Chapter

Microgravity Experiments Using Parabolic Flights for Dusty Plasmas

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Abstract

The chapter is dedicated to descriptions of the microgravity experiments, which were done by using parabolic flights and for analyzing behaviors of dust particles in plasmas, i.e., dusty plasmas under microgravity. There are projects of the microgravity experiments of the dusty plasmas using the International Space Stations, where time for microgravity is long and has a scale of hours. Conversely, it is significant to find out phenomena of the dusty plasmas in the short time scale of a few 10 s including the transition from gravity to microgravity, which is performed by parabolic flights of aircrafts on the earth. Methodology and results of the experiments are shown here for further investigations of the dusty plasmas in future.

Keywords: dusty plasma, coulomb crystal, microgravity experiment, parabolic flight

1. Introduction

Dust particles in plasmas have been investigated under microgravity for this quarter century, since they attract interest of physicists working on the dusty plasmas which are plasmas containing them and the Coulomb crystals formed by them resulting from charging and strongly coupled interactions [1–4]. Experiments of the dusty plasmas under microgravity were initiated by a Russian team accessing to a space station of the Mir in the late 1990s. The team was a pioneer for the experiments and started to collaborate with a German team [5]. After collaboration between the teams, the experiments under microgravity came to be done by other facilities, drop towers in Germany and Japan [6], sounding rockets used by a German team and the International Space Station (ISS) intensively promoted by the Russian-German joint project of the PKE-Nefedov and PK-3 plus [7, 8]. The project on the ISS of PK-4 has been in progress since 2014 by an international team organized by the European Space Agency [9–11]. In this history, microgravity experiments by using aircrafts with parabolic flights have played an important role in feasibility studies for missions on the ISS. Opportunities of the parabolic flights for the dusty plasmas have been mainly provided in campaigns from the ESA and the Japan Aerospace Exploration Agency (JAXA). A Japanese team was engaging in the experiments with apparatuses similar to PK-3 plus and PK-4 to contribute preliminary results of these projects. Here the results obtained by the team are introduced as knowledge for experiments in the future. It costs a lot and takes so long time to prepare and perform the microgravity experiments by the aircrafts. Pieces of information in the chapter help successors to reduce money and time and get much more scientific merit in future microgravity experiments.

2. Microgravity experiments by parabolic flights

2.1 Background

The Japanese team experienced the missions of PK-3 plus, where the team aimed at demonstrating a critical phenomenon in dusty plasmas [12–14]. The PK-3 plus had a configuration of parallel-plate electrodes for rf (13.56 MHz) discharges. The team did microgravity experiments by aircrafts using the chamber the same as the PK-3 plus in Japan. This opportunity allowed the team to proceed to the next parabolic flight campaign for the next project of PK-4. The team built the apparatus of PK-4J whose glass tube for discharges was scaled down from the original one to load a rack system on the aircrafts for parabolic flights in Japan. The PK-4J had two phases of the microgravity experiments in Japan. The Phase 1 was dedicated to sophisticate the apparatus and acquire wide experience for the experiments using the parabolic flights. In the other, Phase 2, the behaviors of the dust particles were observed in cylindrical discharges [15], which had been preliminarily studied in numerical simulations [16, 17]. In parallel with the microgravity experiments, measuring parameters such as ion density and electron temperature in plasmas had been developed to reach comprehensive analyses of phenomena observed under microgravity [18–21].

2.2 Parabolic flights

In Japan, the parabolic flights are carried out by a company, Diamond Air Service, Inc. It has two aircrafts (**Figure 1**). One is smaller than the other and equipped with two racks. The larger one has four racks. Everything for the experiments is integrated into the rack before loading on the aircraft. The whole rack is inspected that all components inside are tightly fixed and checked before flights not to electromagnetically interfere with the aircrafts during operation. The aircraft makes a condition free from gravity with a flight pattern of parabola in an airspace above the Sea of Japan or the Pacific Ocean. It takes 1 h to obtain a set of parabolas not more than 15 times a day. **Figure 2(a)** shows a graph of an altitude as a function of time corresponding to the flight pattern of the aircraft. Angles of elevation and

Figure 1.
Aircrafts for parabolic flights operated by DAS. There are two types of the aircrafts. One is MU-300 from Mitsubishi heavy industries loading two racks (left), and the other is G-II from Grumman aircraft engineering Corp. For four racks (right).

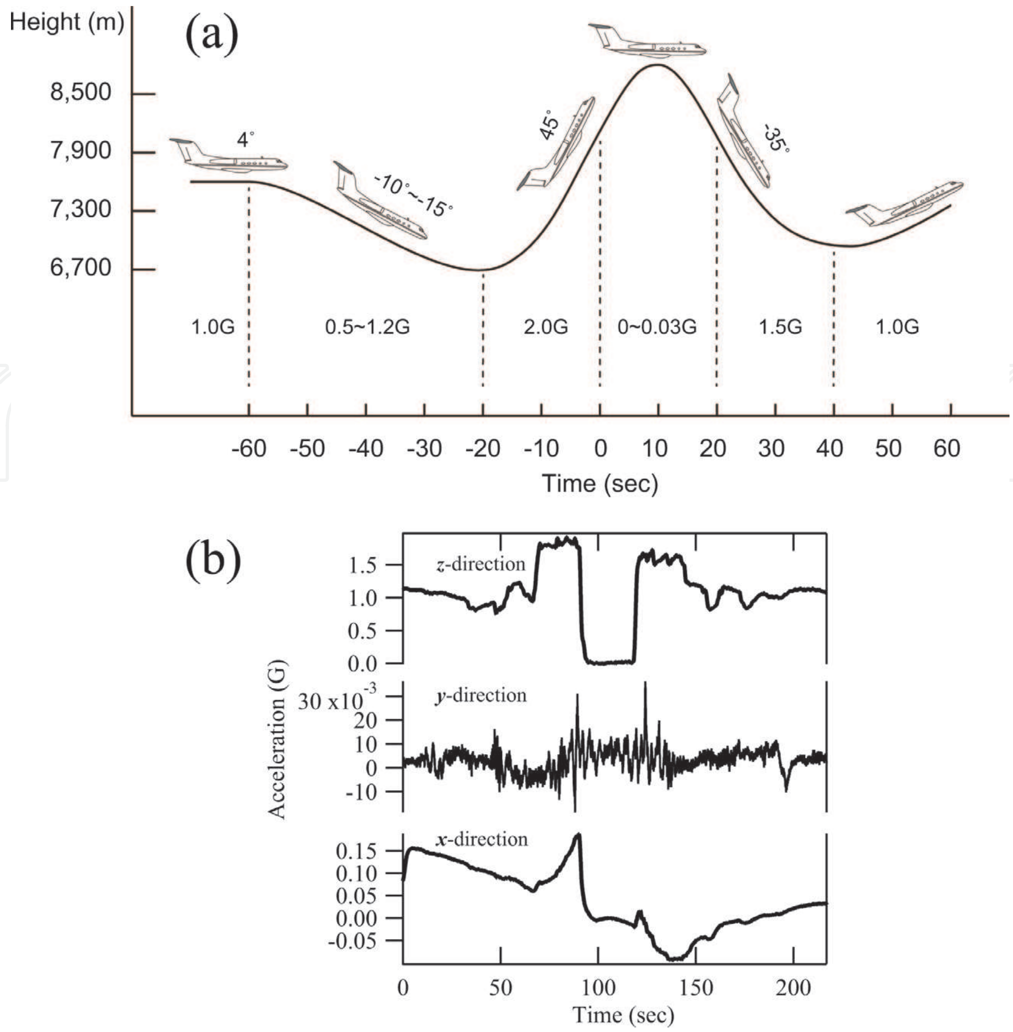

Figure 2.
(a) A flight pattern of the aircraft to obtain a condition under microgravity shown by an altitude of the aircraft as a function of time. The figure shows an angle of elevation and the acceleration parallel to gravity in a unit of G which can be felt by everything onboard. Here the 1 G is equivalent to the acceleration of gravity on the earth, i.e., 9.8 m/s^2. One can feel free from gravity during around 20 s in a parabola. (b) The time variations of accelerations onboard the aircraft measured in a parabolic flight. The x, y, and z are corresponding to the directions parallel to the traveling direction of the aircraft, to its wing, and to the gravity, respectively.

accelerations to be feel onboard are also indicated on the graph. The 1 G is corresponding to the acceleration of gravity on the earth, i.e., 9.8 m/s^2. To make a parabola, the aircraft rapidly accelerates and gains speed while getting the nose down between −60 and −20 s. After that, it elevates steeply while getting the nose up between −20 and 0 s and reaches the release point of an elevation of 45°, where a pilot closes the throttle. The aircraft continues flying by its inertia and makes the parabola between 0 and 20 s, where gravity is well balanced with the inertia. This is why everything onboard does not feel gravity. One can typically have a time of 20 s under microgravity during the aircraft moving up and dropping down in around 1000 m. After the parabola, the aircraft recovers speed and its altitude. Before and after the parabola, a load force normally acts on the aircraft by the acceleration less than 2 G.

Figure 2(b) is a graph of accelerations onboard the aircraft measured in a parabolic flight. The accelerations were detected by the directions of x, y, and z parallel to the traveling direction of the aircraft, to its wing, and to the gravity, respectively. The acceleration in the z-direction, i.e., parallel to gravity, dropped down to 0 G (μG) after an entry to parabola with 1.8 G and kept a constant stable for around 20 s. In the y-direction along to the wing, the acceleration was detected to be less than 4×10^{-2} G and had no effect on the experiments. However, in the x-direction parallel to the traveling direction, the acceleration was increased when the throttle was closed at the entry. It caused a problem in a feasibility study of Phase 1 as described later.

2.3 Methodology and design of apparatus

PK-4 was supposed to observe dust particles in a cylindrical discharge generated inside a glass tube. The Japanese team had built the apparatus of PK-4J based on dimensions and functions of PK-4 since 2011 (**Figure 3(a)**). The glass tube was an π-shape chamber consisting of a main tube with an inner diameter of 30 mm and branch tubes welded onto the main. The glass tube was fixed on an optical bench as the branch tubes being perpendicular to the floor on the aircraft. A pair of electrodes was placed in the branch tubes. Plasmas were generated by a rectangular pulse voltage applied between the electrodes. The voltage was varying between 650 and 750 V peak-to-peak at 1 kHz and supplied to the electrodes out of phase. This meant that polarity between the electrodes alternated at the frequency which did not allow the dust particles to follow an electric field by the voltage. Plasma frequencies of electron and ion are much higher than the frequency of the voltage, so that they are running between the electrodes back and forth. A current around 2.0 mA was observed in the discharge. The Ar gas was fed from a port on either of the branch tubes at a flow rate of four SCCM (SCCM denotes cubic centimeter per minute at the standard conditions) and pumped down from another port closed to the feeding port. Therefore the gas flow was negligible in the main tube like a stagnant pool of the gas. It was aimed at trapping the dust particles inside the main tube without perturbation by the gas flow. The dust particles of melamine-formaldehyde were injected by a dust dispenser mounted on the branch tube. Their diameter was 2.55 μm. The amount of the dust particles was regulated by a pulse voltage driving the dispenser.

The first apparatus was used for a feasibility study of Phase 1 and tested in microgravity experiments of parabolic flights between 2011 and 2012. The size of the main tube, whose length was 550 mm, was identical to the original one of PK-4

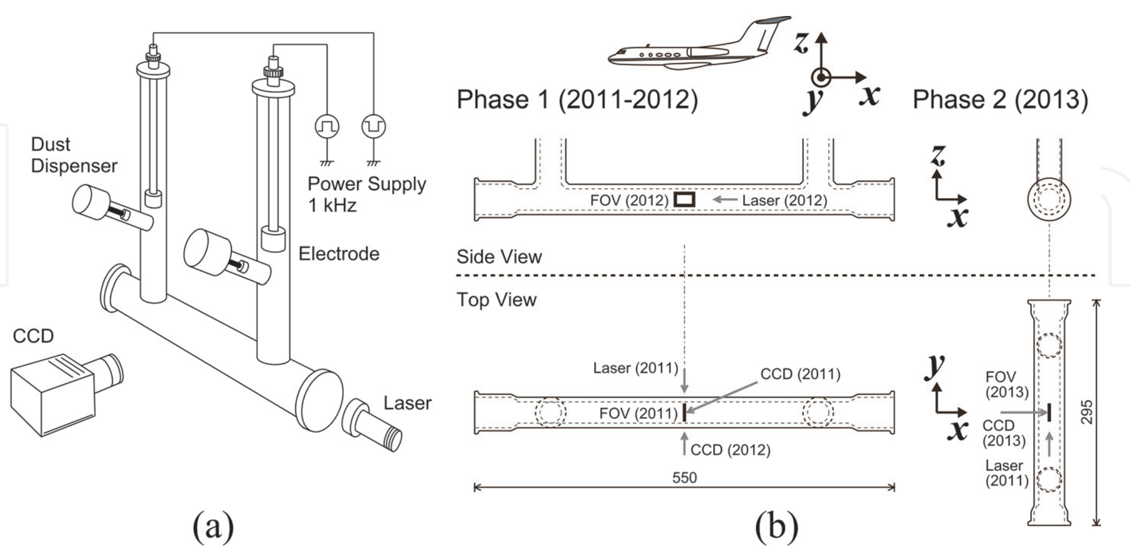

Figure 3.
Schematic of the apparatus of PK-4J. (a) It was developed to be loaded on a rack system of the aircraft operated by Diamond Air Service, Inc. the π-shape tube enabled to observe the dust particles in a cylindrical discharge. (b) Design of the glass tube was progressed from phase 1 to phase 2. In phase 1, the main tube had been placed parallel to the traveling direction. However, it was rotated to be perpendicular to the direction to avoid the effect of inertia by acceleration along the traveling direction of the aircraft just before entry to a parabola. In order to keep the main tube inside the rack, its length was reduced. The field of view (FOV) of the CCD camera was a cross section perpendicular to the axis of the main tube in phase 1 and changed to a plane along to the axis in phase 2.

(**Figure 3(b)**). The main tube was set along to the traveling direction of the aircraft (x-direction). The dust particles were illuminated on the cross section perpendicular to the axis of the main tube by a laser of 532 nm in wavelength, which corresponded to a field of view (FOV) observed diagonally by a charge-coupled device (CCD) camera.

The first campaign of parabolic flights in Phase 1 made it clear that the dust particles were levitated around a plasma-sheath boundary near the bottom of the main tube under gravity and moved up to the center of the tube under microgravity (**Figure 4(a)**). The cloud of the dust particles of μG seemed to elongate along the axis of the tube as a shape of a cylinder since a disk was observed on the FOV. In the next campaign, the FOV was set on the plane parallel to the axis. **Figure 4(b)** shows that the shape of the cloud was a cylinder elongating along the axis and spatial distribution of the dust clouds moved up from around the plasma-sheath boundary at 7 mm to the axial center. Under microgravity, the dust particles seem to form a bundle of thread. Furthermore, it found that the dust particles were forced to be moved by acceleration along the traveling direction. Before the entry of a parabola, they went toward the back of the aircraft. They came to flow to the front of the aircraft after the entry. This was the problem to be solved in order to precisely observe arrangements of the dust particles as mentioned above. Therefore, it was decided that the main tube was placed crossing with the traveling direction of the aircraft in Phase 2 (**Figure 3(b)**). The length of the main tube was reduced to be 420 mm to put it in a frame of the rack on the aircraft.

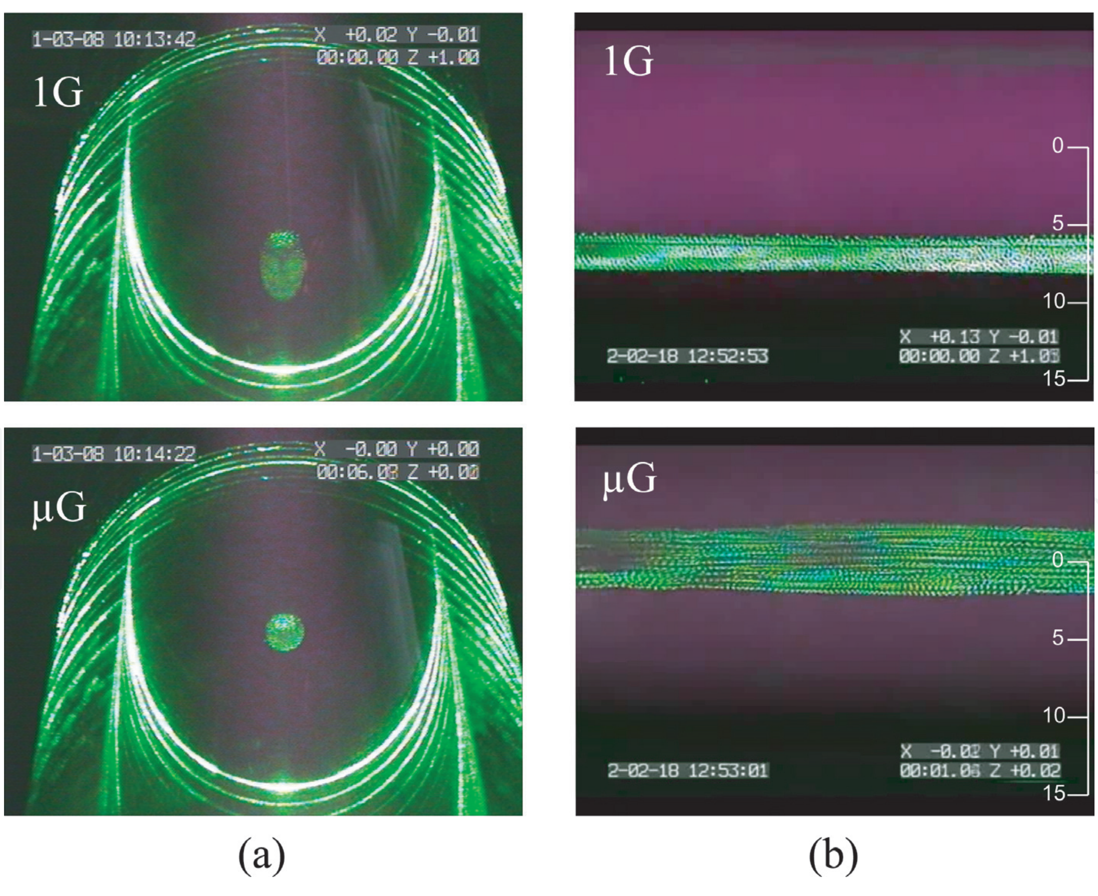

Figure 4.
Images of the clouds of the dust particles obtained in microgravity experiments of phase 1. (a) The cloud was observed on a cross section perpendicular to the axis of the main tube. The cloud stayed around the plasma-sheath boundary near the bottom of the tube under gravity (1G). Under microgravity (μG), it moved up and made a disk. (b) The scale bar shows distance from the axis. The 15 mm corresponds to the inner wall of the glass tube. The dust particles were levitated around the plasma-sheath boundary near the bottom of the tube (at 7 mm from the axis) (1G). The cloud elongated along the axis. The dust particles were distributed around the axis under microgravity (μG).

In Phase 2, a laser of 660 nm in wavelength was used to illuminate the dust particles. Its light was fine-shaped as the thickness (FWHM of intensity) of 50 μm by optics to make slice images of the cloud. The laser and CCD camera were mounted on a translation stage. The stage moved to make a scan in the direction along the traveling direction (x-axis). The CCD of a resolution of 480 × 640 pixels accumulated images at 200 fps while scanning at the speed of 6.5 mm/s. The field of view was 4.3 × 5.8 mm^2.

3. Dusty plasmas under microgravity

Figure 5 shows spatial distributions of the dust particles observed in Phase 2, where the peak-to-peak voltage and gas pressure were set at 700 V and 33 Pa, respectively [15]. The axes of x, y, and z correspond to the direction in traveling, that of the wing, and that perpendicular to the floor of the aircraft, respectively. Two cylinders of the clouds for the cases under gravity (1G) and microgravity (μG) are shown the **Figure 5(a)**. Both of them elongate along the y-axis and seem to be tapered. In the main tube, striations appeared in the discharge. The cloud became fat in swollen parts of brighter glow. In a level flight, i.e., under gravity, the main body of the cloud was placed below the axis, and the dust particles were distributed in $-4.7 \leq z < -2.0$ mm. The cloud of 1G consists of a shell-like structure of three layers clearly appearing in the bottom part as indicated in other experimental and theoretical studies [17, 22, 23]. The outermost shell along the arrow in **Figure 5(a)** was unfolded on a plane of the cylinder surface (**Figure 5(b)**). Coordinates of the dust particles are plotted on the plane as parameters of a circumference of the cylinder (L) and y. The dust particles arranged to make a close packed structure in 2-dimension by a Coulomb repulsive force between them. This arrangement formed the layered structure stacking in the radial direction. Another work proved that the

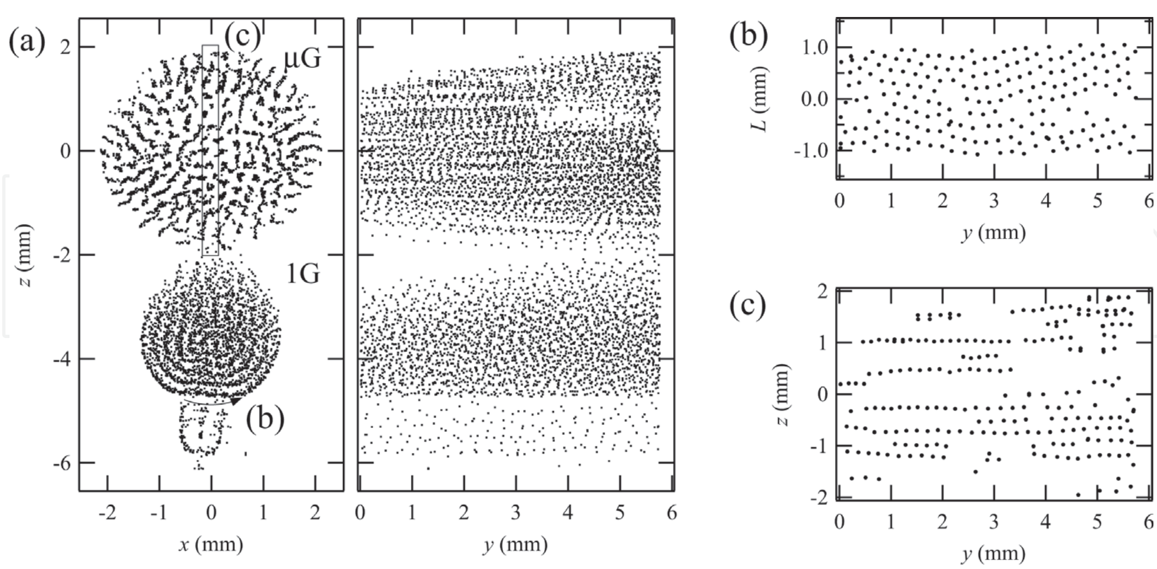

Figure 5.
Spatial distributions of the dust particles observed in phase 2 (the graph was reproduced by the data from the previous paper [15]). Each dot corresponds to each coordinate of a dust particle. (a) The clouds were shown for the conditions under gravity (1G) and microgravity (μG). The x, y, and z-axes correspond to the directions in traveling, of the wing and perpendicular to the floor of the aircraft, respectively. The left graph is a cross-sectional view shown as projection along the y-axis ($0 \leq y < 6$ mm). The right one is a projection along to the x-axis ($-2 \leq x \leq 2$ mm). (b) An axis of L is defined as a circumference of the outermost shell along an arrow in (a). An arrangement of the dust particles is shown on a L-y plane. (c) The coordinates of the dust particles trimmed by the rectangle shown in the figure (a) are plotted on a y-z plane as a projection along to the x-direction.

structure was the face-centered orthorhombic (FCO) lattice [24]. The FCO structure tends to appear rather than isotropic structures such as body-centered and face-centered cubics under the conditions that a stress works in one direction [25–27]. Here the stress means gravity.

Under microgravity (μG), the cloud moved up and the dust particles were distributed around the axis. The cylinder of the cloud got thicker than that under gravity. Its axis was exactly identical to that of the main tube. **Figure 5(c)** shows coordinates of the dust particles in a region trimmed by a rectangle (indicated by **Figure 5(a)**) as a projection along the x-axis. The FCO structure was never found under microgravity. The dust particles formed an assembly of linear chains elongating along the y-axis, i.e., the main tube [28, 29]. The electric field, whose direction is alternatively switched at 1 kHz between the electrodes, makes an ion stream along its direction. The ion stream causes the wake potential around the dust particles which makes them interact by an attractive force in addition to the Coulomb repulsive force [30–32]. Linear chains of the dust particles had normally been observed near the electrodes in rf discharges which accelerate ions in sheath [33–35]. In the discharge of the main tube, the ion stream has two components. One is from the ions going back and forth between electrodes, and the other is from those flowing toward walls by diffusion. At the axis, the ions going through the discharge are much more than those flowing toward the walls. Therefore, the dust particles form the chains around the axis by the wake potential, when they move up from the bottom to the center of the discharge under microgravity. Regarding the wake potential, its characteristics were made clear in several experiments under gravity [34, 36, 37]. Further, microscopic dynamics for causing the wake potential, e.g., visualization of the wake potential, will be expected to be analyzed in experiments under microgravity in addition to a calculation with a classical manner [38].

4. Concluding remarks

An apparatus of dusty plasmas was developed for observing dust particles of cylindrical discharges in a glass tube under microgravity. It was built step by step while testing its functions and observing the dust particles on board an aircraft. In order to analyze the arrangements of the dust particles, positioning the glass tube and field of views were considered in experiments of parabolic flights. It was significant for building the apparatus to suppress an effect of acceleration in the traveling direction of the aircraft caused around entry of a parabola.

In the experiments, coordinates of the dust particles were recorded in conditions under gravity as well as microgravity. They were located near the plasma-sheath boundary below the axis of the glass tube and found to form staking layers in a bottom part of clouds under gravity. The layers were not an isotropic three-dimensional structure such as body-centered or face-centered cubic. The FCO lattice appeared in the cloud, which seemed to be deformed by a stress in one direction originated in gravity. Switching the condition from gravity to microgravity, at first, location of the dust particles was changed around the axis. The dust particles distributing around the axis drastically changed their arrangement from the FCO structure to an assembly of linear chains. The chains were possibly formed by an attractive force from a wake potential. The wake potential was promised to be caused by streaming of the ion which was going back and forth between electrodes and driven by electric field alternative at 1 kHz. The dust particles switched dominant interaction potential from Coulomb repulsive under gravity to wake under microgravity. This was unexpected in simulations removing a term of gravity and an example that the microgravity condition possibly revealed a phenomenon hidden under the influence of gravity.

In microgravity experiments by parabolic flights, it is meaningful to have transition state from gravity to microgravity as well as to have microgravity only. Furthermore acceleration parallel to gravity controlled in operation of the aircraft by pilots is fascinating in precisely analyzing responses of physical phenomena to gravity. This is something that cannot be done on the ISS. The mechanism in formation of the linear chains was clearly understood in observation of the dust particles moving in the transition state where the acceleration was gradually changed. There are likely advantages to use the parabolic flights in diverse fields other than microgravity science.

The behavior of the dust particles, which are visible in an invisible ensemble of plasmas consisting of electrons and ions, clearly reflects phenomena of physics in the plasmas and makes them easily understood. Indeed a phenomenon of invisible wave might be visualized and comprehended by the dust particles. There are so much dust in the universe, pollutants in the atmosphere, cosmic dust in the interstellar, the regolith on the moon, etc. They attract much interest for investigating the origin of the universe from the point of view of natural science. Particulate matter is widely used and produced in industries. The dust particles charged in the plasmas are available for seeking ways of application and new ideas in technology. The microgravity experiments of dusty plasmas are promising to open new ideas in future science and technology. The know-how introduced in the chapter will be hopefully useful for the future.

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References

[1] Hayashi Y, Tachibana K. Observation of Coulomb-crystal formation from carbon particles grown in a methane plasma. Japanese Journal of Applied Physics. 1994;**33**:L804-L806

[2] Thomas H, Morfill GE, Demmel V. Plasma crystal: Coulomb crystallization in a dusty plasma. Physical Review Letters. 1994;**73**:652-655

[3] Chu JH, I L. Direct observation of Coulomb crystals and liquids in strongly coupled rf dusty plasmas. Physical Review Letters. 1994;**72**:4009-4012

[4] Melzer A, Trottenberg T, Piel A. Experimental determination of the charge on dust particles forming Coulomb lattices. Physics Letters A. 1994;**191**:301-308

[5] Morfill GE, Thomas HM, Konopka U, Rothermel H, Zuzic M, Ivlev A, et al. Condensed plasmas under microgravity. Physical Review Letters. 1999;**83**:1598-1601

[6] Hayashi Y. Radial ordering of fine particles in plasma under microgravity condition. Japanese Journal of Applied Physics. 2005;**44**:1436-1440

[7] Nefedov AP, Morfill GE, Fortov VE, Thomas HM, Rothermel H, Hagl T, et al. PKE-Nefedov: Plasma crystal experiments on the international Space Station. New Journal of Physics. 2003;**5**:33

[8] Thomas HM, Morfill GE, Fortov VE, Ivlev AV, Molotkov VI, Lipaev AM, et al. Complex plasma laboratory PK-3 plus on the International Space Station. New Journal of Physics. 2008;**10**:033036

[9] Usachev A, Zobnin A, Petrov O, Fortov V, Thoma M, Kretschmer M, et al. The project "Plasmakristall-4" (PK-4) is a dusty plasma experiment in a combined dc/rf(i) discharge plasma under microgravity conditions. Czechoslovak Journal of Physics. 2004;**54**:C639-C647

[10] Fortov V, Morfill G, Petrov O, Thoma M, Usachev A, Hoefner H, et al. The project 'Plasmakristall-4' (PK-4)—A new stage in investigations of dusty plasmas under microgravity conditions: First results and future plans. Plasma Physics and Controlled Fusion. 2005;**47**:B537-B549

[11] Pustylnik MY, Fink MA, Nosenko V, Antonova T, Hagl T, Thomas HM, et al. Plasmakristall-4: New complex (dusty) plasma laboratory on board the International Space Station. Review of Scientific Instruments. 2016;**87**:093505

[12] Totsuji H. Thermodynamics of strongly coupled repulsive Yukawa particles in ambient neutralizing plasma: Thermodynamic instability and the possibility of observation in fine particle plasmas. Physics of Plasmas. 2008;**15**:072111

[13] Totsuji H. Thermodynamic instability and the critical point of fine particle (dusty) plasmas: Enhancement of density fluctuations and experimental conditions for observation. Journal of Physics A: Mathematical and Theoretical. 2009;**42**:214022

[14] Totsuji H. Possible observation of critical phenomena in fine particle (dusty, complex) plasmas. Microgravity Science and Technology. 2011;**23**:159-167

[15] Takahashi K, Tonouchi M, Adachi S, Totsuji H. Study of cylindrical dusty plasmas in PK-4J; experiments. International Journal of Microgravity Science and Application. 2014;**31**:62-65

[16] Totsuji H, Totsuji C. Structures of Yukawa and Coulomb particles in cylinders: Simulations for fine particle

plasmas and colloidal suspensions. Physical Review E. 2011;**84**:015401(R)

[17] Totsuji H, Totsuji C, Takahashi K, Adachi S. Study of cylindrical dusty plasmas in PK-4J; Theory and simulations. International Journal of Microgravity Science and Application. 2014;**31**:55-61

[18] Takahashi K, Hayashi Y, Adachi S. Measurement of electron density in complex plasmas of the PK-3 plus apparatus on the international Space Station. Journal of Applied Physics. 2011;**110**:013307

[19] Takahashi K, Thomas HM, Molotkov VI, Morfill GE, Adachi S. Estimation of plasma parameters in dusty plasmas for microgravity experiments. International Journal of Microgravity Science and Application. 2015;**32**:320409

[20] Takahashi K, Adachi S, Totsuji H. Measurement of ion density and electron temperature by double-probe method to study critical phenomena in dusty plasmas. JAXA Research and Development Report. 2015;**14-012E**:7-11

[21] Takahashi K, Lin J, Hénault M, Boufendi L. Measurements of ion density and electron temperature around voids in dusty plasmas. IEEE Transaction on Plasma Science. 2018;**46**: 704-708

[22] Mitic S, Klumov BA, Konopka U, Thoma MH, Morfill GE. Structural properties of complex plasmas in a homogeneous dc discharge. Physical Review Letters. 2008;**101**:125002

[23] Totsuji H. Behavior of dust particles in cylindrical discharges: Structure formation, mixture and void, effect of gravity. Journal of Plasma Physics. 2014; **80**:843-848

[24] Takahashi K, Totsuji H. Structure of Coulomb crystals in cylindrical discharge plasmas under gravity and microgravity. IEEE Transaction on Plasma Sciences. 2019;**47**:4213-4218

[25] Fujii Y, Hase K, Hamaya N, Ohishi Y, Onodera A. Pressure-induced face-centered-cubic phase of monatomic metallic iodine. Physical Review Letters. 1987;**58**:796-799

[26] Stoeva SI, Prasad BLV, Uma S, Stoimenov PK, Zaikovski V, Sorensen CM, et al. Face-centered cubic and hexagonal closed-packed nanocrystal superlattices of gold nanoparticles prepared by different methods. Journal of Physical Chemistry B. 2003;**107**:7441-7448

[27] Hayashi Y. Structure of a three-dimensional Coulomb crystal in a fine-particle plasma. Physical Review Letters. 1999;**83**:4764-4767

[28] Ivlev AV, Thoma MH, Räth C, Joyce G, Morfill GE. Complex plasmas in external fields: The role of non-Hamiltonian interactions. Physical Review Letters. 2011;**106**:155001

[29] Dietz C, Kretschmer M, Steinmüller B, Thoma MH. Recent microgravity experiments with complex direct current plasmas. Contributions to Plasma Physics. 2018;**58**:21-29

[30] Nambu M, Vladimirov SV, Shukla PK. Attractive forces between charged particulates in plasmas. Physical Letters A. 1995;**203**:40-42

[31] Vladimirov SV, Nambu M. Attraction of charged particulates in plasmas with finite flows. Physical Review E. 1995;**52**:R2172-R2174

[32] Ishihara O, Vladimirov SV. Wake potential of a dust grain in a plasma with ion flow. Physics of Plasmas. 1997;**4**: 69-74

[33] Takahashi K, Oishi T, Shimomai K, Hayashi Y, Nishino S. Simple hexagonal

Coulomb crystal near a deformed plasma sheath boundary in a dusty plasma. Japanese Journal of Applied Physics. 1998;**37**:6609-6614

[34] Takahashi K, Oishi T, Shimomai K, Hayashi Y, Nishino S. Analyses of attractive forces between particles in Coulomb crystal of dusty plasmas by optical manipulations. Physical Review E. 1998;**58**:7805-7811

[35] Ivlev AV, Morfill GE, Thomas HM, Räth C, Joyce G, Huber P, et al. First observation of electrorheological plasmas. Physical Review Letters. 2008; **100**:095003

[36] Melzer A, Schweigert VA, Piel A. Transition from attractive to repulsive forces between dust molecules in a plasma sheath. Physical Review Letters. 1999;**83**:3194-3197

[37] Chen M, Dropmann M, Zhang B, Matthews LS, Hyde TW. Ion-wake field inside a glass box. Physical Review Letters. 2016;**94**:033201

[38] Melandsø F, Goree J. Polarized supersonic plasma flow simulation for charged bodies such as dust particles and spacecraft. Physical Review E. 1995; **52**:5312-5326