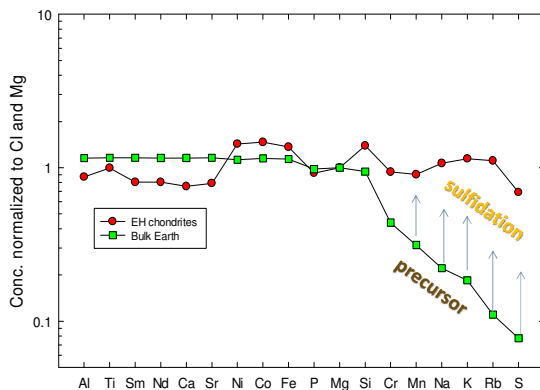


Fig. 2. Comparison of Earth and EH chondrite chemical compositions as a function of volatility in a nebula with C/O ~ 0.6 .

A Conventional Model for EC Formation: The chemical compositions of Earth and ECs as a function of volatility in a reduced nebula (with C/O ~ 1.0) are shown in Fig.3. This plot provides clear chemical evidence against a reduced precursor for the Earth as it is inconsistent with the volatility pattern of the Earth. There is also mineralogical evidence against condensation in a reduced nebula. Neither refractory carbides nor large amounts of graphite predicted by the 'reduced nebula' models are found in ECs. The predicted replacement of Ca and Mg sulfides by silicates has not been observed. Instead, the replacement of silicates by sulfides was recently documented [7]. Another large discrepancy between the 'reduced nebula' models and EC chondrites is the occurrence of FeO-rich silicates in the latter, indicative of their formation under highly oxidizing conditions incompatible with the stability of Ca and Mg sulfides.

New Model for EC Formation: This discrepancy can be resolved by assuming that the Earth and EC had a common nebular precursor but they have experienced different chemical evolution. Such an assumption is supported by the mineralogy and O isotopic data for the most primitive EH3 chondrites. The FeO-bearing

silicates, compositionally similar to those in other classes of chondrites, are abundant in ECs, with most silicates having O isotopic compositions of the bulk EC values. Recent studies [7] showed that the chalcophile behavior of Ca, Mg, Na, and other elements in EC results from secondary processing of FeO-bearing silicates: at 1400-1600 K, in an H-poor environment ($\sim 10^3$ - 10^4 depletion), with high fS_2 buffered by the Fe-FeS, and fO_2 close to the CO-CO₂ buffer. FeO-rich silicates are often replaced by the assemblage of FeO-poor silicates, Fe and Mg sulfides, and free silica. Thus, the FeO-poor silicates and sulfides typical of ECs are products of a non-nebular sulfidation process. FeO-rich materials with lower than EC volatile element abundances have been identified in ECs. It is possible that the initial composition of EC's precursor was like the Earth but it has changed during sulfidation of FeO-rich silicates. We suggest that a nebular reservoir that produced the precursor material of ECs has also produced the building blocks for the Earth, chemically similar to the widely accepted Earth's composition derived from mantle peridotites. This material formed in an isotopically homogeneous inner terrestrial planet region (Oligarchic Zone in Fig. 1). A portion of this material was sulfidized, scattered to an isotopically heterogeneous outer terrestrial planet region (Mars and the asteroid belt) and formed the ECs (arrow in Fig.1).

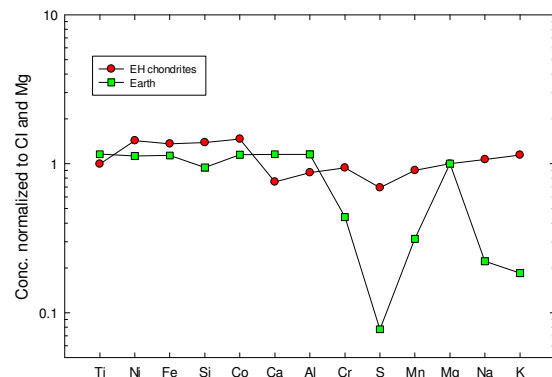


Fig. 3. Comparison of Earth and EH Chondrite chemical compositions as a function of volatility in a nebula with C/O ~ 1.0 .

Finally, the identical isotopic compositions of Earth and Moon is a logical outcome of the proposed model rather than something that has to be explained away.

References: [1] Drake M. J. & Righter K. (2002) *Nature* 416, 39-44. [2] Pahlevan K. & Stevenson D. J. (2007) *EPSL* 262, 438-449. [3] Čuk M. & Stewart S. T. (2012) *Science* 338, 1047-1052. [4] Javoy M. (1995) *GRL* 22, 2219-2222. [5] Ziegler K. et al. (2010) *EPSL* 295, 487-496. [6] Fitoussi C. & Bourdon B. (2012) *Science* 335, 1477-1480. [7] Lehner S. W. et al. (2013) *GCA* 101, 34-56.