Formation and Radial Transport of Chondrules in the Inner Solar System: Model on Ordinary and Rumuruti Chondrite's Oxygen Isotope Compositions

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Introduction: Chondrules are igneous spherical objects found in primitive meteorites, chondrites. Although it is widely recognized that they crystallized from the melts produced via the transient heating events in the solar nebula, the nature of precursor materials, the actual heating mechanisms and conditions, and the following transport in the nebula have not been fully understood yet. Oxygen isotope measurement is a strong tool to elucidate these questions. Oxygen isotope ratios of chondrules are reported at the internal mineral scales and each chondrule shows homogeneous internal compositions [1, 2]. If chondrules were formed in the dust-enriched environments, the isotope exchange between melts and ambient gas must have occurred during the heating so the homogeneity inside chondrules indicates that melts and gas acquired the same compositions kept constant [1, 2]. Therefore, chondrule's oxygen isotope ratios reflect the values of their forming regions which were the average of the solid precursor materials including condensates of volatile species such as water if any.

Ordinary and Rumuruti chondrites (OC and RC, respectively) are both non-carbonaceous meteorites. OC are mostly composed of chondrules while RC have lower chondrule abundances and more abundant matrix [3]. RC have the heaviest mass-independent oxygen isotope compositions ($\Delta^{17}O$) of bulk meteorites while OC have lighter compositions [OC: 4, RC: 3]. Despite of these differences, OC and RC have similar chondrule's oxygen isotope compositions [OC: 5, RC: 6]. Bulk features reflecting the materials at the parent body accumulation regions differ between OC and RC. However, OC and RC show the similar features for the materials at their chondrule forming regions as preserved in chondrules. In this study, we present a model explaining these findings which incorporate the oxygen isotope exchange during the heating events into the viscously accreting nebula model.

Methods: To understand the requirements for reproducing the findings above, we conduct parameter surveys and compare model results for the difference between chondrule's oxygen isotope compositions at OC and RC accumulation regions determined by matching the respective chondrule abundances.

We use α turbulence viscosity model for nebula accretion. Material radial transport via inward advection and random diffusion is described in Ref. [7]. We solve steady state solutions for simplicity where there are constant net material transport rates throughout the nebula. For oxygen isotope exchange model, we assume that the locally heated solid materials acquire the average values of them via the isotope exchange. We add the isotope exchange into the simple statistical model of the conversion from precursor matrix to chondrules. Occurrence rates of heating events (in other words, conversion rates of matrix to chondrules) at each radial location throughout the chondrule forming regions within the nebula are parameterized. We note that we implicitly assume nebula sources for heating mechanisms such as shock wave heating [8] and lightning [9].

We consider precursor matrix, chondrules, and water ice as solid materials in the model. The evidence for water accumulation in the parent bodies is found in OC and RC [10]. While phyllosilicate is another candidate for water carrier [11], we assume ice for the carrier because OC and RC accumulation regions could have been cold enough to water ice to condense [12]. Chondrule forming regions traverse water snowline. Inside water snowline, water exists as vapor and doesn't contribute chondrule's isotope compositions formed there because chondrules might have been formed in dust-enriched environments. We also ignore the contributions from the highly volatile oxygen carriers such as carbon monoxide.

Results and Discussions: The most important parameters is the width of chondrule forming regions which is inversely correlated to the occurrence rates of heating events in the chondrule forming regions to obtain chondrule abundances of OC at the innermost regions. Equating advection timescale and diffusion timescale, we can obtain the critical width beyond which the inward advection is the dominant transport process and below which the random diffusion is dominant. If the occurrence rates of heating events is so low that the width of chondrule forming regions is wider than the critical width, the significant difference in oxygen isotope compositions between OC and RC chondrules is expected. On the other hand, if the occurrence rates of heating events is so high that the width of chondrule forming regions is narrower than the critical width, the similarity between them is expected.

Conclusions: We find that the following conditions explain both the differences in chondrule abundances and bulk oxygen isotope compositions and the similarity in chondrule's oxygen isotope compositions between OC and RC: (1) the chondrule formation occurred in the regions narrower enough than the critical width which is determined by the competition between the inward advection and the random diffusion, and (2) the occurrence rates of heating events in these regions are sufficiently high enough to convert the matrix precursor into chondrule as found in OC.

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