論文内容の要旨

論文題目

Evolution of Solid Materials in the Protoplanetary Disk: Constraints from ^{26}Al Ages and Cosmochemical Properties of Chondrules in a Primitive CO Chondrite

（原始惑星系円盤の固体物質進化：
始原的 CO コンドライトコンドリュールの
^{26}Al 年代と宇宙化学的特徴による制約）

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Chondrules are major constituent of chondrites, occupying up to 70 vol% of chondrites, which are igneous objects cooled rapidly in the early solar system. In spite of numerous analytical and theoretical investigations, the formation mechanism and the origin of compositional diversities are still not known. Because there are systematic differences in the size, abundance of types, and isotopic compositions of constituent minerals in chondrules among different chemical group of chondrites, it is expected that chondrules in different chemical group of chondrites would represent difference in physicochemical environment for their origin.

Recent development of SIMS (secondary ion mass spectrometry) and its application to small chondrules have revealed that chondrules were formed in a fairly long time interval in the early solar system (2 to 3 m.y.), which makes understanding of their origin more difficult. Although the number of age measurements has been increasing, the information is still limited and more extensive and systematic study is required for better understanding of the origin. In particular, systematic investigation of formation age, chemical compositions, and mineralogical characteristics among different chemical groups of chondrites is crucial in connection with the origin of chemical group of chondrites. Also important is evaluation of the ^{26}Al-^{26}Mg system, which has not been fully done in previous works and the possibility of inclusion of isotopically disturbed ages is contained in literature data. In the present study, I have carried out petrological and ^{26}Al-^{26}Mg chronological study on chondrules in Yamato-81020 (Y-81020), the most primitive CO3.0 chondrite, and compared the results with those in ordinary chondrites. Then, their similarity and difference are used to constrain the differences in physicochemical environments of chondrule formation and evolution of the early solar nebula.

Magnesium isotopic composition of plagioclase is measured on fourteen FeO-poor Type I, two FeO-rich Type II, and one aluminum-rich (Al-rich) chondrule in Y-81020 with SIMS. Excesses in ^{26}Mg with sufficient precision (0.5-2‰) are found in all chondrules studied. Chemical zoning of Na and Mg in anorthite shows that the zoning was produced during crystallization from liquid but not during thermal metamorphism in a parent body. Thus, the chronological data in individual plagioclase grains keeps initial information with regard to the formation age without secondary isotopic disturbance. The ^{26}Al-^{26}Mg ages are obtained to be 1.3-2.4 Myr for Type I, 2.0 Myr for Type II, and 2.4 Myr for Al-rich chondrules, assuming homogeneous distributions of ^{26}Al and the initial ^{26}Al/^{27}Al ratio of a canonical value (5×10^{-5}).

The formation age of chondrules in Y-81020 is in good coincidence with that of Semarkona, Bishunpur, and Krymka, LL 3.0 to 3.1 chondrites, in literature, which indicates that Type I chondrules in the CO chondrite were formed contemporaneously with ferromagnesian chondrules in LL chondrites (Figure 1). The concurrent formation of chondrules of CO and LL chondrites suggest that the cosmochemical differences between CO and LL chondrites might be caused by spatial distinction of their chondrule formation in the protoplanetary disk.

Systematic examination of relationship among texture, mineral assemblage, mineral composition, bulk chemical composition, and ^{26}Mg isotopic compositions shows that there seem to be no correlation among those properties except for the formation age difference between Type I and Type II chondrules. It is worth noting that Type II chondrules tend to have later forming age, and the relative abundance of Type I and Type II chondrules differs between CO and LL chondrites. The bulk chemical compositions of Type I and Type II chondrules obtained by averaging several hundreds of point analyses of EPMA show similarities in almost all elements and the major difference is in the state of iron, either metallic Fe or FeO in silicates, that is, the redox state in another word.

The similar formation age of chondrules in LL and CO chondrites, later generation of Type II chondrules compared to Type I chondrules in Y-81020, and larger abundance of Type I chondrules in CO chondrites than LL chondrites are modeled by taking the stability of silicate, organic materials and ice, temperature evolution of the nebula, and plausible physical process of chondrule formation into consideration. Most plausible way to change the redox state of the solar nebula would be the change of relative abundance of carbon and oxygen, of which main carrier in the solar nebula is organic materials and ice, respectively. Dust grain in the protosolar molecular cloud are thought to have a layered structure with silicate core, organic mantle, and icy crust (Greengberg, 1998), which were heated at the high temperature stage of the early evolution of the nebula to evaporate partially or totally. The extent of evaporation should be a function of radial distance from the star (the sun); silicate is most refractory, organic materials next, and icy component is most volatile. The protoplanetary disk was heated in the early stage of evolution, which is a function of radial distance from the protosun, and the disk is divided into three regions: the ice and organic materials were evaporated in the inner region, only icy component evaporated in outer region, and all the components remained in the outermost region. Although the heating mechanism for chondrule formation is one of the most severely debated theme in planetary science which has not yet been in consensus, the present study give some constrains; the heating process took place repeatedly in fairly wide region of the disk and lasted for almost 2 Myr. If shock wave should have attacked the surface layer of the dust enriched midplane of the disk to evaporated the condensed materials, the redox state of gas differed in the three regions because of the difference of the materials existed: the inner most region was oxidizing due to evaporation of the silicate component alone, reducing in the outer region due to evaporation of silicate and organic materials, and intermediate in the outermost region due to evaporation of all the three components. The oxidizing inner region should be responsible for formation of Type II chondrules, and the reducing outer region for Type I chondrules, and the outermost region for Type II chondrules. The boundaries between the regions moved inward with time because the nebula continuously cooled. After 2 to 3 Myr, chondrule forming heating ceased, the relative abundance of Type I and II chondrules varied with distance from the star: chondrules in CO chondrites were formed in the outer or outermost region, where Type I is abundant, whereas those in LL in the inner region, where Type II is abundant (Figure 2). The present scenario can explain the relationships between chondrule forming ages of Type I and Type II in the CO chondrite, and the difference in the redox states between LL and CO chondrites. Considering the complementarity between chondrule and matrix (e.g. Kong and Palme, 1999) from volatility-controlled fractionated solar nebula (e.g. Wasson and Chou, 1974), enstatite chondrites were located in the intermediate distance from the sun between ordinary and carbonaceous chondrite regions. The formation process of chondrules and chondrites proposed in this dissertation is successful in explaining all their major properties (e.g. the redox state of chondrule and chondrite, the relative abundance of chondrule types, chondrule formation time) as a function of the distance from the proto-sun and the protoplanetary disk evolution.

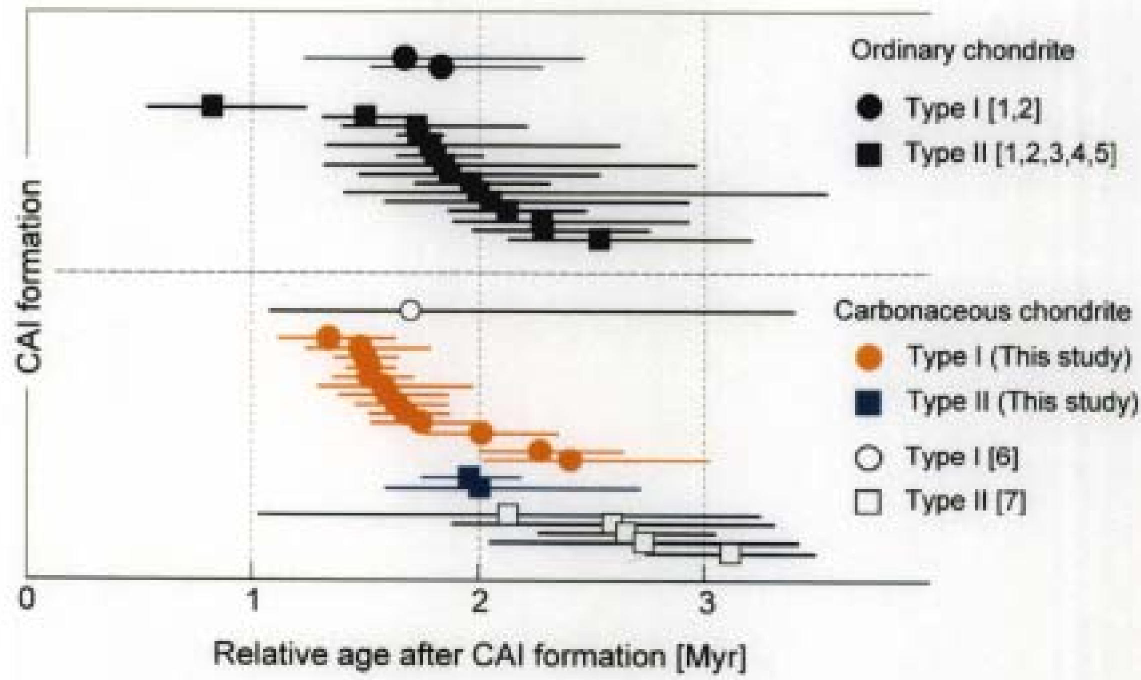

Figure 1. Comparison of relative ^{26}Al ages of chondrule formation after CAIs from SIMS study. The datat from [1] Kita et al. (2000), [2] Mostefaoui et al. (2002), [3] Hutcheon and Huchison (1989), [4] McKeegan et al. (2000), [5] Kita et al. (2005), [6] Srinivasan et al. (2000), and [7] Kunihiro et al. (2004).

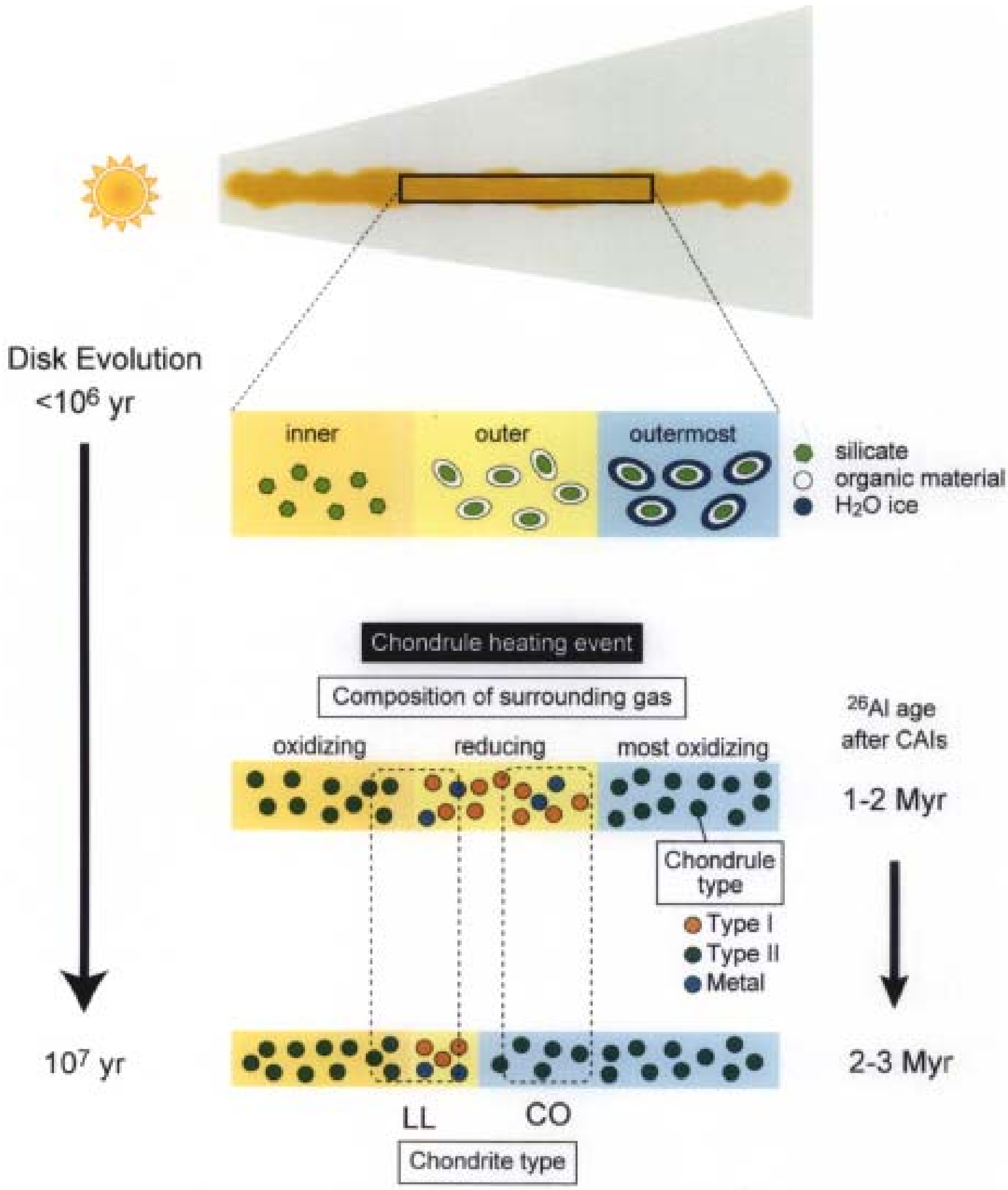

Figure 2. Schematic diagrams of protoplanetary disk evolutions relating to LL and CO chondrule formations. See in text for details.