IIIIII Microgravity Experiments by Aircraft Parabolic Flights Ⅱ IIIIII
(Review)

Study of Cylindrical Dusty Plasmas in PK-4J; Experiments

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Abstract

Dusty plasmas have been studied under microgravity with utilities boarding on the International Space Station in a joint Russian/German research project. Dynamics of dust particles in cylindrical plasmas is investigated in the next term of the project with the apparatus of PK-4. A research team in Japan studied the cylindrical dusty plasmas to contribute to the project with the PK-4J similar to the original one and developed for microgravity experiments of parabolic flights in Japan. The dust particles distributed in the off-centered position close to the bottom in balancing of gravity. They changed the distribution and moved to around the center axis in a cylindrical discharge under microgravity. Several particles arranged in a line parallel to the axis, and the lines piled up to a bundle in the discharge.

Keyword(s): dusty plasma, complex plasma, microgravity, parabolic flight experiment, PK-4, PK-4J

1. Introduction

Dusty (Complex or Fine particle) plasmas correspond to the plasmas excited by electrical discharges, and including micrometer-sized dust particles. The dust particles are charged by fluxes of electrons and ions, and have several hundreds or thousands of elementary charge in typical experimental conditions. The highly-charged dust particles are the strongly coupled Coulomb system which is regarded as a model for general physics, statistical physics, crystallography, and so on.

In the plasmas, gravity as well as electrostatic and ion drag forces act on the dust particles. The particles are levitated around plasma-sheath boundary by a balance of the forces. Cloud of the particle is often localized at bottom side of the plasma by the gravity. Experimental condition free from the gravity brings the large volume of the cloud which enables to observe behaviors of the particles without boundary effects. The large system of charged particles is preferable for statistical analyses and significant in demonstrating physical phenomena. Plasmas can typically trap few particles beyond 10 μm in diameter on the earth. Conversely, microgravity enables the large and heavy particles, which are highly charged and strongly coupled, to be trapped in the plasmas. Therefore experiments under microgravity have attracted with apparatus carried on board parabolic flights, sounding rockets, and the International Space Station (ISS) in recent years [1)].

Several phenomena, e.g., crystallization, wave propagation and so on, were reported in the experiments on the ISS, which were done by an apparatus of PKE-Nefedov started to be utilized in 2001 [2-4)]. The abbreviation of PKE means a German word of “Plasmakristall Experiment”. The PK-3 plus improved from the PKE-Nefedov have been used from 2005 to 2013 [5)], in which new aspects of dusty plasmas, electrorheological fluid [6)], non-linear wave [7)] and so on, have been observed.

A Japanese scientific research team has joined to the mission of PK-3 plus to demonstrate a critical phenomenon in dusty plasmas [8-10)]. This allows the team to plan experiments in the next generation apparatus of PK-4, which is scheduled to be launched to the ISS in 2014. The PK-4 installs glass tube for cylindrical discharges driven by DC/AC mode [11, 12)]. Numerical simulations have been performed for dust particles in the cylindrical discharge by the team [13, 14)]. The dust particles are expected to make an arrangement of shell-like structure in the simulation. In addition, microgravity experiments have been continued since 2011 with the apparatus of PK-4J modified for parabolic flights in Japan [15)]. In the present paper, results of the parabolic flight experiment are reported.

2. Experimental

The PK-4 has a glass tube welded two glass branches with electrodes and dust dispensers [11, 12)]. For integrating apparatus to aircrafts of parabolic flight experiments in Japan, the main tube was modified and shrunk for PK-4J, whose size was adapted to a rack of the aircrafts (**Fig. 1**). The main tube was 420 mm long and its inner diameter was 30 mm. The branches were separated 300 mm. The setup of the glass tubes was placed as the branches standing perpendicular to floor of the aircrafts.

The electrodes inside the branch tubes were applied by rectangular pulse voltage of 700 V peak-to-peak at 1 KHz. The voltage was supplied to each electrode in out of phase. The Ar

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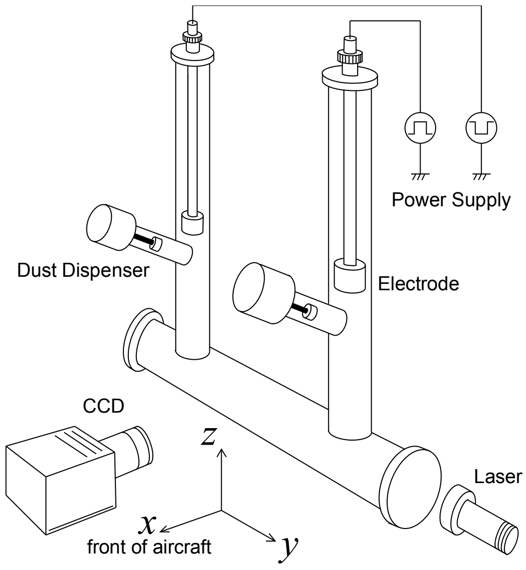

Fig. 1 Schematic of the apparatus PK-4J

gas flew through a branch tube at a flow rate of 4 sccm (sccm denotes cubic centimeter per minute at standard temperature and pressure), preventing from blowing the dust particles in the main tube. The gas pressure was maintained at 33 Pa. The melamine-formaldehyde particles were used, whose size was mono-dispersed and 2.55 μm in diameter.

The particles were illuminated by the laser of 532 nm in wavelength, which formed a sheet light parallel to *y*-*z* plane (**Fig. 1**). The light appeared to be Gaussian distribution in thickness, whose full width at half maximum (FWHM) was 50 μm. The scattering light from the particles were observed by a CCD camera with a resolution of 480X640 pixels. Field of view of the camera was 4.3X5.8 mm^2. A translation stage mounted the laser and the camera. Sliding in *x*-direction of the stage enabled to record scanning images of dust clouds. The images processed by a software derived 3-dimensional coordinates of the particles. Scanning speed of the stage was 6.5 mm/sec and frame rate of the camera was 200 fps, in which a space was 33 μm for a flame of image. Spatial resolution for the coordinates of the particle was actually determined by superposition of the space and the FWHM of the laser sheet.

On an aircraft for parabolic flights, the gas is introduced to the glass tube, discharge is initiated, and the dust particles are injected in level flight. After observing steady state of clouds of the dust particles, pilots are called to start the parabolic flight. A signal for trigger pulse is obtained when microgravity less than 0.1 G is detected for more than 2 sec in *z*-direction. The microgravity less than 10^{-2} G is generally maintained for 20 sec in a parabola. The translation stage and the camera are triggered to record the images by the signal or operated manually. It takes 4 min approximately for a cycle of experiment including one

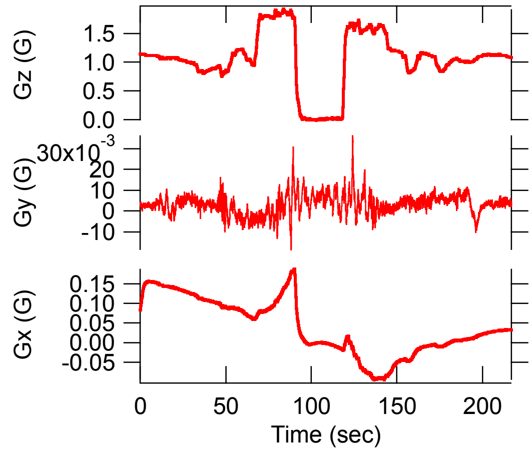

Fig. 2 Accelerations of gravity in *x*, *y* and *z* directions

parabola. Regulation for the flight allows 15 cycles of the experiment for one day. A campaign includes 2 or 4 flights, 30 or 60 parabolas.

3. Results and Discussion

Figure 2 shows accelerations of gravity detected by sensors on the aircraft, and varying as a function of flight time in a cycle for one parabola. In the figure, Gx, Gy and Gz correspond to the accelerations in *x*, *y* and *z*-directions as shown in **Fig. 1**, respectively. The microgravity was obtained between 95 and 118 sec. Before and after the microgravity, hypergravity appeared for several tens seconds. Furthermore, just before the microgravity, acceleration was detected in *x*-direction. This acceleration transported the dust particles to the tail of the aircraft in the setup of glass tubes placed as the main tube parallel to the direction of travel of the aircraft in feasibility experiments. Therefore the setup was improved in the present study.

Figure 3 shows spatial distributions of the dust particles under gravity (lower) and microgravity (upper). In the figure, coordinates of the dust particles are plotted by dots, the *y*-axis (x=0, z=0) corresponds to the axial center of the main tube along to wing of the aircraft, and the *x* and *z*-axes are along to the direction of travel of the aircraft and to the direction perpendicular to floor of the aircraft, respectively. When the dust particles in level flight (1 G) were observed to be below the axial center of the main tube (**Fig. 3** (lower)), the vertical line (to the earth) tilted to the *z*-axis due to nose of the aircraft looking up to horizontal line (generally, 4 º). The cloud of dust particles seems to be divided to a main part ($-4.7 \leq z < -2.0$) and a sub-one ($-6.0 \leq z < -4.7$). The sub-part may contain heavier particles as impurities or agglomerates, although any differences in dots of dust particles cannot be seen on flame images. The main part seems to be a shell-like structure, which consists of several cylindrical surfaces with a concentric axis (x=0, y=-3.5). The shells look clear near the bottom, which indicates that potential including gravity for trapping the cloud varies steeply. Coulomb repulsive forces between the particles compressed by the potential becomes dominant in interaction between the particles. Hence the shells are stuck up near the bottom. A bottom part of the outermost shell was unfolded to a plane, assuming that the shell was a cylindrical surface (**Fig. 4**). In the figure, coordinates of the dust particles are plotted as parameters of distance in circumference direction denoted by L and y-axis. Here it should be noted that the dust particles arrange triangular lattices of closed-packed structure in 2-dimensional plane. The lattices are figured out to be formed on an equipotential surface of the shell.

Turning gravity from 1 G to microgravity, the dust particles were moved upward and distributed around the axial center of the main tube. The dust particles were distributed homogeneously in z-x plane and the cloud shaped a cylinder along to y-axis (**Fig. 3**). The cylinder was tapered, in which diameter was changed in striation of discharge. A bright part of the striation corresponded to a thick part of the cylinder. **Figure 5** shows distribution of the dust particles extracted from the area of $-0.1 \leq x \leq 0.1$, $-2.0 \leq z \leq 2.0$. The coordinates of the particles are plotted as projection along to x-axis. Strings of the dust particles appear along to the y-axis. The strings vary in length in **Fig. 5**, which means that they extend out of the trimmed area of $-0.1 \leq x \leq 0.1$. Hence variation of the length is not in principle. The cloud consists of a bundle of the strings. The strings indicate an attractive force between the dust particles only acting along to the main tube, i.e., flow of discharge current. The dust particles seem to be coupled more strongly in the direction of the current than in the radial direction of the tube. The attractive force maybe caused by a wake of ion flow [16, 17]. The strings resulted from the attractive force appear only under microgravity. The fact indicates that plasma parameters may change under microgravity and the attractive force is effective. Plasmas are affected by the dust particles, and electron temperature is typically enhanced. Enhancing of the electron temperature leads to increasing floating potential on the dust particles. Thus, ion flows around the dust particles are strongly affected to form wakes. Frequency of the applied voltage, 1 kHz is not greater than ion plasma frequency. Therefore, the wakes are formed at both sides of the dust particles along to the discharge current. In fact, glow was observed to become brighter under microgravity than 1 G, which implies that the electron temperature was enhanced by the distribution of the dust particles switching from 1 G to microgravity. Details of the mechanism for the string formation, however, should be discussed with several plasma parameters measured under

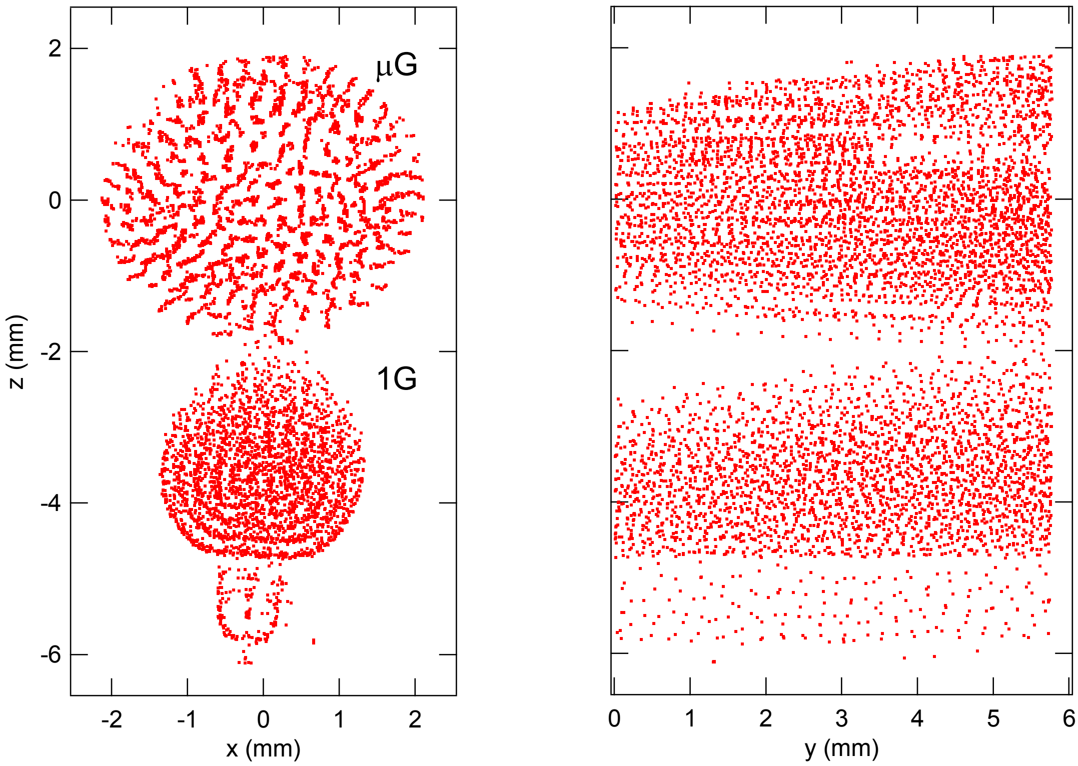

Fig. 3 Spatial distributions of the dust particles under gravity (lower) and microgravity (upper). Left: projection along to the y-axis parallel to the wing direction, right: to the x-axis parallel to the direction of travel of the aircraft.

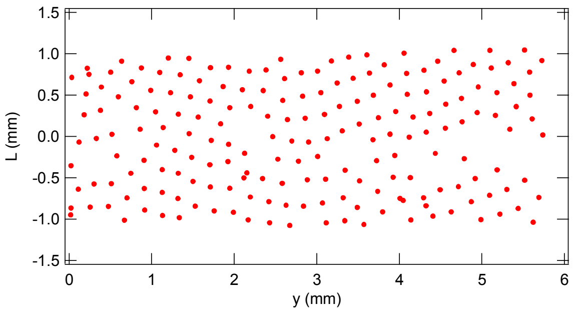

Fig. 4 Distribution of the dust particles near the bottom part on the outermost shell unfolded to a plane. The L is distance in circumference direction.

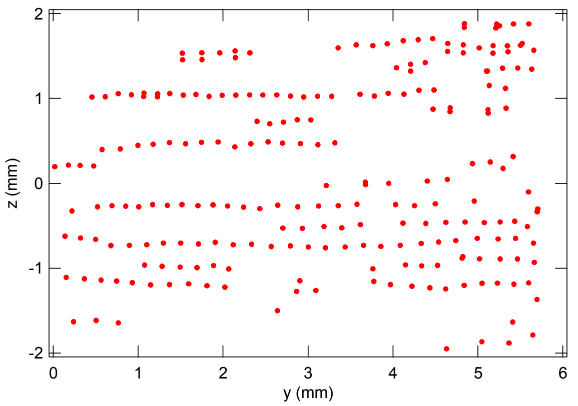

Fig. 5 Distribution of the dust particles under microgravity extracted from the domain of $-0.1 \leq x \leq 0.1$, $-2.0 \leq z \leq 2.0$. The coordinates are plotted as projection to the x-axis.

gravity and microgravity. The distribution of the dust particles and the structure of arrangement are simulated in an ideal positive column [8-10]. These are expected to bring ideas to understand the mechanism and further conditions for the experiments.

4 Conclusion

The microgravity experiments with PK-4J were reported in this paper, which aimed to motivate a contribution of a Japanese team to international collaboration in a join Russian/German research project of PK-4. The PK-4J has been developed in 2011 and improved for parabolic flight experiment in Japan.

Distribution of the dust particles was switched from 1 G to microgravity. The dust particles located below the axis center were moved up and distributed around the center. The arrangements of the dust particle formed the shell-like structure of cylinders under gravity. Microgravity changed the arrangements to a bundle of the string of the dust particles. The mechanism of the string formation seems to be resulted from wake potential, which should be discussed with evidence of measurement for plasma parameters.

The string formation originated from ion effect has a significant role in analyzing ion drag force which is a key issue to understand spatial distribution of the dust particles under microgravity. Ion dynamics obtained by observing the string formation leads to the spatial distribution well-controlled with or without void, which should be discussed elsewhere [14].

The results of shell and string formations, and transition of the structures are associated with several phenomena in nature. It will be expected that behavior of the dust particles should be connected to understanding the phenomena, and vice versa.

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