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スウェーデンの観測ロケットを用いた炭素質宇宙ダストの微小重力環境下での再現合成

Reproduction of carbonaceous cosmic dust in microgravity using a Swedish sounding rocket

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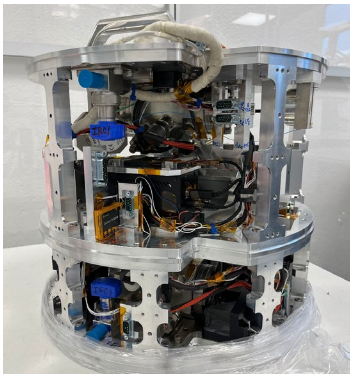

Abstract: We investigate the homogeneous nucleation of carbon nanoparticles under microgravity to understand the formation of cosmic dust from late-type giant stars. A key uncertainty in astrophysical models is two physical quantities of sticking probability and surface free energy, critical parameters for nucleation. Our experimental approach uses the gas evaporation method to mimic formation processes of cosmic dust particles. To eliminate convection current that interfere with ground-based measurements, we utilize a sounding rocket to achieve a microgravity environment, enabling a more accurate determination of physical quantities. Preliminary ground experiments revealed that carbon nucleates at a high supersaturation ratio (2.9×10^4), yielding a sticking probability of 0.39 ± 0.15 and surface free energy of 4.2 ± 0.2 N m^{-1}, values significantly lower and higher than commonly used in astronomical models, respectively. This presentation will report on these findings and present the latest results from our sounding rocket experiment conducted in November 2024.

Keywords: Nucleation, Nanoparticle, Gas evaporation method, Sounding rocket, Dust

1. Introduction

We are conducting research aimed at understanding the mechanisms of the initial crystallization process, from atoms and molecules to the formation of crystal nuclei, by elucidating the elementary processes involved. Until recently, it was believed that the final stable nuclei formed directly from the mother phase during the initial crystallization process (classical nucleation). However, recent studies have reported the existence of non-classical nucleation processes, such as particle fusion growth[1)] and the involvement of pre-nucleation clusters[2)], and it has become clear that these processes dominate nucleation in various systems[3)]. In response, we have experimentally demonstrated that, in addition to non-classical nucleation, the physical properties of nanoparticles must be incorporated into nucleation theory to predict and explain the early stages of crystallization[4-7].

2. Experimental Approach

When high-temperature gas is generated in an inert gas, nanoparticles are formed through homogeneous nucleation under ultra-high supersaturated conditions obtained during the cooling process. The temperature and number density at the moments of nucleation were determined with an interferometer. In addition, time scale for cooling and particle size were added into the modified classical nucleation theory. Then, we can determine two physical quantities (surface free energy and sticking probability) that give large uncertainties to nucleation theory[5,6]. In ground experiments, it is difficult to determine these physical quantities accurately because density-driven convection occurs and promotes nucleation. Therefore, we are using a microgravity environment provided by sounding rockets.

3. Specific Aim

In the early stages when late-type giant stars release high-temperature gas into space, there are no substances that can serve as substrates for heterogeneous nucleation. Then, homogeneous nucleation, which is not seen on Earth, occurs predominantly in very large supersaturation condition[4-8]. Therefore, using the physical quantities obtained in our homogeneous nucleation experiments, we can directly discuss the formation process of nanoparticles called cosmic dust that form in the gas released from late-type giant stars. Carbon is an important element that exists throughout the universe and has various allotropes with vastly different physical properties. Its surface free energy has been reported to range widely from 0.04 to 4.8 N m^{-1} [9], although values of about 1.40 N m^{-1} have typically been used for astronomical estimations of grain formation[10]. In this presentation, we will focus on the results of a sounding rocket experiment conducted in November 2024 to understand the nucleation process of carbonaceous dust.

4. Preliminary Experiments in Gravity Condition

The nucleation temperature and partial pressure were determined to be 2495 ± 50 K and ~2766 Pa for C. The supersaturation ratio for nucleation ($P/P\mathrm{e}$, where $P\mathrm{e}$ is the equilibrium vapor pressure of the corresponding material) was 2.9×10^4 for C. The equilibrium vapor pressure of carbon is given by the expression $\log P_{\mathrm{M}}$ (atm) = 10.609 – 41523/T [11]. The particles produced under gravity were collected directly on TEM grids. The grids were loaded into a TEM and the crystalline structure, size, and size distribution of the particles were investigated. The average diameter was 12 nm. Many fine particles with 1.6 nm in diameter were also present. Using these values, the sticking probability and surface tension can be determined to be 0.39 ± 0.15 and 4.2 ± 0.2 N m^{-1}, respectively, under the supersaturation conditions where carbon grains are nucleated[7].

Acknowledgments

Microgravity experiments were conducted with the technical support of the Swedish Space Corporation (SSC) with financial support from the German Space Agency (DLR) and the Institute of Space and Astronautical Science (ISAS), the Japan Aerospace Exploration Agency (JAXA). Development of the experimental system was supported by the Technical Division of the Institute of Low Temperature Science, Hokkaido University, and the Advanced Machining Technology Group of JAXA. This work was supported by FY2016 ISAS Small-Scale Science Projects of JAXA, Grant 50WM1846 of DLR, and Grantin-Aids for Scientific Research (S) from KAKENHI 15H05731 and 20H05657.

Conflicts of Interest

The authors declare no conflict of interest.

References

1) Y. Kimura and K. Tsukamoto: New perspectives on mineral nucleation and growth: From solution precursors to solid materials, 339-351, Springer (2017), DOI: 10.1007/978-3-319-45669-0_17.

2) D. Gebauer, A. Volkel, and H. Colfen: Stable prenucleation calcium carbonate clusters. *Science*, **322** (2008) 1819-1822, DOI: 10.1126/science.1164271.
3) J. J. De Yoreo, et al.: CRYSTAL GROWTH. Crystallization by particle attachment in synthetic, biogenic, and geologic environments. *Science,* **349** (2015) aaa6760, DOI: 10.1126/science.aaa6760.
4) Y. Kimura, K. K. Tanaka, H. Miura, L. Tsukamoto, Direct observation of the homogeneous nucleation of manganese in the vapor phase and determination of surface free energy and sticking coefficient. *Cryst. Growth Des.*, **12** (2012) 3278–3284, DOI: 10.1021/cg300417c.
5) Y. Kimura, K. K. Tanaka, T. Nozawa, S. Takeuchi, Y. Inatomi, Pure iron grains are rare in the Universe. *Sci. Adv.*, **3** (2017) 1601992, DOI: 10.1126/sciadv.1601992.
6) Y. Kimura, K. K. Tanaka, Y. Inatomi, F. T. Ferguson, J. A. Nuth III, Inefficient growth of SiOx grains: Implications for circumstellar outflows. *Astrophys. J.*, **934**, (2022) L10, DOI: 10.3847/2041-8213/ac8002.
7) Y. Kimura, K. K. Tanaka, Y. Inatomi, C. Aktas and J. Blum: *Sci. Adv.*, **9** (2023) eadd8295.
8) M. Bose, C. Floss, F. J. Stadermann, An investigation into the origin of Fe-rich presolar silicates in Acfer 094. *Astrophys. J.,* **714** (2010) 1624–1636, DOI: 10.1088/0004-637X/714/2/1624.
9) R. G. Tabak, J. P. Hirth, G. Mevrick, T. P. Roark, The nucleation and expulsion of carbon particles formed in stellar atmospheres. *Astrophys. J.,* **196** (1975) 457–463, DOI: 10.1086/153425.
10) H.-P. Gail, R. Keller, E. Sedlmayr, Dust formation in stellar winds. I. A rapid computational method and application to graphite condensation. *Astron. Astrophys.,* **133** (1984) 320–332.
11) *The Refractory Carbides*, E. K. Storms, Ed. Academic Press (1967).