論文の内容の要旨

Crystallization and evaporation experiments of type B CAI melt: Estimate for disk gas pressure in the early Solar System
（隕石中難揮発性包有物の蒸発・結晶化実験による初期太陽系円盤圧力の推定）

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Protoplanetary disks formed around young stars are the places where planet formation occurs. The protoplanetary disks form as a natural consequence of star formation, and their properties such as size, mass, density distribution, thermal structure, dynamics, lifetime, and chemistry affect the characteristics of planets formed in the disks. Recent astronomical observations have demonstrated that protoplanetary disks have a wide variety of physical and chemical characteristics. The important properties of the disk include disk mass and density distributions, but they have not been observationally well constrained.

Solar System planets also formed in the Sun's protoplanetary disk (the protosolar disk) 4.6 billion years ago. The characteristics of protosolar disk should have reflected initial conditions of the Solar System and affected planets formed later within the disk. The evolution of the protosolar disk is recorded in primitive extraterrestrial materials such as chondrites and returned asteroidal and cometary samples, but the gas pressure of the protosolar disk that is related to the disk density distribution has not yet been constrained.

This thesis focused on the formation condition of calcium-aluminum-rich inclusions (CAIs), which are the oldest materials in the Solar System, to constrain the hydrogen gas pressure of the protosolar disk. CAIs consist of refractory minerals that are stable at higher temperatures than major minerals such as magnesium silicates and metallic iron. Their refractory nature suggests that CAIs formed in the high temperature region of the protosolar disk, i.e., the inner region of the disk. The isotopic evidence of CAIs (^{10}Be and oxygen isotopes) also suggests CAI formation in the innermost region of the gas disk. Therefore, CAIs should record the gaseous environment during their formation. Among various types of CAIs, type B CAIs are mostly igneous and experienced melting and subsequent crystallization in the disk. There are two textural types of type B CAIs; one is type B1 CAIs with melilite mantle, and the other is type B2 CAIs without melilite mantle.

It has been suggested that evaporation of Mg and Si, less refractory than Ca and Al, from the melt would have played a significant role in the variation of chemical, mineralogical, and petrologic characteristics of the igneous CAIs. Evaporation rates of elements depend on hydrogen pressure (P_{H2}) and are enhanced at higher P_{H2}. When evaporation rates are high, elemental diffusion within the melt may not be able to homogenize the melt because of continuous escape of Mg and Si from the melt surface, and Al-rich melilite may crystallize from the surface enriched in Ca and Al. On the other hand, at lower P_{H2}, evaporative elemental fractionation at the surface may be homogenized within the melt owing to slow evaporation relative to diffusion, which may result in production of type B2-like texture. Therefore, the variation of igneous texture of CAIs may record the hydrogen pressure during the CAI formation.

In this study, in order to test the above hypothesis and to obtain a quantitative constraint on P_{H2} for the CAI formation, open-system crystallization experiments of CAI analog melt under disk-like low-pressure hydrogen (P_{H2}) conditions of 10^{-6}, 10^{-5}, and 10^{-4} bar with different cooling conditions appropriate for igneous CAI formation (5, 20, and 50°C h^{-1}) were conducted. The results demonstrated that at $P_{H2} = 10^{-4}$ bar, the samples were mantled by melilite crystals ($Ca_2Al_2SiO_7$-$Ca_2MgSi_2O_7$), which is similar to the texture observed in type B1 CAIs. On the other hand, the samples heated at $P_{H2} = 10^{-6}$ bar exhibited random distribution of melilite, as in type B2 CAIs. At the intermediate P_{H2} of 10^{-5} bar, type B1-like texture formed when the cooling rate was 5°C h^{-1}, whereas the formation of type B2-like texture required a cooling rate faster than 20°C h^{-1}. In the samples with melilite mantle, the compositional distribution of melilite is Mg-poor at the sample rim and becomes Mg-rich toward the inside, suggesting that these melilites crystallized inward from the melt droplet surface, as inferred from petrological studies of type B1 CAIs. Such Mg-poor melilite at the rim has melilite composition as low as ~$Åk_{10}$ (10 mol% of $Ca_2MgSi_2O_7$), which is more depleted in Mg than that expected for the melt of starting composition to crystallize. Such Mg-poor melilite can only crystallize from a melt which has lower Mg and Si concentrations. The compositional zoning within the melt was also confirmed in the sample heated at $P_{H2} = 10^{-4}$ bar and 1420°C for a short duration (1 h), where MgO composition decreased towards the melt surface, which is in line with the formation of melilite mantle. The three-dimensional diffusion modeling with surface evaporation for the obtained compositional zoning provided the evaporation and diffusion rates of MgO, which are consistent with those obtained in the present study and in previous studies. The results also determined that samples with a well-developed melilite mantle show elevated δ^{25}Mg values at the sample rim compared to the interior. This can also be attributed to diffusion-limited evaporation of Mg from the melt surface, where preferential evaporation of a lighter isotope (^{24}Mg) results in enrichment of a heavier isotope (^{25}Mg).

This study demonstrated that the hydrogen pressure during type B CAI formation would have been in the range of 10^{-4}–10^{-6} bar. CAI precursors might have existed in the high temperature region of the protosolar disk (>1300 K), where magnesium silicates and metallic iron were not present. The presence of ^{10}Be and mineralogically controlled O isotope composition suggest the CAI formation close to the Sun (~0.1 au). If this was the case, the disk with low mass accretion rate (~10^{-8} $M_{\odot}$ yr^{-1}) or the disk evolved for >1

Myr satisfies the T-P_{H2} condition for CAI formation. If CAIs formed at ~1 au, which was recently proposed based on new interpretation of V isotopes in CAIs, the 1 au region of the disk with higher mass accretion rate (~10^{-6}–10^{-7} $M_{\odot}$ yr^{-1}) or the young disk (<1 Myr from the core collapse) satisfies the T-P_{H2} condition for CAI formation. While further constraints on the CAI forming location from natural samples are required, the present study puts a new quantitative constraint on the hydrogen gas pressure of the inner protosolar disk.