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Oxygen isotopic evolution of protoplanetary disks associated with redistribution of H2O

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Diversity in the chemical and isotopic compositions of chondritic materials suggests that the early solar nebula had evolved not only dynamically, but also compositionally. In particular, oxygen isotopes provide important clues to the compositional evolution because of its large elemental abundance and simultaneous occurrence in both gas and solid phases under the nebula conditions. Oxygen isotopic systematics of CAIs and chondrules suggests the existence of ^{17,18}O-rich and ^{17,18}O-poor reservoirs and mechanical mixing of them in the inner solar nebula. In addition, formation ages of CAIs and chondrules put constraints on the chronology of the evolution. Time interval between the formation of CAIs and chondrules implies that the oxygen isotopic composition of the inner nebula had evolved from ^{17,18}O-poor (CAIs-like) one to ^{17,18}O-rich (chondrules-like) one in ˜1 Myr. Moreover, the little isotopic variation among chondrules (and planetary materials) indicates that the nebula was spatially and temporally almost homogeneous in oxygen isotopic composition during their main formation epoch (1–2.5 Myr after CAIs).

Recently, CO self-shielding effect in a parent molecular cloud is proposed as a possible formation process of the ^{17,18}O-poor (CO gas) and ^{17,18}O-rich (H_2O ice) reservoirs. Yurimoto and Kuramoto (2004, hereafter YK04) have applied an enrichment process of vaporized species due to radial gas-dust fractionation to the ^{17,18}O-rich H_2O and given an explanation for the isotopic heterogeneity between CAIs and chondrules. However, the time and spatial variations of the nebula oxygen isotopic composition are poorly revealed because their calculation was limited to the quasi-steady states for CTTS and WTTS stages.

In this study, we improve the YK04 model to simulate time-dependent oxygen isotopic evolution of a protoplanetary disk, and perform advanced comparisons with the isotopic composition and chronology of CAIs and chondrules. The details of our calculation are as follows. First, a set of disk parameters (the disk radius, the column density profile, the accretion rate, etc.) are adopted after observations of T Tauri disks. Next, transports of H$_2$O in both gas and solid phases are calculated under the disk conditions to determine H_2O distribution at each time. The latter calculation requires the typical size of dust particles. We estimate it assuming that it is maintained by collisional disruption. Finally, the H_2O distribution is translated into the local mean oxygen isotopic composition of the disk, based on the initial isotopic fractionation of CO and H_2O.

Here we discuss the typical behavior of the oxygen isotopic evolution. The concentration of H_2O vapor inside the snow line increases with time over the first ˜2 Myr. This is mainly because H_2O supply to the inner disk increases associated with dust growth, while H_2 supply decreases with decay of the disk accretion. The H_2O enrichment leads to the monotonic change of the local mean oxygen isotopic composition from ^{17,18}O-poor one to ^{17,18}O-rich one, which is consistent with the isotopic heterogeneity between CAIs and chondrules. After ˜2 Myr, depletion of H_2O ice outside the snow line results in decrease of the H_2O supply to the inner disk.

Thus the increase of H_2O concentration begins to decelerate, then turns into decrease. During this epoch, the time variation of the local mean isotopic composition is kept small for ˜1 Myr. This possibly explains the small oxygen isotopic variation among chondrules.