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Effects of impact-induced atmospheric erosion and core formation on Earth's volatile composition

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Abstract

We present one possible scenario of Earth's accretion from chondrites which can explain the differences in volatile composition between them.

1. Introduction

Unveiling the origin of Earth's volatile composition is crucial for understanding how Earth developed its habitable environment. Carbon (C), nitrogen (N), and hydrogen (H) are the main components of the atmosphere and oceans and the key elements for life. The volatiles in rocky planets are thought to have been delivered by chondritic materials [e.g., 5]. However, the elemental composition of the bulk silicate Earth (defined as the sum of atmosphere, oceans, crust, and mantle, hereafter BSE) shows the depletion of C and N relative to H, a high C/N ratio, and a low C/H ratio compared to chondrites [e.g., 1].

During the accretion stage, Earth has experienced several element partitioning processes. The core-forming metal could have removed a part of light elements from the magma ocean (MO) during the main accretion stage [e.g., 9]. After the MO solidification, the formation of oceans would initiate the carbonate precipitation [e.g., 3]. Through the full accretion, the impacts would have been removed some amount of volatiles due to the impact-induced atmospheric erosion.

The goal of this work is to understand how the impact-induced atmospheric escape and the core segregation during the accretion stage affect Earth's volatile composition. We examine the plausible accretion scenario which can explain the current Earth.

2. Model

We modeled both the main accretion and the late accretion stages. We define the main accretion as the accretion in the MO stage before the last 1% by mass and the late accretion is the last 1% accretion after the MO solidification, which is often called Late Veneer. Our model calculates the amount of C, N, and H in each reservoir on Earth considering impact degassing, element partitioning, and atmospheric erosion through the full accretion.

The main accretion model considered the elemental partitioning between the atmosphere, MO, and metal which segregates into the core. We adopted a box model of the equilibrating reservoirs for the element partitioning (Figure 1). The late accretion model considered the partitioning between the atmosphere, oceans, and carbonates (the crust) (Figure 2). For the impact-induced atmospheric erosion, we used the models proposed by [7] and [8]. By calculating the evolution for a wide range of partitioning coefficients, solubilities, and impactor properties (the volatile composition and size distribution), we constrained Earth's formation conditions.

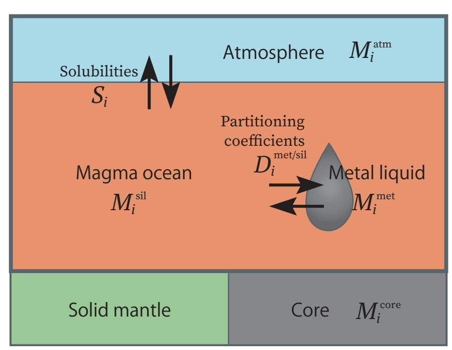

Figure 1: Cartoon of a MO equilibrating with an overlying atmosphere and with liquid metal droplets as it transits to the core (revised from [3]).

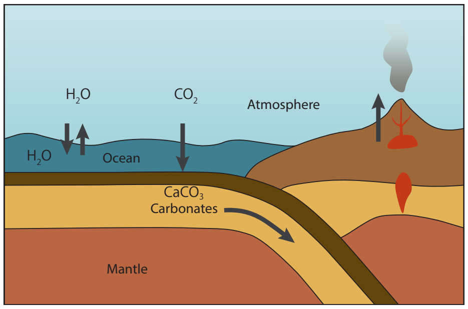

Figure 2: Schematic image of the surface environment in the late accretion stage. We consider the oceans and the carbon-silicate cycle driven by the plate tectonics on the surface [6].

3. Results

As a result, we succeeded to reproduce the abundances of major volatile elements (C, N, and H) in current BSE from chondritic building blocks when we chose the appropriate parameter values (standard model).

Figure 3 illustrates the evolution of the C/H ratio and C/N ratio of BSE during the accretion in the standard model. The ratios of the total amount of C, N, and H in BSE are plotted as a function of cumulative accreted mass fraction. During the main accretion, both C/H and C/N ratios decreased because C is the most siderophile element among other volatile elements so that much larger amount of C was sequestered to the core than N and H. While the elemental fractionation during the main accretion ended up with the excess of N/C, the preferential loss of N from the atmosphere during the late accretion reproduced BSE's volatile pattern even with chondritic impactors having low C/N ratio.

4. Discussion

We investigated the dependence on the impactor's size distribution $dN/dD \propto D^{-p}$, where D and N(D) are the diameter and cumulative number of impactors. Low p values correspond to shallow size-distributions where most of the mass of the impact population is in the large projectiles, whereas high p value corresponds to a steeper slope of a mass frequency distribution. A shallower size-distribution led the larger amount of volatiles left in BSE because the atmospheric erosion becomes inefficient in that case.

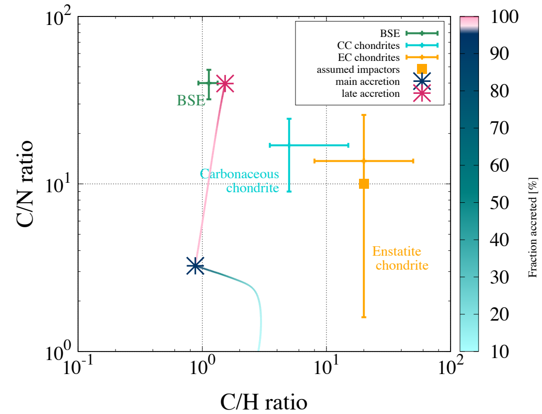

Figure 3: Evolution of the C/H ratio and C/N ratio of BSE during the main accretion (blue line) and the late accretion (magenta line).

In this study, we succeeded in exploring the accretion scenario which can reproduce the current volatile element composition of Earth completely. For impactors' properties, a shallower slope ($p = 2$) during the main accretion and an asteroid-belt-like slope ($p = 3$) during the late accretion were required. The change in the slope in time is naturally expected from the collisional evolution of planetesimals. This scenario is consistent with the studies of the size distribution of asteroids [2].

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