

ダスト形成実験, プレソーラー粒子分析, 赤外線観測から探る宇宙鉱物の形成と進化
Astromineralogy from dust formation experiments, analysis of presolar grains, and infrared spectroscopy

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In these twenty years, space and ground based infrared spectroscopic observations have revealed the common presence of circumstellar and interstellar dust grains such as silicates, oxides, carbides, ice, and organics. Presolar grains are rare components of primitive meteorites identified on the basis of their highly anomalous isotopic compositions. They have formed around evolved stars as circumstellar dust grains and have survived the processing in the interstellar medium and the protosolar disk before their incorporation into the meteoritic parent bodies.

It is, however, difficult to directly compare presolar grains with circumstellar dust emissions because (1) infrared (IR) dust emission reflect an enormous number of dust grains with various composition, size, shape, crystallinity, and aggregation degree, (2) dust properties are poorly constrained due to lack of laboratory studies on dust formation processes, and (3) there are limited mineralogical and crystallographical studies on presolar silicates and oxides. The grain morphology and crystal structure of circumstellar dust may reflect condensation conditions in circumstellar envelopes of asymptotic giant branch (AGB) stars and that of presolar grains additionally reflect processing in the interstellar medium (ISM) and protosolar disk. Corundum ($\alpha\text{-Al}_2\text{O}_3$) is predicted to be the most abundant refractory dust species condensed in envelopes around oxygen-rich AGB stars. In this talk, we summarize our recent results of corundum condensation and evaporation experiments, calculation of the IR spectrum of condensed corundum around AGB stars, and analysis presolar alumina grains in order to link the mineralogical and astronomical investigations on circumstellar dust formation and evolution.

Evaporation experiments of single crystals of corundum in vacuum at 160-1785 deg C and condensation experiments at 1575 deg C and a supersaturation ratio of around 4 were performed to obtain anisotropic evaporation and condensation coefficients of corundum. The IR spectra of anisotropically condensed corundum grains were calculated assuming the ellipsoidal shapes. Presolar alumina grains were identified from acid residues of unequilibrated ordinary chondrites (QUE97008 LL3.05, RC075 H3.1, and Bishunpur LL3.15) by oxygen isotopic measurements. The focused-ion-beam sections of the presolar grains were prepared and observed with a transmission electron microscopes.

Evaporation coefficients of corundum are 0.02-0.2 at 1600-1785 deg C, which increase with temperature. The evaporation coefficient along the crystallographic m-axis is largest and that along the c-axis smallest irrespective of temperature. The obtained condensation coefficients along the c-, a-, and m-axes at 1575 deg C and a supersaturation ratio of about 4 are 0.04-0.06, 0.06-0.08, and 0.1-0.2, respectively. Eighteen presolar alumina grains were identified and the average size was 1 μm , and neither whiskers nor extremely flat grains were observed. All presolar alumina grains are corundum but some of them have distorted crystal structures. Fifteen grains have irregular shapes covered with rough surfaces. The distorted crystal structures and rough surface structures may indicate that these grains have experienced the cosmic ray irradiation in the interstellar medium or solar wind irradiation in the early solar system.

The condensed corundum is most likely to be oblate slightly flattened to the c-axis, consistent with the fact that no presolar corundum with eccentric shapes has been found. The mass absorption coefficient of oblate corundum slightly flattened to the c-axis shows a peak at 13 μm without any accompanying strong peaks, which correspond to the unidentified 13- μm feature of around O-rich evolved stars. These results strongly indicate that corundum condensed anisotropically in circumstellar environments and have experienced space weathering prior to their incorporation into the meteoritic parent bodies.

キーワード: 星周ダスト, プレソーラー粒子, 実験, コランダム, 赤外線分光, 宇宙鉱物
Keywords: circumstellar dust, presolar grain, experiment, corundum, infrared spectroscopy, astromineral

イオン誘起微粒子核生成 III: 反応速度論的アプローチ Ion-induced nucleation experiment III: Approach to reaction kinetics

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Mechanisms of grain nucleation have attracted many researchers in connection with the formation of atmospheric aerosols and cosmic dust grains. Many works have been performed assuming homogeneous nucleation in gas phase or heterogeneous nucleation on the bulk surfaces. For the homogeneous nucleation, very high supersaturation condition is often required to gain the efficient formation rate over a "critical size" of particle, while the heterogeneous nucleation on the bulk surface may not be relevant to the first stage of grain formation in realistic environments. It is therefore reasonable to propose another nucleation mechanism occurring in the realistic environments. Ion-induced heterogeneous nucleation would be one of important mechanisms for the gas phase nucleation, because ion-neutral interaction can overcome the difficulty of the critical size expected in neutral-gas-phase homogeneous nucleation. In this context, we have started a series of experiments to clarify the early stage of the ion-induced nucleation, that is, cluster ion formation. For the first step, using a newly-developed apparatus, we measured the free energies of water-cluster ions at each size, of which parameters are closely related to the cluster formation rates. These results were presented in this session last year. As a next step, in order to directly investigate the reaction kinetics of cluster ions, we further developed an ion trap apparatus where charged particle can be stored within the volume of $\sim 0.5\text{cm}^3$ in vacuum for a long time. We will present the details of apparatus and the results of preliminary experiment.

キーワード: イオン誘起微粒子核生成, クラスターイオン, イオントラップ
Keywords: ion-induced nucleation, cluster ion, ion trap

非晶質フォルステライトの結晶化における水蒸気圧効果 An experimental study on the effect of water vapor on crystallization of amorphous forsterite

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Infrared spectroscopic observations (e. g. ISO and Spitzer Infrared Telescope) have provided the evidence of existence of crystalline silicate dusts in comets and protoplanetary disks (Henning, 2010 and references therein). Wagstaff and Richards (1966) suggested that water vapor enhances the crystallization rate of SiO₂ glass by breaking [Si-O-Si] bonds and forming hydroxyl groups. Thus, if amorphous silicate dust is exposed to relatively water vapor-rich environments such as the post shock region of shock wave (Ciesla et al., 2003) and impact plumes generated by asteroid impacts (Fedkin & Grossman, 2013), amorphous silicates may crystallize more effectively with the aid of water.

In this study, in order to investigate the effect of water vapor on the crystallization kinetics of amorphous forsterite, crystallization experiments were conducted in vacuum condition ($\sim 10^{-4}$ Pa) using a gold-image vacuum furnace (Thermo-Riko GFA430VN) at 500, 680, 730, 750 °C, and in sealed glass tubes, in which water vapor pressure is kept at 0.65 bar by a Ca(OH)₂ – CaO buffer system, at 500 °C in a box furnace. Amorphous forsterite powder, synthesized by a thermal plasma method, was provided by A. Tsuchiyama, Kyoto University. Temperature of both furnaces was calibrated against the melting points of NaCl, KBr, LiBr and In. Run products were analyzed with FT-IR (KBr pellet method). Quantitative analysis of the degree of crystallization was made with the spectral fitting of run products in the 10 μm band, where the structural evolution of amorphous forsterite can be observed as a change of Si-O stretching features.

The time-dependence of crystallization in vacuum was estimated by the Johnson-Mehl-Avrami equation for each temperature, and the Arrhenius plot of the time constant of crystallization, τ , showed a linear correlation with the reciprocal temperature. The obtained value of E_a/k_B was 4.94×10^4 K, where E_a is activation energy for crystallization and k_B is the Boltzmann constant. Kinetic parameter n in the Johnson-Mehl-Avrami equation obtained at 680, 730, 750 °C in vacuum were ~ 1.5 . Assuming that the crystallization mechanism in vacuum does not change at lower temperatures, we can estimate the timescale of crystallization at 500 °C in vacuum, which is about 430 years for the crystallization degree of 26 %. On the contrary, experiments at $P_{H_2O}=0.65$ bar showed that the degree of crystallization reached about 26 % only for 12 hours. It was also experimentally confirmed that amorphous forsterite remained unchanged by heating at 500 °C in vacuum for 72 hours. This clearly indicates that the crystallization of amorphous forsterite is promoted in the presence of water vapor. Kohara et al. (2004) reported the structure of Mg₂SiO₄-composition glass synthesized by a containerless liquid phase processing technique, and MgO_x units act as a network former and SiO₄ units form polymer and dimer. We proposed that water molecules diffuse into the amorphous structure to break Si-O-Si bonds and MgO bonds by acting as a network modifier and promote the crystallization of amorphous forsterite.

Experiments at lower water vapor pressure conditions are needed for a direct application to the crystallization of amorphous silicates in canonical protoplanetary disks, but the present results imply that the crystallization of amorphous silicates might take place more effectively in the water-enriched regions compared with canonical solar nebula condition.

キーワード: 非晶質ケイ酸塩, フォルステライト, 結晶化, 水蒸気, 原始惑星系円盤
Keywords: amorphous silicate, forsterite, crystallization, water vapor, protoplanetary disk

赤外線衛星「あかり」による黄道光微細構造の観測 Small-scale structure of the zodiacal dust cloud observed in mid- and far-infrared with AKARI

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The zodiacal light emission (ZE) is the thermal emission from the interplanetary dust and the dominant diffuse radiation in the mid- to far-infrared wavelength region. The zodiacal dust cloud has a relatively smooth distribution. However, from the results of the Infrared Astronomy Satellite (IRAS) observations, it was found that there are many small-scale structures in the ZE distribution, such as asteroidal dust bands and a circumsolar resonance ring.

The Japanese infrared satellite AKARI, a dedicated satellite for infrared astronomical observations, is the mission to survey the whole sky in the mid- and far-infrared. AKARI detected the small-scale structure of the zodiacal cloud, such as the asteroidal dust bands and the circumsolar ring. There are three major bands (± 1.4 degree, ± 2.1 degree, and ± 9.3 degree) among dust bands that form small-scale latitude features in the ZE. These three prominent asteroidal dust bands can be clearly seen in the AKARI far-infrared all-sky maps at 65 and 90 micron bands.

We also present spectra of the zodiacal light observed in mid-infrared wavelength region with Infrared Camera (IRC) onboard AKARI. The IRC spectra (5.5–12.5 micron) show a trapezoidal excess emission feature in 9–11 micron region which can be reasonably accounted for by a combination of amorphous and/or crystalline silicate. Although this excess feature is rather smooth and lacking sharp peaks, a possible 10.5 micron peak and small peaks around 9.3 and 11.35 micron can be seen at the shoulder of the trapezoidal excess. The spectrum around $\beta=10$ degree toward the asteroidal dust band seems to have a slight different shape of the silicate feature from those of other regions.

キーワード: 黄道光, 惑星間塵, あかり, 赤外線
Keywords: zodiacal light, interplanetary dust, AKARI, infrared

Evolution of organic molecules in space: characteristics and properties of experimental organic residues.

Evolution of organic molecules in space: characteristics and properties of experimental organic residues.

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In the interstellar medium (ISM), dense clouds and circumstellar regions around young stars are favorable environments for the accretion of ice mantles around dust grains and their irradiation by energetic particles (UV-photons and cosmic rays). The partial collapse of dense cloud gives birth to stars generally surrounded by disks of dust and gas which can lead to planetary systems.

Organic-rich mantled dust is thus among the potential building blocks of our solar system and could be at the origin of a part of the organic matter found in comets and meteorites. However, it is not clear how the organic components formed in the ISM may have evolved before being incorporated in their parent bodies.

A new laboratory experimental apparatus PICACHU (Photochemistry in Interstellar Cloud for Astro-Chronicle in Hokkaido University) was recently developed to simulate the formation and evolution of organic ice mantles. This apparatus is focused on organic compound evolution through UV irradiation and heating. Typical ISM gases (H₂O, CO, NH₃, CH₃OH) are deposited onto the three faces of a refrigerated substrate (about 12K) and simultaneously irradiated by UV under ultra-high vacuum. The gases, desorbed from the ice during heating and post-irradiation, are monitored by a quadrupole mass spectrometer in the vacuum chamber. The final organic residues obtained after warm-up and/or post-irradiation are then characterized.

Here we report the first descriptions of the organic residues produced by the experiments. At the micron scale, the thin deposits are not homogenous showing desiccation-like networks. From atomic force microscope observation, it seems that the main deposits are made of the aggregation of round particles of some tens of nanometers. Porous membrane-like textures are also observed for post-irradiated sample. Transmission electron microscopy confirms the presence of round organic particles and shows their amorphous nature. These particles could resemble to the organic nanoglobules commonly found in the organic matter of carbonaceous chondrites, which contain isotopic anomalies and a dusty core [2, 3, 4]. Moreover, the porous nature of organic aggregates may enhance the efficiency of dust aggregation in the early solar system [5, 6].

[1] Herbst E. and van Dishoeck E. F. 2009. *Annu. Rev. Astron. Astrophys.* 47:427-480. [2] Garvie L. A. J. and Buseck P. R. 2004. *EPSL* 224:431-439. [3] Nakamura-Messenger et al. *Science* 314:1439-1442. [4] Hashiguchi M. et al. 2013. *GCA* 122:306-323. [5] Kouchi A. et al. 2002. *Astrophys. J.* 566:121-124. [6] Kudo T. et al. 2002. *Met. Plan. Sci.* 37:1975-1983.

キーワード: organic synthesis, low temperature experiment, UV irradiation, thermal evolution, Interstellar medium, meteorite & comet

Keywords: organic synthesis, low temperature experiment, UV irradiation, thermal evolution, Interstellar medium, meteorite & comet

模擬分子雲環境下で合成した有機化合物のLC/MS分析 A LC/MS analysis of organic matter produced in the laboratory simulating interstellar molecular clouds

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Chemical and isotopic compositions of organics in astrophysical environments are important information not only to understand their origins and evolution, but one of key topics to discuss the origin and evolution of the solar system. This study focuses on the early step of the chemical evolution in interstellar molecular clouds, from primitive gaseous molecules to ice with organics, which is thought to be one of the precursors of extraterrestrial organic matter in the solar system.

Photochemical synthesis experiments were conducted using a high vacuum chamber “Photochemistry in Interstellar Cloud for Astro-Chronicle in Hokkaido University” (PICACHU). In the chamber, a gold substrate (30 x 40mm) was set and cooled down to about 15K. Gaseous mixtures, prepared in a dedicated line, were admitted onto the surface of the substrate where they condensed forming ice samples. During the deposition the ice on the substrate was simultaneously irradiated UV light emitted from a deuterium lamp. After the photochemical process, the ice sample was warmed-up to room temperature, leading to form refractory organic residue that remained on the surface of the substrate. Then the substrate was stored in a sealed sample container under atmospheric air.

Each sample residue on the substrate was extracted with about 50 μ L of CH₃OH (LC grade reagent) to analyze the contained organics by liquid chromatography coupled to mass spectrometry (LC/MS), using “Ultimate 3000” LC and “Q Exactive” MS (Thermo Fisher Scientific). 1 to 10 μ L of sample solution was injected to electrospray ionization (ESI) source. Both positive and negative mass spectra were acquired in the range of m/z 80 to 800 with its resolution (M/ Δ M) is 140,000 at m/z 200. The mass accuracy is generally less than ~0.001Da (1mDa) for positive ion.

This paper reports the results of 3 samples; A(H₂O : CH₃OH : NH₃ = 2 : 1 : 1, UV 71hours), B(H₂O : CH₃OH : NH₃ = 10 : 1 : 1, UV 165hours), and C(H₂O : CO : CH₃OH : NH₃ = 10 : 2 : 1 : 1, UV 240hours). All samples contained more than 1000 ion masses in the range of m/z 80 to 800. Major 1000 peaks were extracted using “Xcalibur” software (Thermo Fisher Scientific) for further data processing. The procedural background was calibrated using the mass spectra of CH₃OH extracted from the blank surface of the other gold substrate which are not exposed to both gases and UV, but kept about 15K for 3days in PICACHU. 700 to 900 ion peaks less than m/z 700 were distinguished. About 70 to 80% of the mass spectra can be grouped in various series of alkyl homologues consisting of CHN, CHNO and CHO. The alkyl homologues are discrete with the interval of 14.0156Da that infers methylene chains (-CH₂)_n. Various alkyl homologues were also reported in the literature, e.g. Danger *et al.* (2013).

The stoichiometric composition was estimated for each ion peaks by Xcalibur, and most of them have less than C₃₀. More than a half of estimated C contained formulae also have both O and N. On the other hand, those without hetero elements (O and N) were minor. The distribution of m/z values of the mass spectra and their corresponding stoichiometric formula were different for each sample. That is due to both the composition of gaseous mixture, especially the existence of CO, and the duration time of UV irradiation.

Reference:

Danger *et al.* (2013) *GCA* **118**, 184.

キーワード: 模擬星間有機物, 化学進化, LC/MS

Keywords: Inter stellar organic analogs, Chemical evolution, LC/MS

量子トンネル効果による固体ベンゼンの水素・重水素付加 Hydrogenation and deuteration of solid aromatic hydrocarbon by quantum tunneling

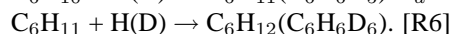
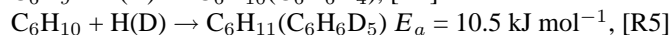
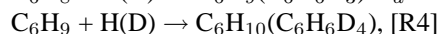
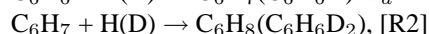
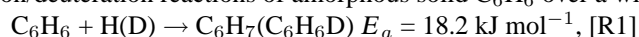
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Surface tunneling reactions on interstellar dust (e.g., CO + H or D) are crucial to explain the abundances of organic molecules like methanol and their deuterated isotopologues observed in cold dense interstellar regions (≤ 100 K), such as molecular clouds, where thermally activated reactions rarely occur at low temperatures. Aromatic and aliphatic hydrocarbons are two of the main components of interstellar and circumstellar dust, and benzene (C_6H_6) must be a precursor of interstellar polycyclic aromatic hydrocarbons (PAHs) and hydrogenated amorphous carbon grains. The present study investigates the following hydrogenation/deuteration reactions of amorphous solid C_6H_6 over a wide temperature range (10-50 K).



E_a is the activation barrier for H-atom addition in the gas phase. The radical recombination reactions R2, R4, and R6 are barrierless on the surface. We experimentally demonstrate that cold H and D atoms can efficiently add to solid benzene by tunneling at temperatures as low as 10-50 K. The present study is the first report on a nonenergetic deuteration process of aromatic hydrocarbons at low temperatures. In comparison to C_6H_6 , PAHs tend to have lower activation barriers to H or D addition owing to the higher flexibility. Therefore, we suggest that interstellar aromatic hydrocarbons including PAHs and C_6H_6 can be hydrogenated or deuterated by the tunneling of H or D atoms at low temperatures. The deuteration of interstellar aromatic hydrocarbons is of particular importance, because these molecules represent a major carrier of deuterium enrichment observed in carbonaceous meteorites and interplanetary dust particles. As the gaseous atomic D/H ratio in molecular clouds can be also strongly enhanced for elemental ratios of 1.5×10^{-5} to 10^{-2} - 10^{-1} , our results suggest that tunneling might represent a major deuteration mechanism for interstellar aromatic hydrocarbons, because surface tunneling is especially facilitated in the cold dense interstellar environments.

キーワード: 芳香族炭化水素, 水素化, 重水素濃集, 量子トンネル効果, 分子雲

Keywords: Aromatic hydrocarbons, hydrogenation, deuterium enrichment, quantum tunneling, molecular clouds

星間物質候補フェノキシラジカルの実験室分光 Laboratory Spectroscopy of Phenoxy Radical as a Candidate of Interstellar Matter

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星間空間には光を遮る希薄な分子雲が存在し、その分子雲の物質による可視光領域の星間未同定吸収線 Diffuse Interstellar Bands (DIBs) が観測されている。その起源となっている分子は、地球外有機物であり、宇宙の分子進化のひとつの段階を示すものと考えられている。DIBs の起源の分子は、可視光領域に吸収線を持たなければならない。そこで、芳香族のラジカルが有望視されている。本研究では、DIBs を同定するため、芳香族のラジカルの生成にホロカソード放電を用い、測定に Cavity Ring Down 分光器を用いた。そして、フェノキシラジカル (C_6H_5O) の電子遷移を 570 — 630 nm 帯で測定した。星間空間で観測された DIBs スペクトルと実験室のスペクトルの比較検討を行った。

キーワード: 星間未同定吸収線, 星間分子, キャビティリングダウン, 分光, 分子雲, 放電

Keywords: Diffuse Interstellar Bands, interstellar molecule, cavity ring down, spectroscopy, molecular cloud, discharge

量子化学計算による星間ダストでのグリシン生成の研究 Quantum chemical calculations of glycine formation in the interstellar medium

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Amino acids in the primitive earth may have been originated in the interstellar medium (ISM). Many amino acids and their precursors were found in the meteorites and were detected in laboratory experiments of UV irradiation on interstellar ice analogs. Moreover, various organic molecules were detected in molecular clouds; recently the detection of amino acid has been expected, especially by ALMA

In this study, we would like to make clear the mechanism of the simplest amino acid, glycine formation in the ISM using accurate quantum chemical calculation (density functional theory; DFT). Glycine formation pathway via hydantoin, which is glycine precursor detected in Murchison meteorite, were investigated. At first, the reactions in the gas-phase were examined. As a result, it was unlikely that glycine was formed during the lifetime of molecular clouds. However, there is a possibility that the reactions proceed with catalysis or the outside energies such as UV and heat.

Organic molecules in the ISM are considered to be generated on icy interstellar dust grains. In a previous study, the reaction barriers in aminoacetonitrile precursor formation pathway become lower with water molecules than those in the gas-phase, since water molecules on the ice core can play crucially a proton-transfer role, facilitating the basic transformations in the glycine formation pathways, [1]. We investigate the hydantoin and glycine formation pathway with one water molecule as a simplest model of ice.

[1] D. M. Koch, et.al. J. Phys. Chem. C112, 2972 (2008)

Keywords: interstellar medium, amino acid

アンモニアの粘土鉱物への吸着実験：星間分子雲における窒素同位体分別解明に向けて Adsorption experiments of ammonia and clay minerals to understand nitrogen isotopic fractionation in molecular clouds

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Nitrogen is the fifth abundant element in the universe and also essential component of organic molecules. Various nitrogen-containing organic compounds have been found by laboratory analysis of extraterrestrial materials. The stable isotopic composition of nitrogen ($^{15}\text{N}/^{14}\text{N}$ ratio) will give information about evolutionary history of the organic molecules. Primitive solar system materials such as chondrites, comets, and interplanetary dust particles (IDPs) show various degrees of ^{15}N -enrichment compared to the solar system value of -400‰ [1]. They display up to $+1500\text{‰}$ in the bulk $\delta^{15}\text{N}$ value (‰ , normalized as vs. AIR) [2, 3]. Furthermore, anomalously high ^{15}N -enrichments, as called hot spots, have been frequently found within a single material with the highest $\delta^{15}\text{N}$ values reaching as high as $+5000\text{‰}$ [4]. These ^{15}N -enrichments are considered to be originated in cold interstellar environments. However, the mechanisms of isotopic fractionation of nitrogen in the interstellar medium are not well understood and only a few models have been proposed [e.g., 5].

In this study, we focused on adsorption process of ammonia on grain surface of interstellar dusts as a potential mechanism for the extreme ^{15}N -enrichment and its high-heterogeneity found in extraterrestrial materials. Ammonia is a primitive nitrogen-containing compound and also one of major molecules in molecular clouds. Since ammonia is a highly reactive chemical, it is a precursor for nitrogen-involving organic molecules. The adsorption of ammonia on grain surface would be the first step for the formation of more complicated organic molecules. In order to examine the isotopic fractionation of nitrogen through adsorption of ammonia on grain surface, we performed experiments using ammonia gas and several adsorbents. For the experiments, six clay minerals (montmorillonite, saponite, dickite, kaolinite, pyrophyllite, and halloysite) were selected as the adsorbents. They were kept at 110 °C prior to the experiments to minimize adsorbed water. The each clay mineral was enclosed into a vacuumed glass vial and then ammonia gas (27‰ , SI science) was introduced. A few days later, the glass vial was opened and the nitrogen isotopic composition of the adsorbed ammonia was determined by nanoEA/IRMS [6]. The results showed a relationship between $\delta^{15}\text{N}$ values and the adsorbed ratio, which is explained by Rayleigh fractionation model. The adsorbents with low adsorption ratio have higher $\delta^{15}\text{N}$ values compared to initial ammonia gas. The difference in the degree of ^{15}N -enrichment and adsorption property among clay minerals was also observed. These results imply that the adsorption of ammonia on grain surface should be considered as one of potential scenarios for ^{15}N -enrichment.

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キーワード: 窒素同位体分別, 吸着, アンモニア, 星間分子雲

Keywords: nitrogen isotopic fractionation, adsorption, ammonia, molecular clouds

降着衝撃波で固体氷は蒸発するか？ Do icy grains evaporate by an accretion shock?

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Gravitational collapse of a molecular cloud is a transient process to form protostars and protoplanetary disks. The infalling envelope onto the Keplerian disk often induces accretion shocks at their boundary. Recent ALMA observations suggested evaporation of icy grains at the shocked region [1,2]. The icy grain evaporation would considerably affect the chemical environment of the nebula. The shock conditions for the icy grain evaporation were calculated numerically in a few papers [3,4]. However, the effect of emissivity of icy grains has not been investigated systematically. The smaller the emissivity is, the higher the temperature of icy grains will become even in the same shock condition. The emissivity generally varies with the size, composition, and structure of icy grains, and then may change the evaporation condition. In this study, we revisited the evaporation condition for various icy grains using realistic emissivity.

We adopt a two-step calculation method to obtain the detailed thermal history of icy grains in the post-shock region. First we calculate the post-shock gas structure as a function of the distance from the shock front [5]. The shocked gas parameters just behind the shock front were determined by the Rankine-Hugoniot relation using the pre-shock parameters: a shock velocity and a pre-shock gas number density (J-type shock). The shocked gas is gradually cooled by line emissions from CO molecules and thermal collisions with non-evaporating sub-micron silicate grains. We consider a one-dimensional plane-parallel post-shock geometry, so the gas temperature and density are determined as a function of the distance from the shock front. Second we calculate the thermal evolution of icy grains using the post-shock gas structure obtained in the first step. The emissivity of icy grains was given by performing a Planck mean of a wavelength-dependent absorption efficiency, which was calculated from the dielectric function or the complex refractive index data. We solved the evaporative shrinkage of icy grains to obtain the evaporation condition, namely, the shock parameters with which the icy grain evaporates completely.

The numerical results indicate that the shock condition for the icy grain evaporation strongly depends on the emissivity. For example, the icy grain composed of pure CO₂ is evaporatable by the observed accretion shock [1,2] because of its small emissivity. However, if the icy grain contains considerable amount of silicate components, it has much larger emissivity and therefore hardly evaporates by the same accretion shock. Our results showed that the emissivity of the icy grains is one of the important factors to determine whether the icy grain evaporates by shock heating or not. This implies that it is possible to constrain the size, composition, and structure of the interstellar icy grains from the observational evidence of icy grain evaporation by accretion shocks.

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キーワード: 降着衝撃波, 氷ダスト, 衝撃波加熱, 蒸発
Keywords: Accretion shock, icy grain, Shock heating, Evaporation

氷微惑星衝撃波加熱の ALMA による観測的検証法 Diagnosing Evaporation of Icy Planetesimals due to Shock Heating in Protoplanetary Disks by ALMA Observations

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原始惑星形成後、周囲の氷微惑星は重力相互作用により軌道進化し、円盤ガス中に衝撃波をおこす。この衝撃波により氷微惑星は加熱され、蒸発すると考えられ、氷微惑星の蒸発率や軌道進化に関する研究が行われてきた (Tanaka et al. 2013, Nagasawa et al. 2014)。本研究では、ダスト表面分子の気相への蒸発を初期条件とした、非平衡・時間発展する気相化学反応計算を行い、氷微惑星の蒸発により気相に放出された分子およびその娘分子を ALMA で観測することにより、氷微惑星の衝撃波加熱を検証する可能性について調べた。

宇宙空間において衝撃波により氷分子が蒸発する過程は、例えば若い星に付随するアウトフロー中の衝撃波面などで良く調べられてきた。蒸発した分子は、分子イオンとの気相反応、あるいは低温下ではダストへの凍結により気相から減少する。分子イオンとの気相反応による減少の時間尺度はおおよそ1万年なのに対し、ダストへの凍結の時間尺度は、ダスト量にも依存するが、円盤赤道面では1万年よりも十分に短い。従って蒸発した分子は、その分子の凍結温度よりも高温領域では1万年程度気相中に存在し、低温領域ではすぐにダストに凍結する。ダスト表面分子としては、有機分子あるいは窒素や硫黄を含む分子などがあるが、ダスト凍結温度は分子によって異なり、例えば有機分子は水と同様、比較的高温 (>150K) である。ここでは、円盤ガス中の存在量が比較的低くかつダスト凍結温度はあまり高くない、硫黄を含む分子に着目した。

硫黄を含むダスト表面分子として H₂S があるが、計算の結果、蒸発した H₂S は気相反応により壊され硫黄原子になった後、酸素分子あるいは OH と反応して SO および SO₂ を生成した。この時間尺度は1万年程度であり、H₂S や SO の蒸発温度よりも高い領域で氷微惑星の衝撃波加熱が起きた場合、H₂S や SO の輝線はそのよいトレーサーとなることが示された。一方 SO₂ は H₂S や SO に比べてダスト凍結温度が高い。よって SO₂ の凍結温度よりも低温領域では、SO₂ はダスト密度に応じた時間尺度でダスト表面に凍結するため、その輝線強度はダスト密度のトレーサーになる可能性が示された。

原始惑星系円盤からの分子輝線のこれまでの電波観測では、H₂S, SO, SO₂ 輝線はまだ未検出であったが、ALMA による高感度・高空間分解能観測は、これらの輝線の検出が可能になると期待される。本講演では、H₂S, SO 分子輝線などが ALMA 観測で検出できる条件について議論する予定である。

キーワード: 原始惑星系円盤, 氷微惑星蒸発, 星間化学

Keywords: protoplanetary disks, evaporation of icy planetesimals, astrochemistry

原始惑星系円盤の化学反応と、H₂O スノーラインの分光観測による検出可能性 Chemical Reactions in Protoplanetary Disks and Possibility of Detecting H₂O Snowline using Spectroscopic Observations

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原始惑星系円盤において、中心星近傍では高温のため H₂O はダスト表面から脱離し気体となるが、遠方では低温のためダスト表面に凍結する。この境界が H₂O スノーラインであり、ダストの合体成長で惑星を作る際、H₂O スノーラインの内側では地球型の岩石惑星が形成される。一方外側ではダストの総量が増加する。このため重力で周りのガスを大量に集める事が可能となり、木星型のガス惑星が形成される。太陽質量程度の前主系列星周りの円盤の温度分布を計算すると、H₂O スノーラインは中心星から数 AU 程度に存在するとされている。しかし系外惑星系の場合空間分解能が足りず、撮像観測による H₂O スノーラインの検出は困難であった。

一方最近 Spitzer や Herschel で円盤から放射される H₂O 輝線を検出できるようになった。異なる波長の H₂O 輝線の強度比を用いて H₂O スノーラインの位置を見積もる研究もなされつつあるが、円盤の温度分布のモデルに依存するものであった (Zhang et al. 2013)。しかし今後波長分解能の高い分光観測が可能になれば、輝線スペクトルの速度プロファイルを解析する事で、モデルに依存せず H₂O スノーラインを同定できると考えられる。

そこで我々はこれまで、このような観測による H₂O スノーライン決定の可能性を調べてきた。具体的にはまず原始惑星系円盤の化学反応計算を行い、H₂O の存在量とその分布を調べた。すると H₂O スノーラインの内側の円盤赤道面付近だけでなく、円盤上層部の高温領域でも H₂O ガスの存在量が多い事が分かった。またその計算結果を元に、円盤から放出される H₂O 輝線のプロファイル、近赤外線からサブミリ波までの複数の輝線について計算した。その結果放射係数 (アインシュタイン A 係数) が小さく励起エネルギーが高い複数の輝線のプロファイルを分光観測で調べる事で、H₂O スノーラインを同定できる事が分かった。

また本研究では、新たに化学反応計算においてダスト表面反応を導入した場合と、ダストサイズを成長させた場合についての結果についても報告する。

まずダスト表面反応を導入した場合は、スノーライン内側の円盤赤道面付近では H₂O ガス存在量が増加する一方、円盤上層部の高温領域では減少した。その結果放射係数が小さく励起エネルギーが高い H₂O 輝線の放射強度が増加し、かつその増加幅は波長が短い輝線ほど大きい事も分かった。そして円盤上層部の高温領域からの寄与が小さくなった事で、放射係数がより大きな輝線も H₂O スノーラインの決定に使える可能性が示された。

一方ダストサイズを成長させた場合は、円盤上層部の高温領域での H₂O ガス存在量が増加する事が分かった。そのため、この場合は H₂O スノーラインの同定のためにはより小さな放射係数を持つラインを使用する必要があると考えられる。

本発表ではこの解析結果、及び将来の中間赤外線、遠赤外線、サブミリ波高分散分光観測 (ALMA, TMT, SPICA etc.) との関係について議論する。

キーワード: H₂O スノーライン, 原始惑星系円盤, 化学反応計算, ダスト表面反応, ダストサイズ成長, 分光観測

Keywords: H₂O snowline, protoplanetary disk, calculation of chemical reactions, grain surface reaction, dust size growth, spectroscopic observation

原始惑星系円盤における有機物粒子の時空間変化 Temporal and spacial variation of organic materials in the proto-solar disk

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More than 80 distinct amino acids are discovered in meteorites, which, in addition to their precursors, are suggested to be extraterrestrial origin. Even the detection of glycine, the simplest amino acid, has been claimed in samples from comet 81P/Wild 2 returned by NASA's Stardust spacecraft. These discoveries suggest that interstellar chemistry can produce such complex molecules. Motivated by these studies, some observational search for complex molecules in the interstellar medium reported to detect acetic acid, acetamide, aminoacetonitrile, and ethyl formate in Sagittarius B2 molecular cloud. More recently, ALMA observation is expected to find more complexity of such organic materials.

Organic materials in the asteroids and comets may be partially derived from molecular clouds and partially processed in proto-solar disk. It is one of the critical problems whether organic materials in the interstellar dusts formed in molecular cloud could survive and accreted to planetesimals. Interstellar dusts were incorporated into the proto-solar molecular cloud and were heated to evaporate in the proto solar nebula. Since the degree of evaporation depends on temperature and pressure conditions of the solar nebula, the distribution and chemical compositions of the dusts in the solar nebula would vary from place to place and with time.

We calculated disk evolution and particle motion simultaneously in order to investigate temperature change of individual particles, which enables us to trace the change of average chemical composition of organics. The fundamental difference from the chemical network reactions on the surface of solid materials at lower temperatures of molecular clouds is that the reactions in this work are thermal processes at higher temperatures ($T \geq 297\text{K}$).

We calculate viscous disk evolution model and particle-tracking model by Ciesla (2011). Particles are released at each 10AU at $t = 0$. Particles are supposed to be small enough to well couple with gas and they are thermally equilibrated.

The starting material is assumed to be *Greenberg particle*, which consists of silicate core and organics, and the chemical composition is taken from that for 297K of Nakano et al. (2003). When heated, the C and N composition of particles varies according to Nakano et al. (2003), but do not vary if temperature decreases. By summing up all the grains with different thermal history located at every 1AU at a certain time, the local bulk chemical composition of organics in the disk is obtained.

The temporal change of gas temperature and distribution of particles shows that particles initially located in the low-temperature outer region drift inward, and that thermally unprocessed organic particles were present in the inner region after 10^6 years because the temperature of disk decreases with time where particles from outer regions move.

The temporal-spatial variation of C and N contents and C/N ratio of organic particles indicates chemical variation of the inner region ($\leq 10\text{AU}$). Silicate-organics complex grains from a molecular cloud were partially evaporated to be poor in organic materials inside 5AU at the early stage of the proto-solar disk. As temperature decreases with time, primitive grains are transported inward and chemical composition of organic materials in the inner regions of the disk changed from fractionated to unfractionated composition with disk evolution. A small amount of diffuse cloud organic materials survive at the most inner region and partially evaporated molecular cloud organic materials and diffuse cloud organic materials are mixed at C/N ratio-decreasing region. This result shows that composition of organic materials accrete to a planetesimal depend on when the planetesimal is formed.

キーワード: 分子雲, 原始惑星系円盤, 有機物, 星間塵

Keywords: molecular cloud, protoplanetary disk, organic materials, interstellar dust

初期太陽系星雲中でのFT型触媒反応による分子形成の再現実験 Reproduction experiment of molecular formation based on Fischer-Tropsch-type catalytic reaction in the early solar nebula

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Catalytic reactions such as the Fischer-Tropsch type and Haber-Bosch type reactions are able to produce organic molecules efficiently on the surface of cosmic dust analogues, such as iron, magnetite, amorphous iron silicate and graphite at temperature above 573 K and pressure at 10^5 Pa in the laboratory [1-4]. In these experiments, organic molecules ranging from methane (CH_4), ethane (C_2H_6), benzene (C_6H_6) and toluene (C_7H_8), to more complex species such as acetone ($\text{C}_3\text{H}_6\text{O}$), methyl amine (CH_3NH_2), acetonitrile (CH_3CN) and N-methyl methylene imine (H_3CNCH_2) have been produced so far. However, it is not obvious the reaction similarly works in the solar nebula and is able to extrapolate to the actual early nebula environment at lower temperature below 500 K and lower pressure under 10^2 Pa. Therefore, we developed a new experimental system to test the catalytic chemical reactions in the early nebula environment [lower temperature (100-500 K) and pressure (10^{-3} - 10^0 Pa)] using a substrate of magnesium silicate or iron. Our experimental system has a temperature-controlled substrate, a Fourier transform infrared spectrometer (FT-IR), and two quadrupole mass spectrometers (Q-MSs). FT-IR measures the vibration modes of adsorbed and produced molecules on the surface and the Q-MSs detect volatile molecules, respectively. As a preliminary experiment, the substrate of a magnesium silicate thin film was used in a continuous gas flow of a mixture gas of H_2 and CO for Fischer-Tropsch type reactions. Unfortunately, however, we do not find any signal of the Fischer-Tropsch type reaction and resulting organic molecules on the amorphous magnesium substrate, whereas the signal of CHO molecule and ethane (C_2H_6) have been detected on the Q-MS spectra in some experimental condition on a different substrate. In the workshop, the detail results using iron substrate will be presented as a function of temperature and pressure.

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キーワード: 有機物, 触媒反応, 分子生成, 低温科学, 太陽系星雲

Keywords: organics, catalytic reaction, molecular formation, low temperature science, solar nebula

隕石有機化合物生成におけるオリビン触媒の効果 Effects of olivine as a catalyst for the formation of organic compounds in meteorites

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INTRODUCTION

Many classes of organic compounds have been identified in carbonaceous meteorites, which imply a complex history of chemical evolution in extraterrestrial environments. In the previous study (Yamashita and Naraoka, 2014), saturated- and unsaturated-alkylpyridines were reported with extensive homologous series ranging from C₁ to C₂₀ in the Murchison meteorite, which could be produced through aldol condensation of aldehydes in the presence of ammonia. The pyridine-derived compounds such as pyridine carboxylic acids (including nicotic acid) and alkylpiperidines were also found in Murchison, probably resulting from the alkylpyridines by oxidation and reduction, respectively, on the meteorite parent body.

EXPERIMENTAL

The simulation experiments were performed in this study to pursue reaction mechanisms for the occurrence of alkylpyridines and their derivative compounds in meteorites. Aqueous solution containing aldehydes (HCHO and/or CH₃CHO) and ammonia were heated in the presence or absence of olivine powder as a catalyst in a glass ampoule after N₂-purging at 50-100 °C for 5-26 days. The reaction products were analyzed by high performance liquid chromatography/mass spectrometry with electrospray ionization.

RESULTS AND DISCUSSION

Alkylpyridines were commonly observed in the reaction products. However, the alkylpyridine distribution was different depending in the presence or absence of olivine. Longer alkylated (up to C₂₀) pyridines were produced with olivine, while only shorter alkylated (up to C₇) ones were produced without olivine. The olivine surface can provide reaction sites to support elongation of alkylpyridines during aldol condensation. In addition, pyridine carboxylic acids were present with olivine, but absent without olivine. The chemical oxidation of alkylpyridines could be promoted by olivine. Thus, the effects of olivine are remarkable as catalysis to control the compound distribution observed in carbonaceous chondrites.

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キーワード: 炭素質隕石, 有機化合物, カンラン石, 触媒作用, 水質変成, 分子進化

Keywords: carbonaceous chondrites, organic compounds, olivine, catalysis, aqueous alteration, molecular evolution

投影型イメージング質量分析装置を用いたマーチソン隕石の測定 Imaging Measurement of Murchison Meteorite by using Stigmatic Imaging Mass Spectrometer

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地球に存在する生命の起源に関して、これまで様々な議論がなされてきている。近年、可能性が高いとされているのは、宇宙空間において生成した有機物が太陽系形成の初期段階において地球にもたらされ、その有機物をもとにして生命へと至ったとする説である。このような太陽系の初期段階に関する始原的な情報は現在も特定の小惑星や惑星間塵（宇宙塵）などに残っており、それらを調べることでどのような有機物がかつて地球にもたらされたのかを知ることができる。

このような研究では、始原的小惑星に由来して地球に飛来した炭素質コンドライト隕石を主な測定対象としている。その中でも有機物を多く含有するマーチソン隕石は、これまでに多くの研究がなされている。含有されている有機物は、アミノ酸、炭化水素、カルボン酸など多岐にわたり、クロマトグラフィーと質量分析を組み合わせた手法により物質が同定されてきた。このように隕石中の有機物を分析する場合には、全体を溶媒で抽出する大域的な測定がもっぱら行われてきた。しかし、より局所的な観点から、隕石中の有機物の分布構造や隣接する鉱物との因果関係を知ることができれば有機物の生成過程についての重要な情報を得ることができる。これまで、隕石中の有機物の空間分布はラマン分光や放射光などを用いた測定による化学結合に着目したものがあつたが、この手法では詳細な分子組成はわからない。質量分析により分子の質量を高精度で測定できれば分子組成などより多くの情報を得ることができる。表面分析の手法では、イオンビーム照射によるイオン化を用いた質量分析イメージングがあるが、イオン化時にフラグメント化が起るため有機物の分析には適していなかった。大阪大学で開発した MALDI イメージング質量分析装置は高分子のイオン化が可能で、高質量分解能かつ高空間分解能での有機物の分布情報を測定することができる。レーザーによるソフトなイオン化であるため、有機物分子を壊すことなくイオン化できる。さらに、これまでの走査型では空間分解能は 10-100 μm 程度が限界であつたが、投影型では 1 μm の空間分解能を実現している。この装置を用いてマーチソン隕石における構成成分の分布を測定した。

キーワード: イメージング質量分析, アストロバイオロジー, マーチソン隕石
Keywords: Imaging Mass Spectrometry, Astrobiology, Murchison Meteorite

超伝導 NbTiN を集積した 1.9THz 帯導波管型ホットエレクトロンボロメータ・ミクサ検出素子の開発 Development of 1.9 THz Band Waveguide-type Hot-electron Bolometer Mixer Employing Superconducting NbTiN Microbridge

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星間ガスや惑星大気分子・原子・イオンの多くが、ミリ-サブミリ波帯において回転・振動・微細構造線などのスペクトル線を放射している。電波天文学で採用するこの波長域のヘテロダイン分光の手法は、高い周波数分解能 ($\Delta f/f > 10^6$) の特徴を有し、星間ガスや星形成領域、惑星大気ダイナミクスや密度、温度、組成などの基本的な物理・化学的状態を探る強力なツールとなっている。ただし、1 THz を超えてくると、これまで威力を発揮してきた超伝導 SIS 検出素子はクーパ対が破壊されて動作原理上機能しなくなるため、未開拓の観測波長領域となっていた。こうした中、超伝導ホットエレクトロンボロメータ (HEB) ミクサ素子は次世代の高感度ヘテロダイン検出素子として着目されている。

我々は現在、1.8-2 THz 帯 HEB ミクサ素子の開発を進めている。この波長域には、地球・惑星大気中の OH ラジカル、星間ガス中の炭素イオンや酸素原子、その他の高励起スペクトル線が沢山眠っている。この素子の心臓部である超伝導微細線には、我々のプロセスにおいて性能実績のある NbTiN 薄膜を *in situ* の手法により集積する。また、フィードは、従来の準光学型から、ビームパターンの優れた導波管/ホーン型へと改良する。素子チップとのインピーダンス整合の設計には 3次元高周波電磁界シミュレーター HFSS を用いて行った。また、光学伝送の設計は GRASP ソフトウェアを用いた。この HEB 素子の基板チップの最適サイズは幅 44 μm 、厚み 19 μm と非常に微細となる。そこで、ダイシング装置やマルチプレッ研磨システムを用いて実際にチップを試作し、膜応力によるチップの反りや、加工時のクラック、その他ワイヤーボンディングなどのハンドリングなどの検証も行った。この結果、歩留りは 90%以上を達成し、実用に耐えるチップの微細化が十分に可能であることを確認した。この素子を実装するチップスロット/導波管、ホーンアンテナの微細加工も今回初めての試みとなるが、マシンニングによる切削の目処がたっている。本講演ではこの新しい 1.9THz 帯 HEB ミクサ検出素子の設計・開発の進捗について講演を行う。

キーワード: テラヘルツ天文学, 星間ガス, 惑星大気, ヘテロダイン分光, 超伝導検出器

Keywords: Terahertz Astronomy, Interstellar Medium, Planetary Atmosphere, Heterodyne Spectroscopy, Superconducting Detector

ダストの空隙率とシリケートフィーチャーの関係 The effect of the porosity of dust aggregates on the 10-micron silicate feature

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岩石惑星の主要な材料であるシリケートダストの光吸収係数は波長 10 μm 付近に特徴的なフィーチャーを示し、このフィーチャーは Spitzer 望遠鏡等による中間赤外線分光観測によって数多くの原始惑星系円盤から見つかった。従来は、観測されたフィーチャーをダストのサイズや組成をパラメーターとして変化させ、再現することで、円盤に存在するダストの特性に制約を与えてきた。近年、原始惑星系円盤のダストは高い空隙率を持って成長することが示唆されている。しかし、現実の円盤において、高空隙率ダストの存在は観測的に検証されてはいない。そこで、本研究では空隙率というパラメーターに応じて、シリケートフィーチャーがどのように変化するかについて調べ、ここから観測的に高空隙率ダストの存在を検証することを目的とする。

本研究では T-Matrix 法と呼ばれる数値計算法を用いて、空隙を持ったダストのシリケートフィーチャーを計算した。従来、空隙を持たないダスト（コンパクトダスト）はサイズが大きくなるにつれ、フィーチャーのピーク波長が長波長側へとシフトしながら、強度が下がっていく性質があることが知られていた。しかし、我々は空隙を考慮したダストの場合には、サイズを大きくしてもピーク波長は殆ど変化せずに、強度が下がっていく性質があることを明らかにした。これは高空隙率ダストが実効的には真空に近い光学定数を持っているためと理解することができる。また、現実の円盤に存在するダストはサイズ分布を持っていると考えられるが、サイズ分布を持っていたとしても同様の傾向が得られることを有効媒質近似を用いて確かめた。次に、このようなコンパクトダストと高空隙率ダストの違いはフィーチャーのピーク波長付近 ($\sim 10 \mu\text{m}$) での強度と長波長側 ($\sim 12 \mu\text{m}$) での比を取ることで、判別することができることを示した。以上の結果は、観測された 10 μm のフィーチャーにおいて 2つの波長での比を取ることで、観測的に円盤に存在するダストがコンパクトか高空隙率ダストかを判別可能である可能性を示唆している。

キーワード: 原始惑星系円盤, ダストアグリゲイト, 光学特性

Keywords: protoplanetary disks, dust aggregates, optical properties

Mg₂SiO₄-H₂-H₂O 系でのフォルステライト凝縮速度論 Kinetic condensation of forsterite in the system of Mg₂SiO₄-H₂-H₂O

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Equilibrium condensation calculations provide a set of stable minerals under a certain physical and chemical condition, condensation does not necessarily occur in equilibrium in time-variant circumstellar systems, where pressure, temperature, and gas chemistry vary with time. It is thus important to understand the kinetic aspect of dust formation processes, especially the vapor growth kinetics of dust. In this study, we report a quantitative estimate of the condensation coefficient, non-dimensionless parameter representing kinetic hindrance for condensation, for vapor growth of forsterite under protoplanetary disk-like conditions in the system of H₂/H₂O/forsterite.

An infrared vacuum furnace was used in this study. A mixed gas of hydrogen and water vapor was flowed into the system at a controlled rate to keep a pressure constant. Synthetic forsterite powder in an iridium crucible was heated as a gas source. A part of evaporated gases were condensed on a substrate of platinum mesh located at a cooler region in the chamber. The pressure and temperature conditions during the experiment were close to those of protoplanetary disks. The total pressure of the system was kept at 5.6 Pa, and the substrate temperature was ~1235 K. The gaseous H₂O/H₂ ratio was set at ~0.015, which was ~15 times larger than the solar H₂O/H₂ ratio. The experimental duration ranged from 5 to 115 hours.

The platinum mesh was fully covered with sub-micron to micron-sized condensates. Chemical compositions of condensates were consistent with stoichiometric forsterite. A variety of EBSD patterns corresponding to crystalline forsterite were obtained from the condensates. We thus conclude that the condensates are a thin film of polycrystalline forsterite.

The gaseous SiO/H₂ ratio in the flux onto the substrate was estimated to be 5.5×10^{-7} that corresponds to 7.7×10^{-3} of the solar SiO/H₂ ratio. The supersaturation ratio for the present experiment was ~230. Based on the incoming flux of SiO onto the substrate and the ideal evaporation flux, the condensation coefficient of forsterite was evaluated to be 0.038 ± 0.005 at 1235 K and the supersaturation ratio of 230.

The condensation coefficient at 1235 K is well consistent with the evaporation coefficient for forsterite in hydrogen gas and is smaller than that of metallic iron. The difference in condensation and evaporation coefficients for metallic iron and forsterite may be attributed to the difference in atomic bonds in metallic iron (metallic bonds) and silicates (ionic and/or covalent bonds). This difference implies that the growth of forsterite dust, for instance AOAs in chondrites, occurs less efficiently than that of metallic iron dust in circumstellar environments although they have similar equilibrium condensation temperatures.

キーワード: フォルステライト, 凝縮, 速度論, ダスト, 原始惑星系円盤
Keywords: forsterite, condensation, kinetics, dust, protoplanetary disk