I075-018 Room: IC Time: May 28 10:15-10:30

Time scale of accretion and core formation of the Earth: The role of reduction and metal separation

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Introduction: Recent development of the Hf-W isotopic system enables us to give crucial constraints on the timescale of accretion and core formation of terrestrial planets and the moon. Evolution of the Hf-W system through accretion and core formation of the Earth was modeled combined with the constraint from the Pb system by Jacobsen and Harper (1996) and Halliday et al. (1996), and the accretionary mean life is suggested to be between 25 and 40 m. y. under the conditions of homogeneous accretion and continuous core formation at exponentially decreasing rates. In those models, the metal to silicate ratio of the accreting materials was assumed to be the same as the present earth. Thie assumption is, however, not necessarily guaranteed, which would affect the timescale of evolution. In this study, the effects of metal separation rate and the reduction reaction rate of accreting materials are examined for quantitative evaluation of the accretion and core formation timescale of the Earth.

Model: We have developed a model that describes the mass balance of W and Hf in the mantle as a function of the initial abundance, accreting mass, separated mass to the core, and generated or decayed mass due to radioactivity. The time scales of metal-silicate separation and reduction on evolution of the mass of core and the Hf/W ratio and 182W isotopic compositions of BSE were investigated. Three parameters control the results; the reduction reaction rate, accretion rate of the unfractionated material, and the metal separation rate from the mantle to the core. All the chemical and physical parameters used are the same as those used by Halliday and Lee (1999).

Results: The evolution of mass of the core, mantle (BSE), and bulk earth with time was studied. When the accreting materials are oxidizing, BSE mass increases rapidly in the early stage but decreases in the later stage and the core mass grows slowly regardless of metal separation time. The accretion and reduction timescales that satisfy the observed variation of Hf/W ratio (10-40) and e(W) (less than 1.0) for accretion of fairly oxidizing (metal fraction = 0.01; C chondrite like) and moderately oxidizing (metal fraction = 0.1; O-chondrite like) materials are investigated in the space of accretion time scale and reduction time scale.

Reduction of oxidized material significantly expands the permissible lower limit of accretion timescale. It could be less than 10 m.y. for fairly oxidizing accreting materials if the metal separation rate constant is 0.02 and reduction time scale is about 10 m.y. However, it should be greater than 20 m.y. if the metal separation rate constant is 0.05. The reduction timescale of material with metal fraction less than 0.1 should be greater than 10 m.y. when accretion timescale is about 20 m.y. in order to explain the observed Hf/W ratio of BSE.

Discussion: The present Hf/W ratio and e(W) value of the mantle are explained even when the accretion time is very short if the accreting materials are oxidizing and reduction was needed before extraction to the core. The condition is significantly dependent on the metal separation rate. The reduction rate of the accreting materials depends on the size of the accreted materials in the mantle, which can vary from mm or cm scale to planetesimal scale depending of the physics of accretion, the type and amount of reducing agent, and the temperature of the mantle. The metal separation rate is strongly dependent on fluid dynamic conditions (Stevenson,1990). Both reduction rate and metal separation rate are thus difficult to be evaluated quantitatively. Recent progress of ultra-high pressure experiments shows that the dihedral angle of metal-silicate interface at the lower mantle conditions is much smaller than the upper mantle conditions (e.g. Shannon and Agee, 1998). Thus the time-limiting process is in the reduction rate of oxidizing silicates in the upper mantle.