Phenomena in Complex (Dusty) Plasma Studied under Microgravity Conditions

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Complex (dusty) plasmas are composed of weakly ionized gas and charged microparticles and represent the plasma state of soft matter. The investigations which are not available on ground have been performed onboard the International Space Station (ISS) with the help of the “Plasma Crystal-3 Plus” (PK-3 Plus) laboratory. A number of interesting phenomena has been observed. The phase transition from isotropic plasma into electrorheological plasma was initiated. The crystal-liquid phase transition was obtained in large 3D isotropic dusty plasma. The slow compression of the dust particle subsystem has been investigated.

Keywords: complex plasma, plasma crystals, solid-liquid transitions, microgravity

1 INTRODUCTION

The research in complex plasmas is a fast growing field with many applications in different areas, e.g. in soft matter physics, solid-state physics and fluid physics [1]. The reason is that various phenomena, like melting, self-organization, wave propagation, transport, etc can be studied at the most fundamental, the kinetic level. Complex plasmas are conventional low temperature plasmas consisting of electrons, ions and neutrals containing small solid particles typically in the range of a few micrometres, so-called microparticles. The particles gain charge through the interaction with the charged component of the plasma, they are shielded by electrons and ions and interact with each other via the resulting electrostatic potential. This interaction can be so strong that the particle system can even show crystalline behavior. The microparticles are typically separated by about 100–500 μm, hence using laser light scattering, the dynamics can be observed at the kinetic level at all relevant time scales. This can provide interesting new insights into the physics of condensed matter.

To perform certain precision measurements, especially of large 3D isotropic systems, microgravity conditions are necessary. Such experiments allow the study of systems and processes not attainable on the ground [1].

Microgravity experiments performed with the help of the complex plasma laboratory PKE-Nefedov [2] led to the observation of many interesting phenomena in liquid and crystalline complex plasmas.

2 SHORT DESCRIPTION OF PK-3 PLUS LABORATORY

The PK-3 Plus laboratory was developed taking into account the experience obtained during an employment of its precursor PKE-Nefedov.

PK-3 Plus has a well-balanced symmetrically driven rf-electrode system that provides a homogeneous distribution of the plasma with identical sheaths on both electrodes [3]. This is necessary for a homogeneous distribution of the microparticles under microgravity conditions. The vacuum chamber consists of a glass cuvette of form of a cuboid with a quadratic cross section. Top and bottom flanges are metal plates. They include the rf-electrodes, electrical feedthroughs and the vacuum connections. The electrodes are circular plates from aluminum with a diameter of 6 cm. The distance between electrodes is 3 cm. The electrodes are surrounded by a 1.5 cm wide ground shield including three microparticle dispensers on each side. The microparticles are dispersed through the sieve into the plasma chamber by electromagnetically driven strokes of the piston.

The optical particle detection system consists typically of laser diodes with cylindrical optics to produce a laser sheet perpendicular to the electrode surface and video cameras observing the reflected light at 90 degrees with different resolutions.

Three progressive scan CCD-cameras observe the reflected light at 90 degrees with three different magnifications and fields of view.

The cameras and lasers are mounted on a horizontal translation stage allowing a depth scan through and, therefore, a 3D view of the complex plasma.

3 ELECTRORHEOLOGICAL EFFECT IN COMPLEX PLASMAS

The experiments with PK-3 Plus show the perfect functioning of the apparatus and provide new insights into the properties of dusty plasmas. As known the void, the microparticle free region in the center of the discharge, prevents the formation of a homogeneous and isotropic distribution of the complex plasma. The origin of the void is the ion drag force which often overcomes the electric force in some vicinity of the discharge center and therefore pushes the particles out of the central region. Under certain conditions, the void can be closed. This is very important for many dedicated experiments. With the PK-3 Plus setup there exist three ways of void closure known until now, first by adjusting lowest rf-power (like in the ISS-laboratory PKE-Nefedov [4]), second, by using a symmetrical gas flow, and third, by low frequency electric excitation [3]. The latter can be used additionally to initiate a phase transition from an isotropic fluid into a so-called electrorheological string fluid.

The formation of such string fluids, or general electrorheological plasmas, is possible due to the manipulation of the interaction potential between the microparticles along the field line. It can be changed from an isotropic screened Coulomb to an asymmetric attractive potential through accelerating ions by the ac voltages at frequencies above the dust plasma frequency applied to the electrodes. Thus, the ions produce a wake region above and below the particles along the electric field axis, while the particles cannot respond.

As it was shown [5] the effective interparticle interaction in this case is determined by the time-averaged wake potential. The field-induced interactions in dusty plasmas are identical to interactions in conventional electrorheological fluids with dipoles $d=0.65Q\lambda\nu_{ion}/\nu_{th}$, where Q is the particle charge, λ is the ion screening length, ν_{ion} is the ion drift velocity and ν_{th} is the ion thermal velocity. The ac voltage at frequency 100 Hz was applied to the rf electrodes with the amplitude voltage between 26.6 and 65.6 V varied in steps of 2.2 V. At weak voltages charged particles form a strongly coupled (with a screened coupling parameter in the range of 30–100) isotropic fluid phase. As the voltage is increased above a certain threshold, particles rearrange themselves and become more and more ordered, until eventually well-defined particle strings are formed along the direction of the field. In the experiments we used microparticles of different diameters (1.55, 6.8 and 14.9 μm) and Ar gas at pressures between 8 and 15 Pa. The example of the transition to the electrorheological plasma state is presented in Fig.1.

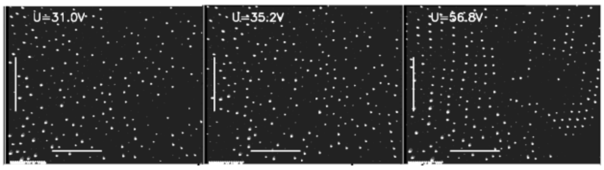

Fig.1: The transition from an isotropic fluid (left) to a string fluid (right) observed in the PK-3 Plus laboratory onboard the ISS. Particles of 6.8 μm, argon pressure is 10 Pa, interparticle distance is 370 μm. Strings are apart from each other at 580 μm. Snapshots are obtained by the high-resolution camera

The transition between the isotropic fluid phase and the electrorheological state is fully reversible – decreasing the field brought the particles back into their initial isotropic state. The trend to form strings increases with a particle size that corresponds to the theoretical estimates.

4 FLUID–SOLID PHASE TRANSITIONS

We performed experimental investigations of the fluid-solid phase transitions in large 3D complex plasmas under microgravity conditions. These phase changes are driven by manipulating the neutral gas pressure. Detailed analysis of complex plasma structural properties allows us to quantify the extent of ordering and accurately determine the phase state of the system. Evaluation of various freezing and melting indicators gives further confidence regarding the phase state. It is 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. This illustrates important differences between generic (e.g. similar to conventional substances) and plasma-specific mechanisms of phase transitions in complex plasmas.

We use two different sorts of particles in the two distinct experimental runs: SiO_2 spheres with a diameter $2a$ = 1.55 µm and Melamine-Formaldehyde spheres with a diameter $2a$ = 2.55 µm.

In this experiment [6] initially we organized the particles structure at 30 Pa. Then the argon pressure was decreased up to 10 Pa and then increased up to 22 Pa. The time of the cycle was equal to 5 minutes. In the repetitive similar cycle of the pressure variation a scanning of the dusty formation was made with a speed of 0.6 mm/s at a depth of 4.8 mm practically at the same pressure. The particle positions are then identified by tomographic reconstruction of the 3D-pictures taken with the high resolution camera observing a region 8×6 mm^2 slightly above the discharge center.

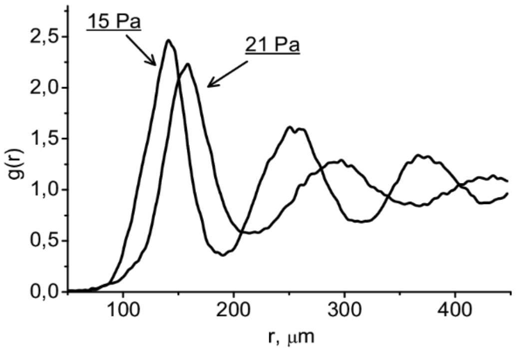

Fig.2: Change of pair correlation function on pressure

The analysis of the ordering degree of the dusty plasma system was made with the help of the pair-correlation function *g(r)*. As an example of the processing results in Fig.2 it is shown a change of *g(r)* on pressure for the dusty subsystem from particles 1.55 µm diameter.

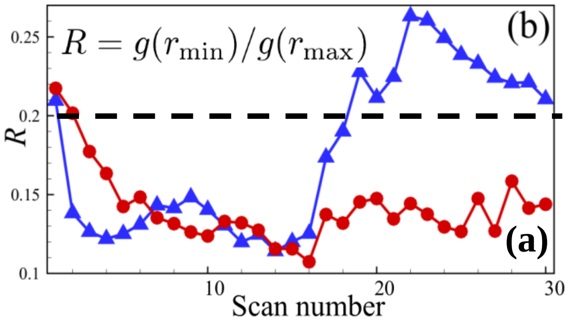

Fig.3: Raveche-Mountain-Streett criterion. a) 2.55 µm particles; b) 1.55 µm particles

To characterize a structural state of the dusty plasma systems observed we shall use as an example the Raveche-Mountain-Streett criterion of freezing [6] that is based on the properties of the radial distribution function *g(r)* in the fluid phase. It states that near freezing, the ratio of the values of *g(r)* corresponding to its first nonzero minimum and to the first maximum, $R=g(r_{min})/g(r_{max})$, is constant, $R\approx0.2$. This criterion describes fairly well freezing of the classical Lennard-Jones fluid, but is not universal. Fig.3 shows the calculated values of the freezing indicator *R* for different scans. Applying the threshold condition $R\approx0.2$ would imply that the system of small particles melts upon an increase in the neutral gas pressure (second half of the observation sequence), while the system of large particles remains in the solid state.

5 PHASE TRANSITIONS ASSOCIATED WITH 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 plasmas 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 SiO_2 spheres with a diameter 1.55 µm. 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 Fig.4), the big particles form an outer cloud surrounding and confining the smaller one, as it is seen in Fig.4. The bigger particles can be added to the system. This effectively increases the strength of the confinement and compresses the small particle system.

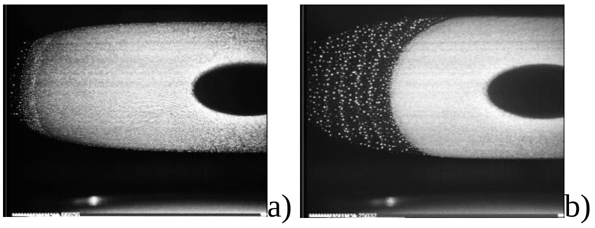

Fig.4: Video images of dusty plasma system a) initial system; b) compressed system. Snapshots are obtained by quadrant camera

Fig.5 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).

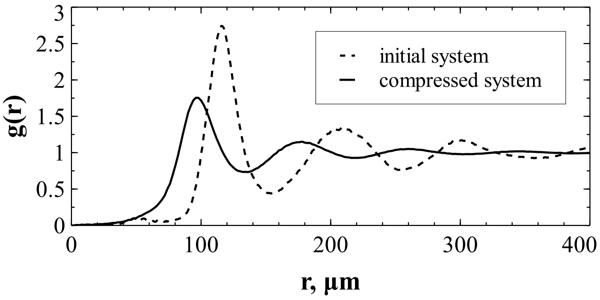

Fig.5: Change of pair correlation function due to compression by bigger particles

Table 1 presents the results of the calculation of some parameters of the dusty subsystem: interparticle distance Δ 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. It is seen from Table 1 that the ratio of the first nonzero minimum of *g(r)* to the first maximum 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

d_p, μm	Δ, μm	n_p, cm^{-3} *10^5	Q, e	$\frac{g_{min}}{g_{max}}$
1.55	125	5.10	2000	0.04
1.55	90	12.0	807	0.21

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