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U, Th, and K partitioning between metal, silicate, and sulfide and implications for Mercury's structure, volatile content, and radioactive heat production

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Abstract

The distribution of heat-producing elements (HPE) potassium (K), uranium (U), and thorium (Th) within planetary interiors has major implications for the thermal evolution of the terrestrial planets and for the inventory of volatile elements in the inner solar system. To investigate the abundances of HPE in Mercury's interior, we conducted experiments at high pressure and temperature (up to 5 GPa and 1900 °C) and reduced conditions (IW-1.8 to IW-6.5) to determine U, Th, and K partitioning between metal, silicate, and sulfide ($D^{met/sil}$ and $D^{sulf/sil}$). Our experimental data combined with those from the literature show that partitioning into sulfide is more efficient than into metal and that partitioning is enhanced with decreasing FeO and increasing O contents of the silicate and sulfide melts, respectively. Also, at low oxygen fugacity ($\log f_{O_2}$ < IW-5), U and Th are more efficiently partitioned into liquid iron metal and sulfide than K. $D^{met/sil}$ for U, Th, and K increases with decreasing oxygen fugacity, while $D_U^{met/sil}$ and $D_K^{met/sil}$ increase when the metal is enriched and depleted in O or Si, respectively. We also used available data from the literature to constrain the concentrations of light elements (Si, S, O, and C) in Fe metal and sulfide. We calculated chemical compositions of Mercury's core after core segregation, for a range of f_{O_2} conditions during its differentiation. For example, if Mercury differentiated at IW-5.5, its core would contain 49 wt% Si, 0.02 wt% S, and negligible C. Also if core-mantle separation happened at a f_{O_2} lower than IW-4, the bulk Mercury Fe/Si ratio is likely to be chondritic. We calculated concentrations of U, Th, and K in the Fe-rich core and possible sulfide layer of Mercury. Bulk Mercury K/U and K/Th were calculated taking all U, Th, and K reservoirs into account. Without any sulfide layer, or if Mercury's core segregated at a higher f_{O_2} than IW-4, bulk K/U and K/Th would be similar to those measured on the surface, confirming more elevated volatile K concentration than previously expected for Mercury. However, Mercury could fall on an overall volatile depletion trend where K/U increases with the heliocentric distance if core segregation occurred near IW-5.5 or more reduced conditions, and with a sulfide layer of at least 130 km thickness. At these conditions, the bulk Mercury K/Th ratio is close to Venus's and Earth's values. Since U and Th become more chalcophile with decreasing oxygen fugacity, to a higher extent than K, it is likely that at an f_{O_2} close to, or lower than, IW-6 both K/U and K/Th become lower than values of the other terrestrial planets. Therefore, our results suggest that the elevated K/U and K/Th ratios of Mercury's surface should not be exclusively interpreted as the result of a volatile enrichment in Mercury, but could also indicate a sequestration of more U and Th than K in a hidden iron sulfide reservoir, possibly a layer present between the mantle and core. Hence, Mercury could be more depleted in volatiles than Mars with a K concentration similar to or lower than the Earth's and Venus's, suggesting volatile depletion in the inner solar system. In addition, we show that the presence of a sulfide layer formed between IW-4 and IW-5.5 decreases the total radioactive heat production of Mercury by up to 30%.

Keywords: Core formation, Mercury, oxygen fugacity, partitioning, metal-silicate, sulfides; Volatile Elements in Differentiated Planetary Interiors