Collaborative Experiments of PK-3 Plus in Space

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Abstract: Microgravity experiments of complex plasmas were carried out through the international collaboration on the International Space Station (ISS). The apparatus is named PK-3 Plus, which is the second-generation apparatus on the ISS. Due to the limitation of weight and size, cameras with four different fields of view are the main diagnostics of PK-3 Plus. Therefore, indispensable parameters to understand behavior of the complex plasmas are estimated from measurements on the ground and calculations. In this paper, several important parameters for the critical phenomena of charged systems are estimated.

Keywords: Complex Plasmas, PK-3 Plus, Microgravity, ISS

1. Introduction

Complex plasmas contain electrons, ions, and particles. This type of plasma is observed in the universe, for example, nebulae, proto-planetary disks, and interstellar molecular clouds. The complex plasmas have a unique feature that strongly coupled plasma is easily achieved. In 1986, it was theoretically predicted that sufficiently strong coupling made the particles ordered structure[1)]. The ordered structure is called a plasma crystal or Coulomb crystal nowadays. This was a good trigger of new research on the Coulomb crystal in laboratories. In 1994, several researchers successfully observed the Coulomb crystal formation in their laboratories[2–5)]. The particles, however, must be levitated from electrodes against the gravity to form the Coulomb crystal on the ground so that they could move freely. This means that the particles are located in the sheath region formed near electrodes. This causes two major problems, that is, one is the particles exist in the non-plasma region, and the other is the structure of the Coulomb crystal is deformed by the ion flow. These problems drastically increase the difficulty of researches on critical phenomena, predicted phase diagrams, equilibrium crystal shapes, crystal formation mechanisms, and so on. This is the main reason why the microgravity is required.

The first apparatus installed on the International Space Station (ISS) was PKE-Nefedov[6–8)], which had been operated from March 2001 to July 2005. In the microgravity experiments, a large area in which the particles do not exist was formed. Today this particle-free region is simply called the void. Although the void influence on the behavior of the complex plasmas is not clear yet, it is clear that the particle existence area becomes smaller. This means that the total number of particles within the observation area and the effective size of the Coulomb crystal are decreased. Therefore, the void-free plasma should be much better for the microgravity experiments.

The second apparatus named PK-3 Plus[9–12)] had been operated from January 2006 to June 2013 on the ISS. This is an improved apparatus based on PKE-Nefedov to suppress the void. We had an interest in this facility to investigate the critical phenomena of the charged systems. Therefore, a new model[13–15)] was proposed to the international research team. The team had a strong interest in this model. Thus multiple machine times were assigned to the critical phenomena research. One of the most important issues was to determine appropriate experimental conditions of three adjustable parameters, that is, particle size, RF power, and gas pressure. Unfortunately, PK-3 Plus has four cameras with different fields of view but does not have any other major diagnostics such as a Langmuir probe, spectrometer, microwave interferometer, and so on. This means the experimental conditions should

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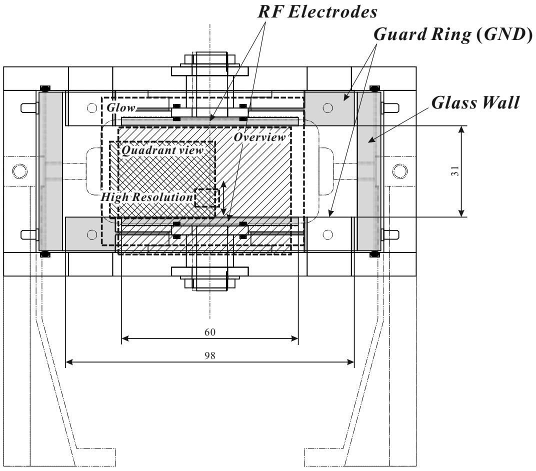

Fig. 1 Schematic view of PK-3 Plus.
Two RF electrodes of 60 mm in diameter, which are surrounded by grounded rings of 98 mm in outer diameter, are set. The distance between the electrodes is 31 mm.

be determined by quantitative estimation based on results of measurements on the ground and calculations. Therefore, we calculate the required parameters such as the charges and Coulomb coupling parameter.

2. PK-3 Plus

The apparatus PK-3 Plus basically has similar structure to PKE-Nefedov, that is, two RF electrodes surrounded by grounded rings. However, the electrodes and grounded rings are bigger than those of PKE-Nefedov so that the void could be suppressed. The schematic view of PK-3 Plus is shown in Fig. 1. Six particle dispensers are installed. The particle sizes are 1.5, 2.5, 3.4, 6.8, 9.2, and 14.9 μm in diameter. The maximum output power from the RF oscillator is 4 W. PK-3 Plus has four cameras with difference fields of view as the main diagnostics. The cameras are called the glow, overview, quadrant view, and high resolution cameras, corresponding to the sizes of fields of view. Each field of view is also indicated in Fig. 1. The glow camera has a optical filter to observe luminescence from excited atoms or ions.

Our objective is to approach the critical point as closer as possible as mentioned above. The theory predicts that the larger particle should be more suitable for the observation of critical phenomena. The large particle, however, makes the void size larger. The large void means the total number of particles and the size of observation area are decreased. As a result, the reliability of structure factor and pair correlation is deteriorated, especially at the long distance. Therefore, experimental conditions that can be reduce the void size as much as possible are required.

The theory also predicts necessary plasma parameters for the critical point. Since PK-3 Plus does not have the diagnostics of plasma parameters such as density and temperature, some parameters are assumed to be the same as those measured on the ground. Other parameters are estimated by calculation and the measurements on the earth. By using these parameters, the experimental conditions are determined.

3. Parameter Estimation Method

There are several parameters indicating the status of the complex plasmas. The important ones are the Coulomb coupling parameter Γ, inter-particle mean distance a, electron and ion densities, n_e and n_i, electron and ion temperatures, T_e and T_i, number density of particles n_d, particle temperature T_d, and particle charges Q_d. The Coulomb coupling parameter Γ is defined as the ratio of the Coulomb energy to the kinetic energy, that is,

$$\Gamma = \frac{{Q_d}^2}{4\pi\varepsilon_0 a k_B T_d} . \tag{1}$$

The electron and ion densities and electron temperature can be measured by a single or double probe in principle. Unfortunately, PK-3 Plus does not have any probes. Prof. Takahashi has been investigating the density profiles in PK-3 Plus on the ground[16)]. The influence of thermal convection of the neutral gas on the density and temperature profiles may be negligibly small. Therefore, it is assumed that these profiles in space are similar to those on the ground.

The ion temperature is difficult to be measured and thus it is usually assumed to be the same as the room temperature. This assumption is reasonable since the number density of neutral atoms is more than 10^6 times higher than the ion density in many cases and thus the ions rapidly lose the kinetic energy by the Coulomb collision with the atoms. The particle temperature is also often assumed to be the room temperature, but the particle energy is not easily reduced by the collision with the neutral atoms as compared with the ion energy due to the much heavier mass than the ion mass. In this paper, the particle temperature is obtained from

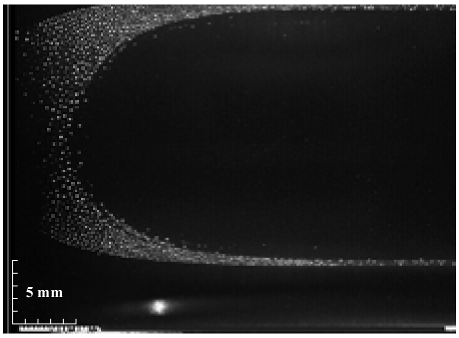

Fig. 2 Typical experimental results in space.
The pressure and RF power are set to 20 Pa and 1.8 W, respectively.

the velocity distribution function (VDF). The VDF is obtained from the data analysis of video data.

The distance between the nearest neighbor particles, d is obtained from the pair distribution function (PDF). The PDF is also obtained from the video data. The charge is estimated by considering the following conditions;

$$Q_d = 4\pi\varepsilon_0 r_d \Delta\phi \,, \tag{2}$$

$$-en_e + Q_d n_d + Zen_i = 0 \,, \tag{3}$$

$$j_e + j_i = 0 \,, \tag{4}$$

where r_d, Z, j_e, and j_i represent the particle radius, charge number of ions, electron and ion current densities, respectively. $\Delta\phi$ is defined as $\phi_d - \phi_p$, where ϕ_d and ϕ_p represent the potential on the particle surface and plasma potential, respectively. The electron and ion current densities are described as

$$j_e = -en_{e0}\sqrt{\frac{k_B T_e}{2\pi m_e}} \exp\left\{\frac{e(\phi-\phi_p)}{k_B T_e}\right\} \,, \tag{5}$$

$$j_i = Zen_{i0}\sqrt{\frac{k_B T_i}{2\pi m_i}} \exp\left\{1 - \frac{Ze(\phi-\phi_p)}{k_B T_i}\right\} \,. \tag{6}$$

The ion current density is came from the orbital motion limited theory. By combing those equations, the final equation is obtained as follows;

$$-Zen_i\sqrt{\frac{T_i}{T_e}}\sqrt{\frac{m_e}{m_i}}\left(1-\frac{e\Delta\phi}{k_B T_i}\right)\exp\left(-\frac{e\Delta\phi}{k_B T_e}\right) + 4\pi\varepsilon_0 r_d n_d \Delta\phi + Zen_i = 0 \,. \tag{7}$$

In weakly ionized plasma like complex plasmas, the charge number Z is usually 1.

The other important parameters related to the critical point are defined as follows;

$$\xi = \frac{a}{\lambda_D} \,, \tag{8}$$

$$A = \frac{n_e k_B T_e + n_i k_B T_i}{n_d k_B T_d} \,, \tag{9}$$

$$\Gamma_0 = \frac{Q_d{}^2}{4\pi\varepsilon_0 r_d k_B T_d} = \Gamma\frac{a}{r_d} \,, \tag{10}$$

where λ_D represents the Debye length. Although these are not the independent parameters but are calculated from other parameters, these are convenient to understand how close to the critical point.

4. Results and Discussion

The parameters required for the critical point are theoretically predicted. One example of the parameter set is shown in Table 1. These parameters must be translated to operation parameters, that is, the particle size, pressure, RF power.

It is clear from Eq. (2) that the larger particle size is more suitable for obtaining larger particle charge,

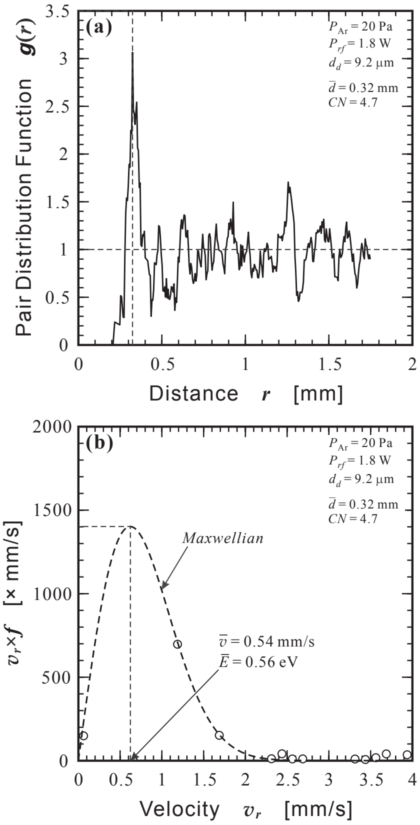

Fig. 3 (a) Pair distribution function and (b) velocity distribution function.
These functions are obtained from the data shown in Fig. 2.

Table 1 Theoretically obtained parameters for the critical point.
T_d is assumed to be the same as T_i.

ξ	4
T_i [eV]	0.03
T_e [eV]	3
n_i [cm^{-3}]	10^9
n_e [cm^{-3}]	10^7
n_d [cm^{-3}]	5×10^5
A	10^4
Γ	2×10^4
Γ_0	2×10^5

Table 2 Experimentally obtained parameters representing the status of complex plasmas.
T_i is assumed to be 0.03 eV.

ξ	2.0
T_e [eV]	1.2
n_i [cm^{-3}]	1.6×10^8
n_e [cm^{-3}]	0.2×10^8
n_d [cm^{-3}]	2.8×10^4
A	8500
Γ	320
Γ_0	1.4×10^4
Q_d	$5000\,e$

which makes the Coulomb coupling stronger. On the other hand, it seems that the larger particle makes the void region size larger. In addition, the higher power is required to obtain the higher density, though the higher power also makes the void region size larger. The research on the critical phenomena needs the observation area as large as possible since the long-range correlation is important to know how close to the critical point. Therefore, the void formation must be suppressed as much as possible. These are the conflicting requirements. Therefore, the prioritization of experimental conditions is indispensable.

We focused on the particle charge first because it is impossible to approach the critical point if the charge is small. From this point of view, the largest particle of 14.9 μm is the best choice but the void will be the largest. Therefore, we select the second largest particle, 9.2 μm in diameter to reduce the void size. The typical experimental result in space is shown in Fig. 2. The bright points are the 9.2 μm-particles. It is found that the large void region is formed. By detecting the particles and obtaining the coordinates of particles, the PDF is obtained. The VDF is also obtained by tracing the time evolution of the particle coordinates. These are shown in Fig. 3. From Fig. 3(a), it is found that d is obtained from the distance at the first peak and is 0.32 mm. The coordination number, which indicates the number of particles surrounding one particle, is 4.7 in this case. By considering that the ideal coordination number is 6 in the case of two-dimensional Coulomb crystal, this number suggests that the Coulomb crystal was not clearly formed or was much deformed. In Fig. 3(b), the curved dashed-line represents the best-fitted two-dimensional Maxwellian. By comparing the experimental data with the Maxwellian, it is found that the average velocity of particle is 0.54 mm/s and thus the particle temperature is 0.56 eV. The temperature is almost 20 times higher than the room temperature. This may increase the difficulty in observing the critical phenomena.

The inter-particle mean distance, or the Wigner-Seitz radius, a is calculated from d to be 0.205 mm. To obtain the three-dimensional parameters from the two-dimensional data, the conversion factor[17)] must be taken in account. Once the parameter a is obtained, the number density of particle is calculated to be 2.8×10^4 cm^{-3}. The electron and ion densities are almost the same at the location being far enough from the Coulomb crystal and are 1.6×10^8 cm^{-3} from the probe measurement on the ground. The electron temperature is also measured by the probe and is about 1.2 eV in this case. The ion temperature is assumed to be 0.03 eV as mentioned previously. Thus Eq. (7) can be solved by substituting these values into the equation. The potential difference $\Delta\phi$ is obtained to be -1.58 V. Thus the charge is estimated to be about $5000\,e$. The other parameters are also calculated and are summarized in Table 2.

By comparing Table 2 with Table 1, it is found that the ion density is too low. This suggests the RF power is low. The low electron temperature supports this suggestion. The parameters ξ and A are not bad, while Γ is too small. Although the Γ value of 320 is larger than the lower limit of the three-dimensional crystallization, i.e., 178, this value is not large enough to ob-

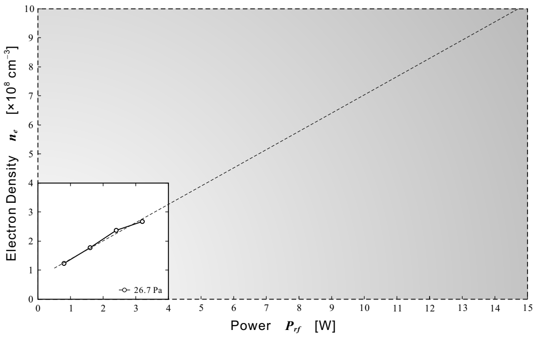

Fig. 4 Required power estimated by extrapolating the density dependence on the power.

tain good long-range order. This is qualitatively consistent with the PDF indicating no good long-range order. To increase the Γ value, the higher power should also be suitable. These results indicate that the current condition of complex plasma is not very close to the critical point.

Therefore, we investigate more appropriate operation conditions. First, we estimated the required RF power by extrapolating the density dependence on the power. The result is shown in Fig. 4. The figure shows that the power of 14 W or more is required to achieve the density of 10^9 cm^{-3} under the assumption of linear dependence. Actually, such the linear dependency is rarely obtained. Therefore, 20 W or more may be necessary, which is much higher than the power of PK-3 Plus. Preparation of such power source is not technically difficult. The large power, however, the large void is formed. As shown in Fig. 2, the observation area is small in the power of 1.8 W. If the 20 W power was supplied to PK-3 Plus, almost all particles might be disappeared. To avoid that, the void formation mechanisms must be understood more deeply. However, the essential solution should be the flatter potential profile. It is difficult to achieve such the profile.

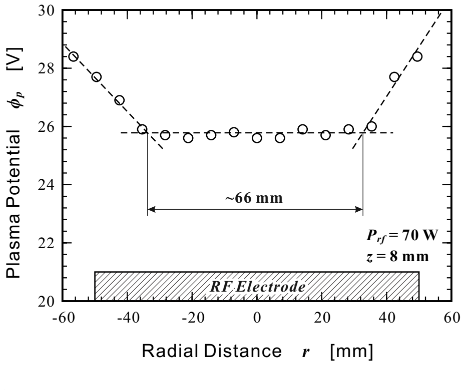

Fig. 5 Radially flat potential profile measured in the large-sized apparatus on the ground.
The electrode diameter is 100 mm, which is similar to the outer diameter of grounded ring.

Fortunately, one of our apparatuses for the ground experiments has a radially flat potential as shown in Fig. 5. Since this apparatus has a large vacuum chamber, the wall influence on the potential should be negligibly small. The Coulomb crystal is formed within the region of flat potential on the ground-based experiments. If the particle is accidentally located at the outer place where the potential increases, the particle runs away from the electrode with acceleration caused by the electric field.

We recently start the investigation by using the smaller model. The current result is shown in Fig. 6. The helium gas of 67 Pa and particle of 2 μm in diameter are used. From the figure, it is found that the particles are filled in almost all the lower half part of apparatus without the void. However, this may not indicate the void is suppressed in space. The short-period microgravity experiments are required to investigate the void formation in this apparatus. Before planning such expensive experiments, we will investigate the characteristics of apparatus more deeply.

5. Conclusions

We joined the international research team for the complex plasmas by using the PK-3 Plus apparatus. One of the objectives was the critical phenomena. The Japanese science team proposed the experimental and operation conditions in space. The international team carried out the micrograivty experiments based on our proposal multiple times. The largest and second largest particles were used in the experiments due

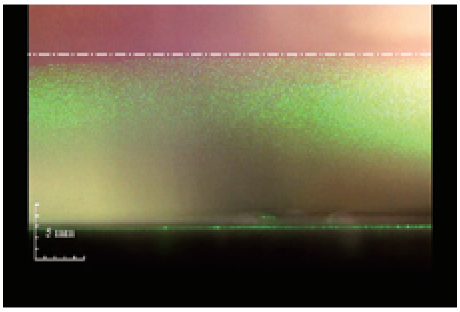

Fig. 6 Coulomb cloud observed in the small apparatus.
The horizontal dot-dashed line represents the midplane of the apparatus.

to the necessity of large charges. The high power was also supplied to the apparatus to increase the plasma density. However, these caused the formation of large void region. As a result, the observation area was much decreased.

By analyzing experimental data, it is found that the power is still small for the critical phenomena. It is estimated that the power of 15 to 20 W may be required by extrapolating the density dependence on the power. Such large power caused the large void formation. Therefore, the void suppression is required. To suppress the void, theoretical and experimental works are necessary. Recently, experimental investigation using a small-sized apparatus having similar dimension to PK-3 Plus. Although the characteristics of apparatus is not well understood yet, some results show possibility of improvement in the void formation.

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