ELEMENTAL FRACTIONATION IN THE SOLAR NEBULA AND PLANETARY COMPOSITIONS: A "PREDESTINATION" SCENARIO. S.R. Taylor, Research School of Earth Sciences, Australian National University, P.O. Box 4, Canberra, A.C.T. 2600, Australia.

The terrestrial planets exhibit variations in volatile-refractory element ratios and in density consistent with metal-silicate fractionation. Both the Earth and the Moon show major depletion in K and Rb and low K/U ratios relative to Cl implying refractory-volatile element fractionation. Since planets of Earth size cannot lose elements of high atomic weight, the question arises as to how and when this fractionation occurred. The meteorites present us with critical evidence. Cl carbonaceous chondrites provide an oxidised sample of the solar nebula (1). E-type chondrites are apparently a highly reduced sample of this composition, with an increased metallic iron content (2). They have ages of 4.55 Ae (3) indicating that strong reducing conditions, unaccompanied by volatile loss were present close to 4.56 Ae. The enstatite chondrites provide important evidence that production and separation of metal was unrelated to volatile-refractory element fractionation. H-type chondrites have similar ages (3), but have undergone both reduction and loss of volatile elements, the latter due either to metamorphic processes (4) or more likely to fractionation in the solar nebula (5).

Good evidence of early solar system fractionation is provided by the eucrites. Derived by partial melting from the mantle of a small asteroid (6), they have low K/U ratios (3100) and are depleted in Ni (~10 ppm) and the other siderophile elements. The W/La relationship indicates that metal was absent in the source regions (7). Sm-Nd and $^{207}Pb/^{206}Pb$ data for eucrites indicate crystallisation ages of 4.54-4.56 Ae. Two possibilities exist

(A) The eucrite parent body was accreted from metal-free volatile depleted precursors

(B) The eucrites were derived from the mantle of an asteroid which had already formed a metallic core.

In either alternative, K and Rb had already been depleted relative to Cl abundances of U and Sr. The refractory element abundances in the parent body, were parallel to those of Cl chondrites, showing no anomalies in the abundances of the more volatile REE, Eu and Yb. In summary, the meteorite evidence indicates production and fractionation of free metal, and loss of volatiles relative to refractory elements on time-scales within 10-50 m.y. of the formation of the Solar Nebula.

What are the implications for planetary formation? If the terrestrial planets accrete from planetesimals, with sweep-up times of about 10^8 years, then the inner planets were not complete until accretion ended about 4.45 Ae (9), about 100 m.y. later than the time scales for element fractionation indicated by the meteorites. It is a consequence of such models that the inner planets thus accrete from a heterogeneous swarm of already differentiated planetesimals, with varying contents of metal and volatile elements.

The implications of pre-accretion metal-silicate and refractory-volatile element fractionation for the compositions of the Earth, Moon, and the inner planets are considerable.

(A) The metal now in the Earth's core, and the silicates in the mantle are accreted as separate phases (but not necessarily in separate planetesimals) whose equilibration was established in precursor events. Thus, there is no necessary relationship for example between the Ni, Co and siderophile element contents of the mantle and the core. Melting and segregation of metal, sulfide and silicate (ie core formation) most likely occurred during or shortly after accretion but new metal-silicate equilibria was not necessarily established, and the bulk Mg/Mg+Fe ratio of the mantle is only indirectly related to core compositions. Partitioning of K, U or Th into the core is thus unlikely.

(B) The light element in the core is probably sulfur. If all element fractionation processes occurred at low pressures in small bodies or dispersed phases in the inner Solar System close to 4.56 Ae, then the meteorites provide the classical Goldschmidtian evidence of siderophile-chalcophile-lithophile (plus volatile-refractory) element fractionation, which points to sulfur, accreted as troilite as the most viable candidate. Arguments based on depletion of elemental sulfur, due to volatility, are complicated if S exists mainly as FeS or CaS. The dichotomy between terrestrial mantle chalcophile elements (Sn, Sb, Ag, Cu, Ga, As, Co, Ni, W, and Mo) which are about 10X more abundant than the strongly siderophile elements (Ge, Au, Pd, Pt, Ru, Rh, Ir, Re, Os) (10), indicates separation based on chalcophile-siderophile characteristics. This indicates relatively greater separation of Fe metal than troilite (or oldhamite) from silicate during core formation. Limited high-pressure reaction between metal and silicate is not precluded, but is not extensive in this scenario, in which the pre-existing metal and some sulfide fall out to form the core, during melting concomitant with accretion.

(C) The differences in composition between the Earth, and the Moon with lower metal content, K/U ratios and higher refractory element content are due to primary differences in the composition of the accreting planetesimals.

Further information about the location and timing of volatile depletion comes from the lunar isotopic data, which sheds light both on volatile and chalcophile element behaviour. The lunar Rb-Sr isotopic data indicates a major fractionation of Rb from Sr at 4.55 Ae. This is interpreted here to have occurred in precursor events before accretion of the moon. The lunar Pb data indicate a major separation of Pb from U at younger times, ranging from 4.42-4.46 Ae (11). Lead is chalcophile as well as volatile, and this fractionation probably refers to differentiation during melting rather than due to volatile-refractory element fractionation. Lead and uranium may thus undergo two independent fractionations, firstly due to volatility differences and secondly due to partitioning of lead into sulfide phases and uranium and thorium into silicates. Thus the change in $\mu(^{238}U/^{204}Pb)$ from the Cl value of 0.3 may be due either to (A) volatile-refractory element fractionation (B) sulfide-silicate solid-liquid partitioning, with the process occurring both during planetesimal and planetary melting.

The complexity of these processes allow many differing model interpretations of the Pb isotopic data for the Earth (12). Thus for single-stage evolution models, the Pb isotopic composition at 4.45 Ae is equivalent to that of Canyon Diablo troilite. On this interpretation, terrestrial lead, as now sampled was in a low μ environment (troilite?) for about 10^8 years, and the present terrestrial μ value of ~8.5 was established at accretion. The single-stage model thus precludes, for the Earth, simple accretion of Pb in silicate phases accompanied by U and Th. Meteorite Pb is preferentially concentrated in troilite (13).

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Possible changes to μ in the early solar system include (a) loss of volatile Pb relative to refractory U (b) isolation of Pb in troilite and oldhamite (CaS) (c) differential accretion of sulfide and silicate phases (d) removal of sulfide phases into the core during early melting. The Pb isotopic record from both the Earth and the moon appear to be dominated by mantle melting (accretion?) episodes, rather than earlier volatile loss, in contrast to the Rb-Sr lunar data.

The mechanism of early volatile refractory element separation remains obscure. Simple condensation from an initial hot nebula is ruled out by the observed heterogeneities, for example, in oxygen isotopic systematics. If volatile elements, along with the rare gases, are removed from the inner solar system by early strong solar winds, then the astrophysical evidence provides stringent time constraints. Nebulae surrounding young stars clear on time scales of 10^6 years (14). Strong T Tauri type solar winds occur on similarly short time scales (15). If one wishes to sweep out gases and volatiles, by such a mechanism, then it operates on times one or two orders of magnitude shorter than the planetesimal sweep up times of 10^8 years. Accordingly, volatile-refractory element separation, if accomplished by such means, can only occur within a few million years of the Sun arriving on the main sequence. The evidence from the meteorites that such fractionation occurs on short time scales at about 4.5 Ae may thus be consistent with such scenarios.

Some further consequences follow. The satellites of the outer planets have low densities, although Ganymede, Callisto, Titan and Triton are about the size of Mercury. Accordingly it appears that free metal was not available in large amount beyond the asteroid belt. Probably volatile-refractory element fractionation, which may be linked to early solar flare-ups in the inner Solar System, was not effective at and beyond 5 A.U. (As is shown, inter alia, by the large amounts of condensed water ice in the Jovian and Saturnian satellites). Accordingly, it may be predicted that the volatile-refractory element ratios (eg K/U ratios) in these satellites are about the same as those in Cl meteorites. This would have the consequence that radioactive heat generation is generally higher in these bodies than for the inner planets.

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