Non-perfect Equilibration of Hf-W System by Giant Impacts: Mechanisms and Suggestions

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Hafnium and tungsten are both highly refractory elements, and hafnium is a lithophile element whereas tungsten is a moderately siderophile element that should strongly partitioned into metal phases during metal/silicate segregation. Hf-W chronometry provides constraints on the timing of planetary accretion and differentiation, as the segregation of a metal core from silicates should induce strong fractionation of hafnium from tungsten. In previous studies, it was assumed a giant impact raise up perfect resetting on Hf-W chronometer. Recently the effect of partial resetting on Hf-W system is starting to be considered.

In the stage of giant impacts, newly accreted W of the impactor's metal equilibrates with W in the silicate melt of the target during the sedimentation of metal in silicate mantle. Suppose that metal of the impactor split into lots of metal sphere with a power law size distribution sinking at the Stokes velocity. When the cumulative power law exponent b = 1, the radius of metal sphere should be less than about 50 centimeter to achieve the perfect resetting of the chronometer.

Recently many works have modeled giant impacts using a method known as smooth particle hydrodynamics, or SPH. However, these calculations don't have enough resolutions to discuss the size smaller than meter-order. On the other hand, the estimated size of metal droplets sinking in silicate melt is about 1 centimeter owing to splitting of metal by Rayleigh-Taylor instability. This is small enough to achieve perfect resetting.

However, even after the splitting of metal layer to small droplets, there is the possibility of Rayleigh-Taylor instability between the layer with metal droplets and that of metal free. Such type of Rayleigh-Taylor instability is observed in laboratory experiments. Then, the regions where metal droplets are not interact with silicate appear because the growth of the Rayleigh-Taylor instability is by far faster than the Stokes sedimentation of metal droplets. Thus, complete metal-silicate equilibration cannot be expected.

So we assumed that each giant impact partially equilibrates the target body and, thus, partially resets its chronometer. A value for the partial resetting ratio and the number of giant impacts are parameters in this model. In this study, we estimate the resetting ratio that is required for fitting the Earth's observational data. It results that we cannot determine the giant impact age or the metal-silicate separation age with Hf-W chronometry without a quantitative assessment of equilibration ratio and the number of giant impacts. On the other hand, this result indicates that the resetting ratio of each giant impact is required to be greater than 0.2. This indicates that more than two-tenth of the protoearth's mantle should have been ejected or vaporized by a giant impact.

The core formation event of Mars can be discussed from the viewpoint of Hf-W chronometry. We also calculated the isotopic evolution of Mars. Our result indicates that Mars must have experienced certain equilibration event after the formation of protoplanets. The required resetting ratio of this event is larger than 0.3. Therefore, Mars should have experienced an event, which equilibrate more than three-tenth volume of Mars' mantle, such as core formation with mantle overturn or a single giant impact.