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H M Thomas 1, M Schwabe 1, M Y Pustylnik 1, C A Knapek 1, V I Molotkov 2, A M Lipaev 2, O F Petrov 2, V E Fortov 2 and S A Khrapak 1

1 Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), D-82234 Weßling, Germany
2 Joint Institute for High Temperatures, Russian Academy of Sciences, 125412 Moscow, Russia

E-mail: hubertus.thomas@dlr.de

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Abstract

Complex plasmas are plasmas containing solid particles typically in the micrometer range. These microparticles are highly charged and become an additional, dominating component of the plasma. Complex plasmas are model systems to study strong coupling phenomena in classical condensed matter. They offer the unique opportunity to go beyond the limits of continuous media down to the fundamental length scale of classical systems—the interparticle distance—and thus to investigate all relevant dynamic and structural processes using the fully resolved motion of individual particles, from the onset of cooperative phenomena to large strongly coupled systems. Unlike ‘regular’ plasma species the charged microparticles are strongly affected by gravity. An electric field in the sheath or a temperature gradient are usually employed to compensate for gravity, which provides favorable conditions to study two-dimensional or stressed three-dimensional (3D) systems on ground. However, in order to perform precision measurements with large isotropic 3D systems in the bulk plasma, microgravity conditions are absolutely necessary. Since 2001, this research under microgravity conditions has continuously been performed on board the International Space Station ISS within the Russian/German (European) Plasmakristall (PK)-Program. In the long-term research laboratories PKE-Nefedov (2001–2005), PK-3 Plus (2006–2013) and PK-4 (2014-ongoing), fundamental processes in liquid or crystalline complex plasmas as well as basic complex plasma issues were addressed. Highlights are: refinement of the theories of particle charging and ion drag, electrorheological plasmas, lane formation and phase separation in binary mixtures, crystallization and melting, wave propagation, shear flow and transition to turbulent motion. In this review, we will address results from microgravity research and discuss the perspectives for future studies.

Keywords: complex (dusty) plasmas, microgravity research, low temperature plasmas

(Some figures may appear in colour only in the online journal)

1. Introduction

The experimental investigation of dynamical processes in plasmas on the level of individual particles is one of the special and unique features of complex plasmas [1]. Complex plasmas are plasmas containing small solid particles with sizes ranging from nanometers to hundreds of micrometers. The solid particles become highly charged due to the collection of electrons and ions on their surfaces and begin to interact with other particles as well as with electrons and ions from the surrounding plasma. Therefore, they become an additional component of the plasma, albeit a very heavy and strongly charged one. Starting from around micrometer size those particles become visible on the individual particle level through the reflection of (laser) light. Particle positions and trajectories can be recorded with state of the art video microscopy. Depending on the optical resolution of the observation system positions can be measured down to micrometer resolution, while the distance between neighboring particles is large—of the order of hundreds of micrometers—due to the strong
Especially the long-term projects PKE-Nefedov rockets or the International Space Station is necessary. A number of complex plasmas, the complementary research under microgravity conditions is investigated in the liquid and crystalline state [4–7]—the plasma crystal—and the investigation of many interesting phenomena on the kinetic level like melting and crystallization [8, 9], defect motion [2], waves and shock waves [10], mode coupling instability [11], the crystallization process [12], etc. The latter allows the formation of large 3D structures in the bulk of the plasma under stress produced mainly through the gas convection within the strong temperature gradient necessary to counterbalance gravity [13]. Investigations in such 3D systems include for example self-induced waves [14], formation of drops, bubbles and surfaces cusps [15], transition from laminar to turbulent flow [16], and shear flow instabilities [17].

Only under microgravity conditions large 3D, homogeneous and isotropic complex plasma systems can be formed and investigated [18, 19]. Therefore, for a full understanding of complex plasmas, the complementary research under microgravity conditions, e.g. on parabolic flights, sounding rockets or the International Space Station is necessary. A longstanding program exists for this microgravity research. Especially the long-term projects PKE-Nefedov (2001–2005) [18], PK-3 Plus (2006–2013) [19–22] and PK-4 (operational since 2014) [23] on the International Space Station (ISS) allow a deep understanding of the physics and opened up new research topics in the field, like electroreological effects in complex plasmas [24], or lane formation and phase separation in binary (regarding the microparticle component) mixtures [25, 26].

The research under microgravity conditions was able to complete the picture of complex plasmas as a new state of soft matter [27]. However, in this paper we would like to draw the attention to basic plasma properties of complex plasmas where the microparticles are an additional component of the bulk (electron and ion) plasma.

2. Fundamental processes

Understanding fundamental plasma-particle interactions is exceptionally important in complex plasmas since these are responsible for a rich variety of observable phenomena. Of particular importance are basic processes like particle charging, interparticle interactions, plasma scattering by the particles and the corresponding ion and electron drag forces. Due to the volume forces necessary for the levitation of the microparticles (e.g. electrostatic or thermophoretic force) on ground those processes are altered and no longer symmetrical. This makes the theoretical modeling quite complex. Under microgravity conditions the physics becomes different since the microparticles are part of the bulk plasma and much weaker plasma forces become important and observable. Therefore significant progress in understanding these basic physical processes has been triggered by microgravity research, and below we briefly summarize some of this progress.

2.1. Charging

A non-emitting particle (grain) immersed in a plasma collects electrons and ions and becomes electrically charged. Its surface (floating) potential is determined from the balance of collected ion and electron fluxes. Since electrons are much more mobile than ions, the surface potential is negative and roughly equal to the electron temperature, \( \phi_s = -zT_e/e \), where \( T_e \) is the electron temperature (in energy units), \( e \) is the elementary charge, and \( z \) is a numerical coefficient of order unity. This ensures that most of the electrons are unable to overcome the potential barrier between the particle surface and surrounding plasma and, hence, ion and electron fluxes can balance each other. The numerical coefficient \( z \) is not fixed, but in general depends on a number of plasma and particle parameters like plasma composition (i.e., on the ion-to-electron mass ratio), electron and ion temperatures, plasma screening length, ion and electron mean free paths with respect to collisions with neutrals, particle size and shape, particle material, etc.

The traditional and most frequently used approach to calculate the particle floating potential in complex plasmas is the orbital motion limited (OML) theory [28]. This approach is based on the analysis of ballistic (collisionless) ion and electron trajectories in the central field of an individual charged particle [29, 30] and allows the determination of the ion and electron collection cross sections from the conservation of energy and angular momentum. Fluxes are then obtained by integrating the collection cross sections over the corresponding velocity distribution functions. In the plasma bulk these are usually taken as isotropic Maxwellian distributions. The resulting ion and electron fluxes on the surface of a spherical particle are

\[
J_i = \sqrt{8\pi} a^2 n_i v_{Ti} (1 + z\tau), \quad J_e = \sqrt{8\pi} a^2 n_e v_{Te} e^{-z},
\]

where \( a \) is the particle radius, \( n_{i(e)} \) is the ion (electron) density, \( v_{Ti} = \sqrt{T_i/m_i} \) and \( v_{Te} = \sqrt{T_e/m_e} \) are the ion and electron thermal velocities, and \( \tau = T_e/T_i \) is the electron-to-ion temperature ratio. From the OML flux balance, \( J_i = J_e \), typical values of \( z \) are in the range \( z \approx 2–4 \) (\( z \) slowly increases with \( m_i \) and decreases with \( \tau \)) [31].
It has been recognized that major deviations from the OML result can be associated with the plasma collisionality. The reduced surface potential exhibits a non-monotonic dependence on the plasma collisionality, the ratio between the maximum and minimum values of $\zeta$ can be as large as $\approx 10$–20 [32]. From the point of view of microgravity experiments, the most interesting regime is that of weak and moderate collisionality, where the ion mean free path $\ell_i$ is longer or comparable to the plasma screening length $\lambda$ (the mean free path of electrons is much longer than that of the ions and electrons are normally collisionless). In this regime ion-neutral collisions enhance the ion flux towards the particle. As a result the reduced potential and charge decrease in absolute magnitude. In the context of complex (dusty) plasmas such tendency was predicted in pioneering works by Zobnin et al [33] and Lampe et al [34] (in the context of Langmuir probe theory similar ideas were discussed earlier by Zakrzewski and Kopiczinski [35]).

The topic has received considerable attention. Theoretical models have been developed and numerical simulations have been performed. Fitting formulas of various accuracy and complexity have been proposed. For a detailed discussion of different approaches we refer to a review paper [32]. A particularly simple and useful theoretical approach is known as the collision enhanced collection (CEC) model [34, 36–38]. In this approach, the ion flux to the particle surface in the weakly collisional regime is approximated as a sum of collisionless OML flux and collisional contribution. The latter is roughly the number of ion-neutral collisions per unit time inside a sphere of a radius $R$, such that inside this sphere the (attractive) interaction between an ion and the particle is sufficiently strong (implying that an ion most likely reaches the particle surface after collision) [39]. In practice, $R$ is usually chosen as the distance at which the ion-particle interaction energy drops to the ion thermal energy $T_i$. Assuming that the electric potential distribution around the particle follows the Debye-Hückel form the expression for the ion flux can be simplified to

$$J_i = \frac{8\pi a^2 n_i v_i T_i}{\sqrt{8\pi n_i v_i T_i}} \left[ 1 + z \tau + 0.1 (z \tau)^2 \frac{\lambda}{\ell_i} \right].$$

The first two terms in the square brackets correspond to the collisionless OML expression, the last term is the collisional correction. It is observed that since $z \sim 1$ and $\tau \sim 100$ under typical gas discharge conditions, the collisional correction becomes important for $\lambda \gtrsim 0.1 \ell_i$, that is even at a very weak collisionality. The success of the CEC formula has been documented by numerous comparisons with results from numerical simulations (see e.g. [32, 38, 40–42]).

Expression (2) is applicable in the weakly collisional regime $\ell_i \gtrsim \lambda$. Simulations and fitting formulas that cover the entire range of collisionality are also available in the literature [40–44]. Detailed comparison between different formulas and simulations can be found in [32, 38, 42].

Among experimental methods to determine the particle charge in the bulk plasma one can mention gravity-driven heavy ‘test’ particle collisions with smaller particles levitating in the quasi-isotropic region of an inductively coupled rf discharge plasma [45]. Two experiments reporting estimates for the particle charge have been performed under microgravity conditions with the use of the PKE-Nefedov facility [18]. In these experiments waves in the particle cloud were excited by applying a low-frequency modulation voltage to the electrodes. The charge was then estimated by comparing the measured dispersion relations with the theoretical ones [46–48]. Analysis of Mach cones was used to measure the speed of sound and then to estimate the particle charge in the PK-3 Plus laboratory [49] (see section 4.2).

Most of the experimental data related to measured particle charges in the bulk of gas discharges have been generated with the PK-4 facility [23] in laboratory and microgravity conditions [36, 50–53]. In a typical PK-4 experiment (see sketch in figure 4) particles are injected in a horizontally oriented dc discharge tube, and their horizontal drift is analyzed (for sufficiently small particles a weak ambipolar radial electric field in the bulk plasma is sufficient to compensate for gravity). The charge is then estimated from the force balance condition using the measured particle velocities. The most important forces taken into account are the electric force, the neutral drag force, and the ion drag force. An example of the measured particle charges in a neon plasma in the pressure range from $\approx 20$ to $\approx 100$ Pa is shown in figure 1. Good agreement with the CEC model and significant deviations from the OML theory are evident.

In subsequent experiments with the PK-4 facility in the laboratory, particle charging at high pressures (pressure range 100–500 Pa) was investigated [51, 52]. This regime corresponds to the transition between the weakly collisional and highly collisional (hydrodynamic) regimes. A minimum in the absolute magnitude of the charge (where $z \approx 0.25$) was observed at about 200 Pa. A simple interpolation formula for the ion flux to the grain in the transitional regime was shown to fit quite well the experimental results.

A detailed comparison between microparticle flows in the PK-4 facility under ground laboratory and microgravity conditions has demonstrated that the particle flow velocities in ground laboratory experiments are systematically higher than those in microgravity for otherwise identical discharge

![Figure 1. The dimensionless particle charge $\zeta$ as a function of the ion collisionality parameter $\lambda/\ell_i$, as measured in the PK-4 laboratory and microgravity conditions.](image-url)
conditions. The velocity difference increases with the particle size and/or with reducing the neutral gas pressure. The explanation for this interesting and unexpected observation has been proposed in [53]. Qualitatively, gravity shifts the particle downwards from the tube axis into a region where the radial electric field is strong enough to compensate for the particle gravity. This region is characterized by faster ion flows. The effect of ion flow suppresses the collisional enhancement of the ion flux to the particle, and the absolute magnitude of the charge increases compared to the micro-gravity situation where the particle is located near the tube axis. Thus, the particles in ground laboratory experiments experience a stronger longitudinal electric force and hence drift faster. An analytical model developed in [53] is able to account for both collisional and ion flow effects and demonstrates reasonable agreement with experimental results, in both laboratory and microgravity.

Finally, we point out that ionization events in the vicinity of a small floating grain in a plasma can play essentially the same role as ion-neutral charge exchange collisions [39]. Thus, ionization can also enhance the ion flux to the particle surface and reduce the absolute magnitude of its floating potential (and, therefore, charge). This effect becomes significant when the electron temperature is sufficiently (but not unrealistically) high and is sensitive to the electron energy distribution function. For electron energies of $\approx 6-8$ eV in neon gas observed in the PK-4 facility [23], the ionization enhancement of ion collection can have non-negligible effects [39].

2.2. Ion drag force

Knowledge of the major forces acting on particles in complex plasmas is necessary to understand dynamic phenomena and equilibrium configurations of particle structures observed in experiments. The forces can be naturally divided into two groups: the first group includes the forces associated with plasma-particle interactions (e.g., ion drag and thermal forces, electrostatic force, polarization force), whereas the second group includes forces which are unrelated to plasma-particle interactions and particle charge (such as gravity, neutral drag, and thermophoretic forces).

The ion drag force—the momentum transfer from the flowing ions to charged particles—is an inevitable and exceptionally important factor in complex plasmas under microgravity conditions. The calculation of the ion drag force can be rather complicated in some cases. Significant progress in understanding this process has been related to the microgravity research program. Therefore, in this section we give a brief historical overview and summarize our current understanding of this important phenomenon.

Active investigations of the ion drag force were mostly triggered by the first experimental observations from complex plasmas under microgravity conditions [54] (at that time using the TEXUS sounding rocket program). In these first experiments it was observed that the particles do not fill the entire bulk quasi-neutral region of a discharge, but instead a particle-free centimeter-size region is formed in the center—the ‘void’. An ion drag-based scenario of this phenomenon was put forward as the most promising [55–57]. In this scenario, the void results from a balance of the electrostatic and ion drag forces acting on the particles. The necessary condition is that the ion drag force, driven by a flow of ions outward from the central discharge area, can exceed the electrostatic force (pointing to the center) at least in the regime of weak electric field. Theoretical models existing at that time (essentially applying standard Coulomb scattering theory to ion-particle scattering in dusty plasma) could not predict such large values of the ion drag force. The ion drag force was significantly underestimated, and hence other effects were invoked (e.g. thermophoresis) [54], or the ion drag force was artificially enhanced [58–60] in order to explain the void formation.

It was, however, soon recognized that the standard Coulomb scattering theory cannot be applied to describe momentum transfer in ion-particle collisions due to the essentially nonlinear character of the ion-particle interactions. Due to the high particle charges, the characteristic length scale of the strong ion-particle coupling is comparable to or exceeds the plasma screening length. The traditional neglect of impact parameters beyond the plasma screening length becomes inadequate. A modification applicable to a moderate level of nonlinearity in the ion-particle interaction was proposed in [61]. The following expression for the ion drag force was derived:

$$F_{\text{id}} = (8\sqrt{2}\pi/3) a^2 n_i m_i v_i u \left[ 1 + 1/2z\tau + 1/4z^2r^2\Lambda \right],$$

(3)

where $u$ is the ion drift velocity relative to the particle and

$$\Lambda = 2 \int_0^\infty e^{-x} \ln \left[ \frac{2(\lambda/a)x + z\tau}{2x + z\tau} \right] dx$$

is the modified Coulomb logarithm. The first two terms in square brackets of equation (3) correspond to the momentum transfer in direct ion-particle collisions (collection part), the last term proportional to the Coulomb logarithm $\Lambda$ corresponds to elastic scattering in the particle’s electric field (orbital part). Equation (3) is applicable for moderate ion-particle coupling (at weak coupling it reduces to the conventional Coulomb scattering result) and for subthermal collisionless ion flows. In later studies, scattering in the Yukawa potential in the limit of very strong attractive interaction was investigated in detail [62–64]. The reduction of the ion drag force in dense particle clouds has been studied in [65]. Effects of deviation from the conventional Yukawa potential have been recently discussed [66]. These works led to an improved theoretical understanding of the ion drag force in the collisionless regime. A spinoff from these studies is the finding that low-energy classical scattering is quasi-universal (the scattering angle is a quasi-universal function of the properly normalized impact parameter) for a wide class of model as well as realistic interaction potentials. In particular, new results for the momentum transfer cross sections for low-energy Lennard-Jones particles have been derived [67, 68].
So far the results discussed have been obtained using the binary collision formalism, where the mechanical problem of the ion motion in the (central) field of the charged particle is solved. Analysis of ion trajectories yields the velocity dependent momentum transfer cross section and then the force. This approach can be applied for any form and strength of the ion-particle interaction, but since one deals with ballistic ion trajectories, the effect of ion-neutral collisions cannot be consistently accounted for. In addition, electrostatic potential anisotropy related to the presence of ion flows is neglected.

An alternative way to calculate the ion drag force is based on the so-called linear plasma response formalism. Instead of calculating single ion trajectories and then the momentum transfer cross section, one can solve the Poisson equation coupled to the kinetic (or hydrodynamic) equation for the ions and electrons and obtain the self-consistent anisotropic component of the electric field induced by the ion flow at the position of the particle, which produces the (drag) force. This approach consistently accounts for ion-neutral collisions and potential anisotropy caused by the ion flow, but is applicable only for weak ion-particle coupling since linearizations are involved. Applications of the linear plasma response formalism to evaluate the ion drag force are discussed in [69–71]. A hybrid approach to calculate the ion drag force in a collisionless Maxwellian plasma with an arbitrary velocity of the ion flow, based on the combination of binary collision and linear plasma response formalisms, is described in [72]. For an overview of different approaches, their comparison, and discussion of the respective limits of applicability see [32, 73, 74].

It is clear from the discussion above that despite the high importance of the ion drag force, a complete self-consistent model for this force, describing all cases of interest, has not yet been and most likely will not be constructed. Rather, there exist two main approximations, binary collision approach and linear plasma response formalism, which can be (separately or in combination) utilized in certain parameter regimes. The reliability of these theoretical approximations has been verified in numerous experiments. For example, the ion drag force acting on micron-size particles in neon plasma at pressures between 20 and 120 Pa was measured using the PKE-4 facility [75, 76]. The ion drag force acting on hollow glass microspheres of a diameter from \( \approx 20 \, \mu m \) [77] to \( \approx 60 \, \mu m \) [78, 79] in a collisionless plasma was measured to cover the regime of strong ion-particle coupling. Generally, experimental results are in reasonable agreement with appropriate theoretical approximations. Indirect confirmation of the adequacy of our current theoretical understanding comes from the success of simulating voids in complex plasmas under microgravity conditions [80–83] and consistency of the observed void closure in the PKE-Nefedov facility at low pressure and discharge power with the ion drag mechanism of void formation [84]. The force field inside the void, measured using the ‘trampoline effect’ (a weak instability of the void-particle cloud interface resulting in periodic injections of particles into the void region), is also consistent with the ion drag origin of the void [85]. The ion drag force acting on an individual particle in a flowing plasma has been determined in numerical simulations in collisionless [86, 87] and collisional regimes [88, 89]. In particular, it has been demonstrated that the finite collisionality initially enhances the ion drag force up to a factor of \( \approx 2 \) relative to the collisionless result [89]. In the strongly collisional regime the ion drag force falls off approximately inversely with collisionality and can reverse sign in the continuum limit [71, 90]. The collisional drag enhancement can be represented by an almost universal function of scaled collisionality and flow velocity, for which simple fits have been suggested [89].

2.3. Thermodynamics and sound velocity of Yukawa systems

In the zero approximation 3D quasi-isotropic complex plasmas can be modeled as systems of point charges, interacting via the Yukawa potential, \( \phi(r) = Q^2/4\pi \frac{e^2}{r^2} \), where \( Q \) is the particle charge. Clearly, such an idealization oversimplifies considerably the actual rather complex interactions between the particles in the plasma, does not account for the variability of the particle charge, and is not consistent with the open character of the system. Nevertheless, many experimentally observed trends can be reproduced by this simple consideration, at least qualitatively. It can be thus considered as a basis for constructing more realistic models.

The phase state of idealized Yukawa systems is conventionally characterized by the two dimensionless parameters: the coupling parameter \( \Gamma = Q^2/aT \) and the screening parameter \( \kappa = a/\lambda \), where \( a = (4\pi N/3)^{-1/3} \) is the Wigner-Seitz radius, \( N \) is the particle number density, and \( T \) is the thermal energy of the particles. Although, thermodynamics and dynamics of these systems have been studied for decades (see e.g. [91–93]), recently there has been considerable renewed interest in a simple and accurate practical description of thermodynamic properties of Yukawa fluids and solids [94–100]. Particularly useful practical formulas expressing the reduced internal energy, pressure, compressibility modulus, and adiabatic index in terms of \( \kappa \) and \( \Gamma \) across coupling regimes have been proposed [97, 98]. These expressions demonstrate very good agreement with the available results from numerical simulations and provide simple and accurate tools to estimate thermodynamic properties of Yukawa fluids and crystals in a broad range of parameters. Among possible applications of these results there is, first of all, the equation of state for the particle component required for the fluid description of complex plasmas [101].

One particular example chosen for the purpose of illustration is related to the sound velocity of the particle component. The sound velocity can be relatively easily measured in experiments, including those under microgravity conditions, by e.g. analyzing the dispersion relation of externally or spontaneously excited low-frequency waves or by observing Mach cones excited by supersonic projectiles (see below). The measured velocity can then be used for diagnostic purposes if its relation to complex plasma parameters is known.

The conventional multi-component plasma approach applied to complex plasmas by Rao et al [102] yields for the sound
function of the screening parameter is the pressure. For sufficiently soft interactions (like the Yukawa potential), the adiabatic index is very close to unity at strong coupling, \( \gamma \approx 1 \). Using practical expressions for the pressure (or isothermal compressibility modulus), the sound velocity of Yukawa fluids can be easily evaluated \[ c_s \approx \sqrt{\frac{\gamma(kT)}{M}} \]

where \( c_s \) is the sound velocity in a one-component fluid. The curves correspond to the simple fluid approach of \( \Gamma \) at different coupling parameters. Here \( \Gamma_m \) is the coupling parameter at freezing/melting.

\[
c_{DA} = \omega_{pd} \lambda, \tag{4}
\]

where \( \omega_{pd} = \sqrt{\frac{4\pi Q^2N}{M}} \) is the dust-plasma frequency and \( M \) is the particle mass. This expression is applicable to the weakly coupled limit where the correlational effects are absent. The particle charges are, however, so high in typical experimental conditions that the interparticle interactions are significant and an expression for the sound velocity in a fluid state would be more appropriate. The conventional definition of the sound velocity in a one-component fluid is \[ c_s = \sqrt{\frac{\gamma}{M}} \frac{\partial P}{\partial N} \], where \( \gamma \) is the adiabatic index, and \( P \) is the pressure. For sufficiently soft interactions (like the Yukawa potential), the adiabatic index is very close to unity at strong coupling, \( \gamma \approx 1 \). Using practical expressions for the pressure (or isothermal compressibility modulus), the sound velocity of Yukawa fluids can be easily evaluated \[ c_s \approx \sqrt{\frac{\gamma(kT)}{M}} \].

The main tendencies are as follows: The ratio \( c_s/c_{DA} \) is very weakly dependent on \( \Gamma \), it can be taken as constant at \( T \lesssim 10T_m \), where \( T_m \) is the temperature at the fluid-solid phase transition; the ratio \( c_s/c_{DA} \) depends considerably on the screening parameter \( \kappa \), approaching unity at weak screening (\( \kappa \to 0 \), one-component plasma limit) and decreasing considerably as \( \kappa \) increases. This behavior is illustrated in figure 2. These properties should be properly accounted for when using the experimentally measured sound velocity to estimate complex plasma parameters.

3. Experimental setups for space

Experimental setups for microgravity research are designed to produce a geometric symmetrical and homogeneous plasma. The first two plasma chambers for the PlasmaKristall (PK) series on board the ISS used a parallel-plate capacitively coupled radiofrequency (rf) discharge \[ 18, 19 \]. The electrodes of the PKE-Nefedov and PK-3 Plus chambers had diameters of 4.8 cm and 6 cm, respectively, at a distance of 3 cm and were driven with a 13.56 MHz symmetrical signal in symmetrical push–pull mode. The rf-power was adjusted to values below 1 W to create a weak plasma of densities below \( 10^9 \) cm\(^{-3} \). A sketch of the PK-3 Plus plasma chamber is shown in figure 3.

The present laboratory on the ISS, PK-4, contains a direct current (dc) discharge tube where complex plasma experiments are performed in the positive column (see figure 4) \[ 23 \]. This special design allows to investigate especially fluid and flowing complex plasmas. The particle cloud can be trapped additionally through polarity switching of the electric field. This can be done with frequencies up to 5 kHz to trap the particles. Microparticles are injected into the arms of the tube from dispensers D1–D6 and transported to the main experiment area by electric field or gas flow. Here, they are illuminated by a sheet of laser light and the scattered light is observed with two particle observation video cameras at 90°. Republished from \[ 23 \], with the permission of AIP Publishing.
field with frequencies up to 5 kHz. This makes it possible for the microparticles to be trapped due to their low plasma frequencies ($\leq 100$ Hz) while the main character of the dc discharge remains. The setup is equipped with particle manipulation devices like a manipulation laser to introduce shear forces, an electrical manipulation electrode for introducing waves and shocks, thermal heaters to produce a temperature gradient and therefore thermophoretic force on the microparticles, and two rf-coils, which can excite an additional rf-plasma for particle trapping and manipulation.

In all setups, microparticles of different sizes and materials are injected into the plasma by microparticle dispensers. These particles are immediately charged and trapped in the plasma. This is a very stable configuration, which can be kept for hours for investigation of different phenomena. Some of these phenomena will be shown in the next section.

4. Experimental results

As mentioned earlier, the portfolio of experimental results from the ISS is manifold, covering all states of the complex plasma soft matter. Here, we concentrate on basic phenomena observed more recently.

4.1. Waves

Dust acoustic or dust density waves [106] can be either self-excited due to ion-streaming instability [102, 107, 108], or excited externally [48, 109–111]. They provide unique insight into wave-particle interactions, since the movement of individual particles can be traced [14]. Figure 5 shows an example of self-excited waves in the PK-3 Plus Laboratory on board the ISS. The waves propagate outwards from the central void towards the chamber walls, following the direction of the ion flow. They are self-excited when the gas pressure is low enough (leading to higher ion velocities and less damping of the microparticle motion), and the microparticle number density is high enough. As the ions accelerate towards the sheaths, the excitation conditions are more favorable in that region, and self-excited waves appear first at the edges of the microparticle cloud.

By modulating the voltage applied to the electrodes, waves in PK-3 Plus can be excited externally, and the dispersion relation measured [48]. At low excitation frequencies (of the order of a few Hz), the microparticles simply follow the excitation by moving up and down [48]. At higher frequencies, waves begin to propagate. When the external modulation frequency approaches that of self-excited waves, the excited waves spread through the cloud, filling the entire volume. At even higher frequencies, the waves disappear.

The PK-3 Plus Laboratory was also well suited to study wave propagation across interfaces. If microparticles of different sizes are injected into the plasma, they demix due to the difference in the ratio of the size dependent ion drag and electrostatic forces acting on them [25]. In figure 5, waves propagate across an interface between subclouds composed of particles with diameter 6.8 $\mu$m (located around the central void) and 9.2 $\mu$m (located further from the center). The wave length of the waves visibly changes when crossing the interface. With a close analysis of the wave dynamics [112], it is possible to identify a ‘collision’ zone and a ‘merger zone’ before and after the interface, respectively. By analyzing the propagation of solitary waves, the influence of the interface can be studied in even more detail, since there is no interference with the next approaching wave front. Then, it is even possible to investigate the reflection of the wave front at the interface [113].

4.2. Interaction of microparticle cloud with projectiles

Sometimes, single microparticles move differently from the rest of the cloud and penetrate the cloud. The reason for this is most likely a combination of radiation pressure and photophoretic force [114, 115].

If those abnormally accelerated microparticles move with a subsonic velocity, they simply displace the microparticles in their way, forcing them on $\alpha$-shaped trajectories around the projectile [49, 116]. However, projectiles moving supersonically excite Mach cones such as that shown in figure 6 [49, 117, 118]. Then, the Mach relation

$$\sin \theta = c_s / v,$$

relating the angle of the Mach cone $\theta$ with the projectile speed $v$ and the speed of sound $c_s$, can be used to measure the speed of sound. Using the measured $c_s$, allows an estimation of the charges of the microparticles in the complex plasma cloud and a test of the various charging theories [49]. The CEC theory [36] and the drift motion limited theory [119] were found to give the best results [49].
4.3. Interaction of microparticle cloud with spheres

The interaction of macroscopic objects with the microparticles immersed in a plasma is of interest for a variety of reasons. For instance, in astrophysical situations, plasma-mediated interactions between polydisperse dust particles might lead to the formation of dusty clumps [120]. Thus, it is desirable to study this interaction in detail. Under gravity conditions, however, macroscopic objects immediately fall to the ground. Experiments under microgravity conditions allow a prolonged investigation.

The interaction between a complex plasma and metallic spheres of 1 mm diameter was studied in the PK-3 Plus Laboratory [121]. The spheres were injected together with the microparticles into an argon plasma at pressures between 15 and 30 Pa. Figure 7 shows a side view of the system. The microparticles are visible only when inside the laser plane, whereas the spheres reflect much more light (also from the plasma glow) and thus are also visible outside the plane. When they cross the laser plane, it becomes visible that they repel the microparticles, and a cavity surrounding the spheres appears in the microparticle cloud. The spheres also cast an extended shadow onto the cloud. This fact, together with the well-known size of the spheres, can be used to measure the transverse velocity of the spheres simply by counting how many frames the shadow is visible.

It is clear that the spheres must repel the microparticles, since they, like all objects immersed in the plasma, acquire negative charges. At intermediate distances, however, the spheres effectively attract the microparticles due to the ion drag force. This ‘repulsive attraction’ can also be seen when studying the interaction between a biased wire or a Langmuir probe with a complex plasma [10, 122].

In the present experiment, the strong influence on the ions can also be observed in the fact that the spheres can trigger the appearance of self-excited waves if the conditions are already close to the excitation threshold. The sphere’s electric field then is added to the local electric field, and the excitation threshold is crossed.

4.4. Turbulence

Under some conditions, the microparticle cloud becomes unstable. One prominent example is the so-called ‘heartbeat instability’, in which the central void oscillates radially [55, 123, 124], probably due to the formation of a sheath at the plasma-complex plasma interface at the void edge [125]. This pulsation leads to shaking of the complex plasma cloud and an effective ‘turbulization’ of the microparticle dynamics. In [126–128], it was shown that, in a complex plasma undergoing the heartbeat-instability, a general radial movement of the microparticles is overlaid with vortex movement on various spatial and time scales.

Figure 8 shows the kinetic energy spectra of the microparticles before and after the onset of the instability. It is visible that the spectrum changes from an exponential to a power law dependence. This reminds of the double cascade predicted for forced 2D turbulence [129, 130].

4.5. Crystallization by external manipulation (pressure change)

In experiments on the ground, plasma crystals can be melted by decreasing the neutral gas pressure [131, 132].

Figure 6. (a) Experimental snapshot of a projectile moving through a complex plasma cloud in neon at a pressure of 20 Pa. Field of view: 26 × 36 mm². (b) Enlarged view of the projectile and the surrounding area. (c) Mach cone visualization. Reprinted from [117], with the permission of AIP Publishing. Contrast and brightness were enhanced.

Figure 7. Experimental snapshot showing the millimeter-sized metallic spheres moving through a complex plasma cloud. While the microparticles are visible only within the thin laser sheet, the spheres can be observed even before and behind the plane. Nevertheless, the interaction of the spheres with the local microparticle cloud is visible only within the laser sheet. Field of view: 26 × 36 mm². [22] 2018 © Springer Nature. With permission of Springer. Contrast and brightness were enhanced.
leads to the formation of instabilities at the sheath edge [11, 133–135], which in turn induce melting. An important melting mechanism is the mode-coupling instability [136]. A decreasing gas quality can also induce melting [137]. For a detailed overview of melting scenarios in 2D plasma crystals see [138].

If the microparticles are located in the plasma bulk, as is typically the case for experiments under microgravity conditions, the influence of the edge electric fields is not as strong. This can lead to a reversal of the situation—reducing the pressure induces crystallization, as can be seen in figure 9 [139, 140–142]. This figure shows results from experiments using particles of 1.55 and 2.55 μm diameter in an argon plasma. The gas pressure was first reduced and then increased, see figure 9(b). During the experimental run, the cameras and laser sheet were moved by a translation stage to scan through the system. This allowed determining the 3D particle positions. From the analysis of particle positions it was identified that change in pressure leads to a change in the vertical extent $L$ of the cloud, and, correspondingly, the interparticle distance $\Delta$ (figure 9(c)). Effectively, the complex plasma cloud was compressed with reducing the neutral gas pressure due to an increase in plasma confinement. This resulted in the crystallization of the particle component (and respective melting by increasing pressure). This mechanism worked for smaller particles (1.55 μm in diameter) only, larger particles were coupled strongly enough to remain in the crystalline phase.

Phase transitions have been identified by evaluating three different melting-freezing indicators. The evolution of an indicator related to a Lindemann-like measure of crystallization,

$$L_{ind} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \left[ \delta_{i}^{2} / d_{i}^{2}(i) \right]}$$

is shown in figure 9(d). In the equation above, $N$ is the number of nearest neighbors and $\delta_{i}^{2}$ denotes the local square deviation of the nearest-neighbor distance from its local mean value $d_{i}(i)$ [139]. An increase in $L_{ind}$ indicates melting as can be observed in figure 9(d). The behavior of other indicators, such as the conventional Raveche–Mountain–Streett...
criterion of freezing and one more indicator based on cumulative distribution of particles over the rotational invariants [143, 144], confirmed the solid-fluid transition in the cloud of small particles. Theoretical estimates of the complex plasma parameters were used to estimate the location of the investigated systems on the relevant (Yukawa) equilibrium phase diagram. Reasonable agreement between theoretical expectations and observations was reported [139].

In related experiments, compression of the system was also achieved by adding additional particles around a pre-existing cloud, which significantly affected particle cloud properties [141, 145].

Studies of the liquid-crystalline phase transition allow a detailed investigation of the growth of crystalline structures [22, 137], and of the structure of fully formed crystals [146].

5. Conclusion, summary and outlook

Complex plasmas are not only a new state of soft matter with many interesting research topics in classical condensed matter physics, but also a special kind of plasma where the heavy microparticle component alters the plasma and introduces new phenomena that can be observed at the kinetic level. This allows new insights into dynamical processes not available in pure plasmas. To reach the full spectrum of complex plasma research topics, experiments under microgravity conditions have to be performed additionally and complementarily to the ground based research. Some highlighted topics of more than 15 years of microgravity research on the ISS have been presented here, combined with a theoretical description.

The research on complex plasmas under microgravity conditions will be continued with the present lab PK-4 on the Columbus Module of the ISS. For the long-term future of this research a new laboratory is in planning—the Ekoplasma Facility [147]. This versatile facility will allow research into many topics, especially regarding the soft matter features of complex plasmas, including the kinetics of nucleation from the undercooled melt, the role of lattice defects during the nucleation and growth, the difference between 2D and 3D crystallization/melting scenarios, as well as tunable interactions between the microparticles, anisotropic and active particles, binary mixtures, non-reciprocal interactions, driven systems, etc. The research portfolio is manifold and always contains a well adjusted complementing experimental program under gravity and microgravity conditions as well as theoretical and numerical modeling.

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ORCID IDs

H M Thomas @ https://orcid.org/0000-0001-8358-2023
M Schwabe @ https://orcid.org/0000-0001-6565-5890
S A Khrapak @ https://orcid.org/0000-0002-3393-6767

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