Experiments on phase transitions in three-dimensional dusty plasma under microgravity conditions

V I Molotkov, V. N. Naumkin, A. M. Lipaev, D. I. Zhukhovitskii, A. D. Usachev, V. E. Fortov, H. M. Thomas

1 Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
2 Institute of Materials Physics in Space (DLR-MP) German Aerospace Center, 51147 Cologne, Germany

E-mail: molotkov@ihed.ras.ru

Abstract. Complex (dusty) plasmas are composed of weakly ionized gas and charged microparticles and represent the plasma state of soft matter. Due to the “heavy” component, microparticles, and the low density of the surrounding medium, the rarefied gas and plasma, it is necessary to perform experiments under microgravity conditions to cover a broad range of experimental parameters which are not available on ground. The investigations have been performed onboard the International Space Station (ISS) with the help of the PK-3 Plus laboratory. This laboratory was mainly built to investigate the crystalline state of complex plasma, the so-called plasma crystal, its phase transitions and processes in multi-particle mixtures. The crystal–liquid phase transition was obtained in large three-dimensional isotropic dusty plasma system. Observations of a transition of the dusty plasma system state due to the particle charge reduction and due to variations of the plasma component density are presented.

1. Introduction

Complex plasmas are plasmas containing small solid particles, typically in the micrometer range, the so-called microparticles. These are dusty plasmas which are specially prepared to study fundamental processes in the strong coupling regime on the most fundamental (kinetic) level, through the observation of individual microparticles and their interactions. Many interesting phenomena can be studied starting from small two-dimensional (2D) and three-dimensional (3D) clusters [1], to larger 2D and 3D systems where collective effects play a dominant role [2].

In laboratory conditions, the microparticles are heavily affected by the force of gravity. Under microgravity conditions, e.g. on the International Space Station (ISS), gravity is negligible. Therefore, the particles are pushed out of the strong electric field region close to the electrodes due to their negative charge and can form large, more or less, homogenous particle clouds in the bulk of the discharge. Under these conditions, weaker forces like the ion drag force and the interparticle interactions become important and often dominate the motion and structure formation in complex plasma.

The laboratory, PK-3 Plus, has been improved considerably compared to the PKE-Nefedov and has been equipped with new diagnostic tools [3]. It has provided the next important step
in research of complex plasmas under microgravity conditions. The obtained results are unique and opened up a new interdisciplinary research directions, in particular, related to the field of soft condensed matter. The purpose of this paper is to present some new results obtained using the PK-3 Plus laboratory onboard ISS.

The PK-3 Plus setup has a well-balanced symmetrically driven rf-electrode system which provides a homogeneous distribution of the plasma with identical sheaths near both electrodes. This is necessary for a homogeneous distribution of the microparticles under microgravity conditions. A cross-sectional and perspective schematic of the microgravity setup, the PK-3 Plus chamber, is shown in figure 1. Technical details of the setup can be found in [3].

2. Results on phase transitions in 3D complex plasmas

2.1. Phase transition by manipulating the neutral gas pressure

We performed experimental investigations of the fluid-solid phase transitions in large 3D complex plasmas under microgravity conditions. These phase changes were driven by manipulating the neutral gas pressure. Detailed analysis of complex plasma structural properties allowed us to quantify the extent of ordering and accurately determine the phase state of the system. Evaluation of various freezing and melting indicators gave further confidence regarding the phase states. It was observed that the system of charged particles can exhibit melting upon increasing the gas pressure, in contrast to the situation in ground-based experiments where plasma crystals normally melt upon reducing the pressure [4].

2.2. Phase transition due to the particle charge reduction

We performed experiments to demonstrate a change of the structural properties of the dusty plasma system due to a change of the particle charge. There have been used two-species complex plasma with one species composed of small (1.55 µm) and the other composed of big (14.9 µm) particles. The experiments have been carried out in argon gas at a pressure of 10 Pa. The particles are SiO₂ spheres with a diameter 1.55 µm, the big particles are melamine formaldehyde spheres. The particles of different size do not mix. The smaller particles form an inner cloud close to the discharge centre (with the central areas free of particles, see figure 2). The big particles form an outer cloud surrounding and confining the smaller one, as it is seen in figure 2. The bigger particles can be added to the system. This effectively increases the strength of the confinement and compresses the small particle system.
Figure 2. Video images of dusty plasma system: (a) initial system; (b) compressed system. Snapshots are obtained by quadrant camera.

Figure 3. Change of pair correlation function due to compression by bigger particles.

Figure 3 demonstrates a change of the pair correlation function for the initial dusty plasma system (only small particles are present) and for the compressed system (with an addition of bigger particles that increases a confinement of the small particles system). Table 1 presents the results of the calculation of some parameters of the dusty subsystem: interparticle distance $\Delta$ obtained from the pair correlation function, dust particle density $n_p$ obtained from the processing of the video images received by the high resolution camera, particle charge $Q$ calculated using the orbital motion limited approximation for the experimental plasma parameters.

For the analysis of the dusty plasma system state we use the Raveche-Mountain-Streett criterion $R$ that is the ratio of the first nonzero minimum of $g(r)$ to the first maximum [5]. Note that in the case when $R$ exceeds 0.2 the dusty plasma system is in the fluid state and in the case when $R$ is less than 0.2 the system is in the well ordered (crystal) state. It is seen from Table 1 that $R$ changes from the small value (0.04) pointing to the high ordering in the subsystem (plasma crystal) to the high value (0.21) pointing to melting of the plasma crystal. Thus, it is a demonstration of the phase transition due to a drop of the absolute magnitude of the particle charge when their density increases.

Table 1. Parameters of the dusty subsystem.

| $\Delta$ (µm) | $n_p$ ($10^5$ cm$^{-3}$) | $Q$ (e) | $R$ |
|---------------|--------------------------|--------|-----|
| 125           | 5.10                     | 2000   | 0.04|
| 90            | 12.0                     | 807    | 0.21|
2.3. Phase transition by changing the plasma component density

Several experiments have been performed to study peculiarities of the crystal-liquid phase transition in the 3D dusty plasma system when varying the voltage between electrodes of the plasma chamber. The change of the interelectrode voltage leads to a change of the plasma component density and one of the important parameters determining a behavior of the dusty plasma system, namely, a screening length \( \lambda \). In the experiments monodisperse SiO\(_2\) particles of 1.55 \( \mu \)m diameter were used.

The procedure of the experiments was the following one. The radio-frequency discharge was generated at the given argon pressure and at the given interelectrode voltage. Then a formation of an ordered structure took place. Figure 4 presents video images of the dusty plasma system obtained by the high resolution camera at the argon pressure 20 Pa at different values of the interelectrode voltage (\( U_{\text{eff}} = 19.0, 16.3 \) and \( 13.1 \) V respectively). It is clearly seen a decrease of the ordering level when rf voltage at the electrodes is decreasing, that is, when the ion density is decreasing.

The video images for the dusty plasma system for the argon pressure 40 Pa show that in this case the ordering level of the system is changing in the direction opposite in comparison with the previous case.

To interpret the results obtained we made evaluations of the parameters of the dusty plasma systems observed using the pair correlation functions determined on the results of a scanning of the each system. The experimental correlation functions give a possibility to evaluate a level of the dusty plasma system ordering and to determine an interparticle distance.

Figure 5 shows a change of the criterion \( R \) when the interelectrode voltage changes, that is, the plasma component density changes. It is seen that a character of the change of the ordering state at two different values of the argon pressure has quite an opposite behavior. At the argon pressure 20 Pa an ordering of the system decreases when there is a reduction of the voltage \( U_{\text{eff}} \):
the dusty plasma system melts at a reduction of the plasma component density. In the case of the argon pressure 40 Pa when the interelectrode voltage increases the dusty plasma system ordering increases as well.

To obtain values of the plasma component density (in the first turn, the ion density) we use the results of calculations on the base of the SIGLO-2D model [3]. The evaluation of plasma parameters was made without taking into account dust particles. The obtained ion densities for pressures 20 Pa and 40 Pa are presented in table 2. In the table there are also the values of the screening length \( \lambda \). The table 2 contains also values of the interparticle distances and the screening parameter \( k \), where \( k = \Delta / \lambda \), \( \Delta \) is interparticle distance. The values of the exponential multiplier \( e^{-k} \) in the interparticle interaction energy \( U = (Q^2/\Delta)e^{-k} \), where \( Q \) is microparticle charge are presented in the table as well.

The presented evaluations of the interparticle interaction energy do not explain the character of the ordering state change with the pressure. We need the more detailed theoretical analysis that is a task of the future work.

CONCLUSION

The presented results show several examples of phase transitions in the 3D complex plasma system under microgravity conditions obtained with the help of the PK-3 Plus laboratory onboard the International Space Station.

The manipulation of the neutral gas pressure allows researchers to observe the fluid-solid phase transitions in the large 3D complex plasma. The system of charged particles can exhibit melting upon increasing the gas pressure.

Compressing the dusty subsystem of small particles by an addition of the bigger microparticles to the system we have demonstrated the phase transition due to a drop of the particle charge.

The other quite a new observation concerns a study of transitions of the dusty plasma system state due to variations of the ion density. It was demonstrated a rather complicated character of the dependence of the system order upon the ion density.

Acknowledgments

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References

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| P (Pa) | \( U_{\text{eff}} \) (V) | \( n_i \) (cm\(^{-3}\)) | \( \lambda \) (\(\mu\)m) | \( \Delta \) (\(\mu\)m) | \( k \) | \( e^{-k} \) | \( Q \) (e) | \( U \) (eV) |
|--------|----------------|----------------|----------------|----------------|------|---------|-------|--------|
| 20     | 19.0           | \( 8 \times 10^8 \) | 43             | 131            | 3.05 | 0.047   | \( 1.6 \times 10^3 \) | 1.34   |
| 20     | 13.1           | \( 5 \times 10^8 \) | 54             | 122            | 2.26 | 0.1     | \( 8.8 \times 10^2 \) | 0.96   |
| 40     | 16.2           | \( 9.0 \times 10^8 \) | 40             | 136            | 3.4  | 0.033   | \( 1.9 \times 10^3 \) | 1.28   |
| 40     | 12.5           | \( 6.5 \times 10^8 \) | 47.5           | 136            | 2.86 | 0.057   | \( 1.4 \times 10^3 \) | 1.19   |