High-temperature fractionations in the solar nebula

Gerhard Schmidt[1,2] and Karl-Ludwig Kratz[1,2]
[1]Institut für Kernchemie, Universität Mainz
[2]Helmholtz Gemeinschaft Deutscher Forschungszentren (HGF)
Virtuelles Institut für Struktur der Kerne und Nukleare Astrophysik

Of particular interest in geochemistry and cosmochemistry is the question of whether the elements Os, Ir, Ru, Pt, Rh, and Pd (HSE = highly siderophile elements) are fractionated in the Earth's mantle [1]. In Fig. 1 the CI-normalized abundances of siderophiles in the Earth's upper mantle as measured by instrumental neutron activation on large homogenized samples and aliquots of 10 to 20 g rock powders, are shown in order of decreasing volatility in a solar gas. The relative abundances of HSE are shown in first order to be nearly CI-chondritic. However, the abundance pattern is inversely correlated with the volatility of the elements [2]. The excess of the non-refractory element Pd and depletions in the ultra-refractory elements Ir and Os appear to be consistent with a high-temperature gas-condensation fractionation process [3]. Continuous loss of ultra-refractory nebular condensates from the late-veneer formation region during condensation could be suggested to account for the depletion and fractionation of refractory elements in the Earth's late accreted component.

The process of condensation along with isolation of metal grains is likely to be responsible for the element pattern of the Earth's mantle. Based on a condensation model, in which metals condense first out of a hot nebular gas, followed by silicates, the highly siderophile components of the Earth's mantle may have formed in the nebular region during gradual removal of solids from the location where these „late material" formed during condensation. It is well known that gas-solid fractionation during condensation from a solar gas is one of the most important processes leading to fractionations in primitive objects of our solar system.

Formation Location of the Late Veneer Material
It is also known that enstatite chondrites were depleted in refractory siderophiles. The carbonaceous, ordinary and enstatite chondrites exhibit successively greater degrees of reduction in combination with successively lower contents of refractory elements. These features are most likely associated with formation at successively smaller radial distances from the Sun in hotter portions of the solar nebula. Many authors favored an enstatite formation location in the innermost solar system (perhaps even less than 1 AU from the Sun: possibly in the Mercury-Venus region). Based on the assumption that the observed gradient in the abundance of the radiogenic ^{53}Cr between the Earth-Moon system, Mars and the asteroid Vesta is considered as a function of the heliocentric distance. The ^{53}Cr excess of the enstatite chondrites would point to a formation location of about 1.4 AU or somewhat closer to the Sun (i.e. >1.0-1.4 AU [4]).
The HSE systematics of upper mantle samples resembles materials more closely to highly reduced EH or EL-chondrites than carbonaceous chondrites. In fact, the HSE in the Earth's mantle are even more fractionated than the enstatite chondrites. This may serve as an indication that some inner solar system materials were more highly fractionated than the latter.

Materials from formation regions closer to the Sun (Mercury-Venus region), as is supposed for enstatite chondrites, might be found in the future. Of course, planetary processes can also affect the distribution of HSE in the mantle. But, an igneous and/or an aquatic process that can exactly mimic the detailed volatility element pattern as shown in Fig. 1 seems unlikely (e.g. [5]).

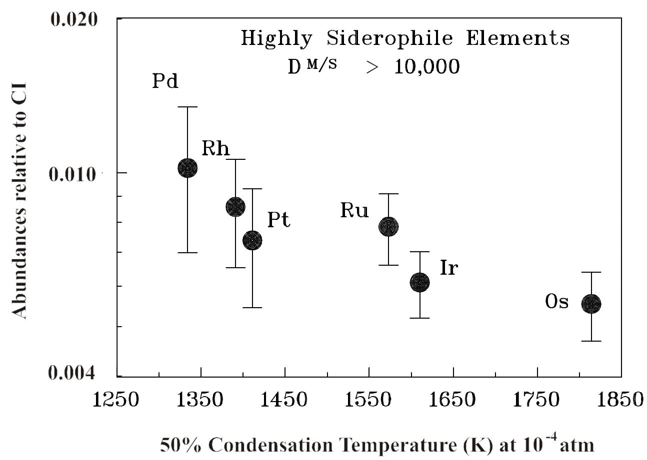

Fig. 1. Abundance pattern of HSE in the Earth's mantle.

Conclusion
The abundances of HSE in the depleted mantle differ from those in CI-chondrites. The abundance distribution of the HSE is remarkably uniform with increasing CI-normalized abundances, and with decreasing 50% condensation temperatures from Os to Pd. A possible interpretation is that the present upper-mantle noble-metal ratios could have been established in the solar nebula by fractionation processes that resulted in the loss of refractory components. The last material to contribute to the growing Earth is likely to have been derived from the innermost solar system.

The database for the elements Sb, Ag, As, W and Mo and some other elements has to be improved for the Earth's mantle and for Rh in the chondrite groups in order to make final decisions about the nature of the late veneer. In future studies, HSE as well as moderately siderophile element-based models might contribute to our understanding of the origin of the solar system and the processes involved to form planetary bodies, and giving the Earth their unique composition.

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