論文の内容の要旨

Formation and evolution of circumstellar alumina
: from evolved stars to the early solar system

(星周アルミナの形成と進化：晩期型星から初期太陽系へ)

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Dust grains, sub-μm- to μm-sized solid particles condensed from vapor in circumstellar environments, are the main carriers of metallic elements and play an important role for the material circulation and evolution in space. Silicate and oxide dust grains absorb and/or emit infrared light; they are observed as characteristic infrared (IR) spectral features around oxygen-rich asymptotic-giant-branch (AGB) stars, red giants, super novae, and protoplanetary disks, which are the main stellar sources of dust in our galaxy. Direct evidence for dust formation in these circumstellar environments is the presence of presolar grains in primitive chondrites, which have large isotopic anomalies reflecting nucleosynthesis in their parent stars prior to the solar system formation. Since the nature of circumstellar dust grains (e.g., composition, size, and density) strongly controls the efficiency of mass-loss from evolved stars, understanding of dust formation processes and conditions in circumstellar environments leads us to reveal the material circulation in the galaxy.

A considerable fraction (up to 15%) of circumstellar dust has been known to be crystalline. Crystals can have specific morphology reflecting the anisotropy in formation processes (crystallographically anisotropic shape), and the IR spectra of dust grains are largely affected by the morphology. Therefore the crystallographically anisotropic shape of crystalline dust grains can be used as a new probe to evaluate the dust formation conditions around stars. Possible processes to change the circumstellar dust shapes are condensation from gas and re-evaporation into gas. However, neither quantitative estimates of anisotropy in dust formation kinetics under circumstellar conditions nor systematic investigation of the dependence of an IR spectrum on dust morphology have been done yet.

Corundum (α-Al_2O_3) is one of the highest temperature condensates formed around oxygen-rich AGB stars. Understanding of the formation process of corundum will provide information about the onset of dust formation in the innermost region of the stellar atmosphere and thus constrains the first step of dust evolution from evolved stars to the protoplanetary systems including the early solar system. The highly refractory and stable nature of corundum is also advantageous for surviving sputtering by accelerated ions and atoms in supernova-induced shock waves in the interstellar medium (ISM). Furthermore, since corundum is highly resistant to acid treatments, many presolar alumina grains were discovered by dissolving bulk meteorites with chemical treatments. Thus, corundum is one of the most suitable dust species as a proxy to understand the formation and evolution of dust grain from evolved stars to the early solar system.

The broad peaks at ~12 μm have been observed in envelopes around oxygen-rich AGB stars by many infrared spectroscopic studies, which indicate the common presence of amorphous alumina in circumstellar environments. The 13-μm peaks have also been observed with the 12-μm features. One of the candidates emitting the 13-μm features has been proposed to be crystalline alumina (corundum). Previous studies showed that a spectrum of spherical corundum grains and an averaged spectrum of corundum grains having random shapes do not reproduce the exact peak position and width of the observed 13-μm peaks. However, crystals having anisotropic structures can have shapes that reflect the growth processes and/or the formation conditions (crystallographically anisotropic shapes). Thus, in order to understand the IR spectral features of corundum dust, the crystallographically anisotropic shapes formed in circumstellar environments should be considered. Moreover, chemical and isotopic compositions of presolar alumina grains have been intensively studied but the astrophysical conditions where presolar grains formed have not yet been well understood because there have been few mineralogical analyses of presolar alumina, such as morphology, surface structure, and crystal structures.

In this thesis, I develop a new approach to understand the astrophysical conditions innermost region of the evolved stellar atmosphere where corundum dust grains form dominantly and cannot be observed directly. I conducted evaporation and condensation experiments of corundum (Chapter 2) and systematic calculations of absorption spectra of corundum grains with various crystallographically anisotropic shapes (Chapter 3) with special interests to the anisotropy in corundum formation processes and the possibility of IR observation of crystallographically anisotropic shapes of corundum. I further analyzed the morphology, crystal structure, and oxygen isotopes of alumina grains in unequilibrated ordinary chondrites to characterize the presolar alumina grains (Chapter 4). Possible scenarios of formation and evolution of circumstellar alumina are discussed in Chapter 5 by combining anisotropic growth kinetics and spectral features of corundum with crystallographically anisotropic shapes, and mineralogical and morphological investigations of presolar alumina.

Evaporation experiments were conducted at 1600-1790°C in vacuum and the evaporation rates along the <0001>*, <11-20>*, and <1-100>* directions, which are referred as to the $V^{evp}{}_{c}$, $V^{evp}{}_{a}$, and $V^{evp}{}_{m}$, respectively, were obtained. The evaporation rate along the m-axis (<1-100>*) is largest and that along the c-axis (<0001>*) is smallest in this temperature range

($V^{evp}{}_{m}/V_{a}^{evp}$ ~2.2 and V_{c}^{evp}/V_{a}^{evp} ~0.6). The evaporation coefficients, showing degrees of deviation from the ideal evaporation rate due to kinetic hindrances, along the c-, a-, and m-axes are between 0.01-0.1 with positive temperature dependence.

Condensation experiments were conducted at 1575 °C at low-pressure molecular-flow conditions and condensation rates along the c-, a-, and m-axes were quantitatively obtained. The condensation rate along the m-axis is largest and that along the a-axis is slightly larger than that along the c-axis ($V^{cond}{}_{c}/V^{cond}{}_{a}$~0.79). The supersaturation condition for heterogeneous condensation and condensation coefficients in the experiments were evaluated to be 4 and 0.03-0.1, respectively, which is the first quantitative results for anisotropic formation processes of circumstellar dust analogues.

In order to examine whether or not the morphology of circumstellar corundum can be evaluated from observed spectra, I calculated the mass absorption coefficients of corundum ellipsoids, cylinders, and rectangular parallelepipeds with various aspect ratios. The calculation showed that that the shape difference of corundum can be distinguished with the peak positions and their relative intensities in the 10 μm band.

The peak position of 13 μm feature, commonly observed from oxygen-rich AGB stars, is well reproduced by corundum ellipsoid slightly flattened along the c-axis (r_{c}/r_{a} ~0.7). The FWHM (full width at half maximum) of the observed 13 μm peak is well reproduced if there are some shape variations around r_{c}/r_{a} of ~0.7, grain size is ~1 μm, or with thin coating of amorphous alumina on a corundum grain.

For mineralogy of presolar alumina grains, I first made detailed morphological and crystallographic observations of 198 alumina grains in acid residues of unequlibrated ordinary chondrites (UOCs) using field-emission scanning electron microscopy (FE-SEM) and electron back-scattered diffraction (EBSD). The oxygen isotopic compositions of 111 grains were then measured by ion microprobe to identify presolar alumina grains that are real circumstellar condensates.

A half of the 198 grains have smooth surfaces, another one third have characteristic rough surfaces with 10- to 100-nm-sized fine structures without crystal facets, and the remaining grains have both smooth and characteristic rough structures. It was also found that >80 % of the alumina grains were single crystals of corundum. The oxygen isotopic compositions of 111 grains were measured, and nine presolar alumina grains were found. Three presolar grains were crystalline corundum; two were single crystals and the other was polycrystalline. Two presolar alumina grains showed weak or blurred EBSD features from limited locations of the grains prior to the SIMS analyses, of which crystal structures could have been partly destructed prior to the solar system formation. Two grains are likely to be amorphous, and their crystal structures may have been significantly destroyed probably in the ISM. The remaining two grains have sub-grains, and it is not clear whether the main grain or sub-grain (or both) is of presolar origin. The fraction of low-crystallinity or amorphous alumina grains was higher for presolar alumina grains with rough surface structures than for solar alumina grains, only 15% of which showed low-crystallinity or amorphous features.

I propose possible scenarios of formation and evolution of circumstellar alumina as follows. The supersaturation ratios (*S*) expected to be achieved in the expanding atmospheres around AGB stars are estimated to be ~5 from the homogeneous nucleation model and the cooling rate of gas in a circumstellar envelope. This value is close to *S* obtained from the condensation experiments (~4.9). The expected shape of corundum condensates is disk slightly flattened to the c-axis, which reproduces the 13 μm features. I also found that corundum grains can grow up to 1 μm in the envelops of low mass-loss-rate AGB stars (slowly expanding envelopes with the expanding velocity of 0.001 km/s), and that condensation of amorphous alumina on corundum could occur at lower temperatures. The grain growth up to ~1 μm is consistent with the size of presolar alumina, and the possible presence of amorphous layer, which could be sputtered in the ISM or dissolved into acids, might be related to the rough surface structures of the presolar alumina grains. The peak position and width of the 13 μm feature are well reproduced by corundum grains slightly flattened to the c-axis with additional contributions from other factors (grain size, shape variation and the presence of amorphous), all of which could be common in circumstellar environments. I thus conclude that corundum is a career of the commonly observed 13-μm feature around O-rich AGB stars. The dominant silicate features observed for the stars with high mass-loss-rates are also explained by nucleation of numerous corundum nuclei and subsequent growth of silicates through heterogeneous nucleation on the corundum nuclei.

The condensed corundum may suffer from the sputtering of ions and atoms in the interstellar medium. Although further study on the sputtering processes of corundum and on the crystal structures of the surface and inner regions of presolar grains are necessary, sputtering processes in the ISM may destruct the surface structures of corundum to form the observed rough surfaces on the presolar grains and make crystalline alumina grains amorphous. A large fraction of presolar alumina grains incorporated into the parent materials of the solar system lost their isotopic signatures in the very early stage of the solar system evolution by the isotopic exchanges with the surrounding gas, but some “isotopically solar” alumina grains may preserve presolar morphological and mineralogical signatures (“ex-presolar” alumina).

In this thesis, the formation and evolution of corundum dust from evolved stars to the early solar system were traced by combining the experimental approach for anisotropy in dust formation processes, the theoretical approach for infrared observation of crystalline dust with crystallographically anisotropic shapes, and the mineralogical approach for presolar alumina grains. Such a combined approach can be a new probe to evaluate dust formation conditions quantitatively, which are important to understand an acceleration mechanism of stellar winds that cannot be astronomically observed directly as well, and will enable us to link the history of our solar system to the evolutional history of the Galaxy.