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The Physics of Complex Plasmas and the Microgravity Programme on Plasma Crystal (PK) Research

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ABSTRACT

The relatively young field of “complex plasmas” has seen a continuous rapid growth in the last 10 years, since the discovery of liquid and crystalline plasma states, with a total of about 3000 publications so far and an annual rate in excess of 400 at present. The scope of the field and the role of microgravity is discussed, as well as some individual research advances made recently. Special attention is given to the microgravity programme, which is currently dominated by the Russian/German “Plasmakristall (PK)” cooperation, but which will become international soon.

INTRODUCTION

Complex plasmas are a relatively new field of research of growing interest in the science community, with investigations under gravity and microgravity conditions [1, 2]. The science topics which can be investigated on the most fundamental – the kinetic level – are widely spread over the field of physical sciences, e.g. solid state physics and material sciences, fluid sciences and plasma physics, to mention just a few. Complex plasmas provide a unique research opportunity to study self-organisation processes in liquid and crystalline, the so-called plasma crystal, systems, nonlinear dynamics of (many) particle systems, strong coupling phenomena in systems with rotational as well as translational degrees of freedom, critical phenomena, phase transitions, transition to turbulence, the transition from discrete to continuous systems, physics at, near and far from LTE in unmagnetised and magnetised states, etc. – at the most elementary, the kinetic level (measuring true distribution functions).
A complex plasma consists of positive ions, electrons, negatively charged microparticles and neutral gas in (quasi) charge equilibrium [3, 4, 5]. The dominant component in the system is the microparticle component due to its high mass and high charge. It introduces new physics to the plasma:

- New interactions.
- New length scales.
- New time scales.
- New processes.

This makes complex plasmas a new field of research with interesting investigations in its own right. The charge on a micronsized particle typically a couple of thousand elementary charges arises from the interaction with the free electrons and ions. The microparticles interact with each other via their screened Coulomb potentials [6]. Due to this interaction the complex plasma can form strongly coupled systems which can undergo phase transitions to the fluid and even to the crystalline state of matter. This (and other properties discussed later) make complex plasmas an unusual new state of matter. The physical states of matter are characterized by an increase of disorder, entropy and temperature from solid to liquid to gaseous and finally to the plasma state (s. Figure 1).

Complex plasmas belong to a new “class” of matter – the physical states of soft (or granular) matter – which are shown in Fig. 2. These allow in some special cases the transition back to a more ordered, lower temperature and entropy system, e.g. for complex fluids the ordering transition to colloidal crystals and for complex plasmas the corresponding transition to liquid and crystalline plasmas – the so-called plasma crystals.

![Physical states of soft (granular) matter](image)

**Fig. 2: the physical states of soft (granular) matter.** Most of the physical systems can be described by the Hamiltonian formalism because they undergo changes by processes that maximise or minimise “action”. Hamilton’s canonical equations of motion have proved extremely useful in many areas of physics, ranging from statistical mechanics, thermodynamics, etc. to quantum mechanics. They have applications in galaxy dynamics, stellar clusters, planetary systems, gases, plasmas, crystals, atoms etc.

Complex plasmas are non-Hamiltonian systems. Two effects are responsible for the non-Hamiltonian properties:

- Charge fluctuations arising from the continuous flux of electrons and ions to the surfaces of the particles, making the interaction potential time dependent [7].
- Charge ‘cannibalism’, appearing at high microparticle densities making the interaction potential density dependent [8].

Studying non-Hamiltonian physics with complex plasmas, as an easily available experimental system (at the kinetic level), will open a whole new field of research in basic physics.

With current technology it is possible to perform complex plasma experiments with up to $10^9$ microparticles. Hence, 3D ‘kinetic’ studies are possible for (linear) system sizes up to ~ 1000 ‘effective’ particle diameters (~2 Debye length). The special properties of complex plasmas are:

- Systems less than $\ell \approx 10$ cm in size are optically thin ($\tau \equiv n a^2 \ell \leq 1$ gives $\ell \approx 30$ cm, where $n = \Delta^{-3}$).
• Studies of fast processes, e.g. of the order of the „Einstein frequency“ and the „dust plasma frequency“ \(\omega_{\text{p}}\) (about 10 - 100 Hz), are possible.
• Controlled active experiments can be conducted (e.g. using laser light pressure, charge manipulation).

Complex plasmas are a unique tool for studying fundamental physics. First, as a physically distinct new (non-Hamiltonian) state of matter – exhibiting properties of crystals, liquids and gases – complex plasma research is of basic relevance in physics. Second, at the same time, the unique feature of observing kinetic properties in real space and time provides the opportunity to study generic universal processes in a detail not possible so far, and at a more fundamental level. Generic universal processes are e.g. self-organising principles in nucleation, phase transitions (crystallisation, gelation), universality and scaling at the critical point, relaxation to the final equilibrium state, self-organisation and scaling in fluid flows, and transition from ‘matter’ to particles (e.g. Nanofluids, clusters).

The available parameter range for such studies is huge – to mention only one example, liquid plasma systems can be "engineered" as a "one-phase fluid" as well as a "two phase fluid" if the conditions are suitably chosen. With the low damping (due to the background gas), the possibility to investigate rapid processes (up to the dust plasma frequency), the diversity of systems available (e.g. homogeneous, binary, anisotropic, stratified…), magnetisation etc., complex plasmas occupy a parameter range for fundamental research that is not covered by any of the other neighbouring research fields, such as complex fluids or granular media.

Thus complex plasma research complements that of the neighbouring fields, at the same time extending the investigations to a fundamental (kinetic) level. In addition, a new “soft” matter state with many unusual properties can be researched, a process which will yield new physics and new applications.

**THE ROLE OF GRAVITY**

As mentioned in the introduction complex plasmas consist of a “normal” plasma – electrons and ions – and an additional component of small solid particles, typically in the range of micrometers. This heavy component in the plasma makes it necessary to perform experiments under microgravity conditions although it is possible to levitate the particles in the laboratory as well. For instance, the charged microparticles can be levitated in a strong electric field. But this induces substantial stresses to the system of strongly interacting particles and implies that under gravity conditions only a small part of the parameter phase space of complex plasmas can be investigated. To complete the research on complex plasmas, investigations under microgravity conditions are mandatory.

![Fig. 3: The figure shows the electrostatic interaction strength, \(\Gamma_{ES}\) (electrostatic potential/kinetic energy), plotted against the mean particle separation normalised to the particle size, \(\alpha = \Delta a\). When \(\alpha = 2\), particles are touching, a value \(\alpha \sim 100\) corresponds roughly to typical complex plasmas, where the mean particle separation is of the order of the (Debye) shielding length, \(\kappa = \Delta^2 a\).](image-url)

The vertical line \(\kappa = 1\) conditionally divides the diagram into weakly screened (Coulomb) and strongly screened (Yukawa) parts. The red line marks the boundary between crystalline and liquid complex plasmas, the black line indicates the transition to a weakly coupled plasma (gaseous phase). Blue dashed lines indicate the regions where the system is similar to a granular medium: Below the lower curve the electrostatic interaction is weak and the momentum exchange is due to direct collisions. Above the upper blue line, the strongly screened electrostatic interaction reduces asymptotically to the hard sphere limit with radius \(\propto a\), forming a “Yukawa granular medium”.[9]

Under gravity conditions only small complex plasma systems of limited extent in the vertical direction – as shown in Figure 4 (a) – can be investigated (in a region where gravity is compensated by a strong electric field). Under
microgravity we observed large complex plasma systems extended in all three space co-ordinates (see Figure 4 (b)). It can be shown that under microgravity conditions much broader and different regions in the parameter phase space are accessible (shown in Fig. 3) providing a means for researching new physics not attainable under gravity conditions [9].

Fig. 4: Microparticle (3.4 µm in diameter) distribution between the two electrodes under gravity (a) and microgravity conditions (b). Under gravity the charged particles sediment towards the lower electrode and can be levitated only by a strong electric field in the sheath. Under microgravity the particles are dispersed all over the experimental volume, forming large 3-dimensional complex plasmas.

The special conditions which Space provides for the investigation of complex plasmas were taken into account very early in the beginning of the research. More precisely, the first proposal to form a plasma crystal was sent to ESA for a microgravity experiment on the “Columbus Precursor Flights” in 1990 [10]. After the laboratory discovery of the crystallisation of complex plasmas to the new state of matter plasma crystal in 1994 at the Max-Planck-Institute for extraterrestrial Physics MPE [11] and two independent groups from Taiwan and Japan [12, 13], the work at MPE on a possible microgravity experiment was increased, financed by the former DARA, the German Space Agency. First parabolic flights in 1996 and the directly followed sounding rocket experiment TEXUS 35 [14] already pointed out the scientific possibilities of complex plasma research without gravity. This was the starting point for a new and very successful field of research under microgravity conditions. Many parabolic flight experiments [15] and a second sounding rocket experiment have been performed since then. The biggest Milestone in the research under microgravity conditions was the installation of PKE-Nefedov on the ISS in March 2001 as the first long-term experiment on complex plasmas [16]. Since than the experiment is operating and providing new insights into the physics of complex plasmas.

Fig. 5: PKE-Nefedov apparatus on the ISS. The hardware consists of two major parts, 1) the experiment and its electronics, hermetically sealed in a vacuum container (right), and 2) the so-called Telescience Apparatus which is used as a console for the cosmonaut to control the experiment and as a storage device for the digital housekeeping and analogue video data. The Experimental Block is shown in Figure 1 (right) and Fig. 2. It can be divided into three different parts:

- **Part I:** Experimental setup. Includes the rf plasma chamber (3, symmetrical parallel plate reactor filled with argon) with assembled microparticle dispensers (2), rf-generator (7), pressure control system (9), cameras (4), and lasers (8) mounted on a translation stage. The rf generator is a special development for lowest rf power values, which are required for stable and large complex plasma systems and for plasma crystal formation. Two CCD-cameras provide two different magnifications of the complex plasmas. The overview camera shows about a quarter of the field between the electrodes, $28.16 \times 21.45 \text{ mm}^2$, while the high resolution camera is used for detailed views inside the overview field covering $8.53 \times 6.50 \text{ mm}^2$. On top of the Experimental Block a vacuum connection (6) is used to pump the
experimental setup. This vacuum port is contacted to outer space.

- **Part II**: Electronics (5, 10) for part I and the system electronics (main power control).
- **Part III**: Experiment computer. Allows real time control of the plasma. Electrical signals produced by the experiment computer and the two video signals are contacted out of the container (1) and are controlled by the Telescience Module (not shown here). The computer visualizes the experimental data and can be used to control the experiment manually. Time codes (VITC signals) are inserted into the video frames and stored on two High-8 video recorders. The original video tapes are transferred to ground by the cosmonauts. The Telescience Module has the capability to transfer experimental data and video to ground and receive commands from ground, allowing full telescience control of the experiment by the scientists.

Monodisperse particles of different sizes – 3.4 µm and 6.8 µm in diameter, as well as a mixture of both sizes – can be injected into the plasma chamber, between the two electrodes. The microparticles are illuminated by a thin (≈150 µm) sheet of laser light perpendicular to the electrode system (produced by a laser diode and cylindrical optics). For each particle size one laser is installed, which is adjusted in power and optics to achieve best results. The reflected light from the microparticles is observed with two monochromatic video CCD-cameras (768 × 576 pixels, 25 Hz, 8-Bit) with different resolution. The microparticles can be identified in a single video frame and are then followed in time to investigate their dynamical behaviour. The frame rate is 25 Hz, which is faster than the complex plasma frequency of ~10 Hz. Slow speed scanning of the laser and optics into the depth of the plasma chamber is used to measure the 3D positions of the microparticles.

The PKE-Nefedov laboratory is operative on the International Space Station ISS since March 2001. It provides fundamental insights into the physics of complex plasmas at the most fundamental, the kinetic level under microgravity conditions where stresses and distortions due to gravitational forces can be avoided. Major achievements and new discoveries so far are: investigation of the structure and dynamics of complex plasmas over long times including crystallisation, void formation and closure, vortices, physics of plasma boundaries, the so-called heart-beat instability, the investigation of waves and shocks propagating through the complex plasma, coalescence of two complex plasma fluids, the discharging of a complex plasma and the agglomeration of positively and negatively charged particles in a charge neutral environment, to form big (mm-sized) agglomerates.

**Fig. 6**: Sketch of the interior of the Experimental Block. The numbers are explained in the text.

**Fig. 7**: 2-dimensional sketch of the plasma chamber for the PKE-Nefedov experiment. Shown is the cross-section through the central chamber axis. The major parts are the two symmetrically driven electrodes, which include the two particle dispensers, and the area in between, where the plasma is located and the microparticles are trapped.
The scientific results which will be presented here will include the most recent developments from PKE-Nefedov as well as some new results from the parabolic flights performed with the science model of PK-3 Plus, as well as some complementary laboratory experiments.

**PK-3 PLUS**

PK-3 Plus, as its precursor PKE-Nefedov, is a joint Russian/German scientific project. The collaborating science teams are from the Russian Academy Institute for High Energy Densities in Moscow and from CIPS-MPE. The scientists and engineers from both institutions have been working since 2002 on the realisation of PK-3 Plus. Currently the training and flight models are in manufacturing and will be delivered to Russia for launch in the beginning of 2005. The science model, which is finished and was tested on two parabolic flight campaigns will be kept with additional diagnostics at MPE for further laboratory investigations, and for the planning and tests of the experiments on board of the ISS.

At the request of ESA, the Russian/ German science team agreed to make PK-3 Plus available for research to other scientists from ESA, thus providing much-needed new science impulses to the community within ESA’s interim ISS utilisation programme.

PK-3 Plus is a symmetrical driven radio-frequency plasma discharge (see Fig. 8 for details) with special features for the investigation of complex plasmas under microgravity conditions. As a second generation laboratory, PK-3 Plus provides major new possibilities for these investigations due to its design improvements relative to the first long-term experiment PKE-Nefedov.

The PK-3 Plus apparatus allows investigations at neutral gas pressures (Argon and/or Neon) between 0.05 – 2.5 mbar and rf-power of 0.01 - 1 W. The complex plasma can consist of monodisperse particles in a size range from 1 – 20 µm. Up to six particle sizes can be added to the experimental volume. It is possible to change the number of particles, the composition of particles, the plasma conditions and the neutral gas pressure during one experiment. The particle cloud can be excited by an electrical low frequency signal on the electrodes (0.1 – 100 Hz at a maximum amplitude of 50 V) or by a low frequency modulation of the rf-amplitude in different wave forms (sinusoidal, square, pulse, etc.).

![3-D drawing of the new plasma chamber](image)

**Fig. 8:** 3-D drawing of the new plasma chamber. Shown are the basic features of the new plasma chamber design: larger electrodes, dispensers included into the ground shield, a new rf-electronic box allowing many important housekeeping and experiment measurements and the mounting of the chamber on supporting legs for highest symmetry.

The apparatus is divided into two units, the experimental block and the Telescience (TS) system, as is PKE-Nefedov. The experimental part is housed in a closed container with electrical and vacuum connections to the outside. It contains the experiment itself, electronics and a computer. An internal turbomolecular pump has been added to reach High Vacuum (<10^{-5} mbar) in the plasma chamber. This is needed for cleaning the plasma chamber after long-term storing on the ISS and to produce very high repeatability of the experiments due to repeatable experiment parameter settings. A valve to space is used to reach the necessary pre-vacuum.

The TS apparatus is the control console for the cosmonaut and allows the storage of the digital and video data. Digital data are available on ground 1 day after the performance of the experiment, the analogue videos are stored on harddrives and have to be transported back via Sojus capsule or the Space Shuttle with the crew change. Quicklook videos are available right after the experimental run and will be transported via S-band and a...
special hardware (ROKVISS) to the DLR centre in Weilheim.

Before performing experiments in orbit the experimental parameters are tested on the science model in Munich and on the equivalent Training Model at IHED. In order to define a sequential measurement an autonomous software procedure is written and uploaded onto the ISS experiment computer. If necessary the cosmonaut can interact or control the experiment by hand via the TS apparatus.

Major differences compared to the first laboratory (PKE-Nefedov):

- a new chamber concept avoiding a temperature gradient across the plasma chamber (thermophoresis eliminated) and therefore producing a more homogenous and symmetric complex plasma.
- larger electrodes and a wider ground shield produce an enhanced homogeneity and symmetry in the plasma chamber. The vortices which always appear with the PKE-Nefedov experiment shown in Fig. 7 are no longer existent.
- continuous gas flow added for stable high purity gas conditions allow high rereatability of the experiments.
- up to six different particle sizes (previously 2).
- rf-control enhanced for investigations at very low power levels (10 mW).
- new function generator with enhanced performance (larger amplitude, different wave forms).
- 3rd camera added to monitor the whole volume in between the electrodes.
- 4th camera added to monitor the glow in the whole volume in between the electrodes.
- an enhanced gas regulation for fine-tuning gas pressure.
- gas reservoirs of more content to be filled with Argon and probably Neon.
- A more sophisticated house keeping system data on many more interesting parameters in a high speed burst mode.
- A turbomolecular pump inside the container provides high vacuum conditions in the $10^{-6}$ mbar range.
- progressive scan cameras
- digital storage of analog video signals on hard disks
- modular concept for experiment electronics

All of this makes PK-3 Plus an ideal laboratory for investigating complex plasmas on the ground and under microgravity conditions. The science model, which will stay at CIPS/MPE is fully functioning and equipped additionally with more diagnostics and other features. For example, it requires only slight changes to the plasma chamber and a temperature gradient can be established between the lower and the upper electrode allowing particle levitation of a certain size through the thermophoretic force. This opens up a broad field of interesting scientific observations.

PK-4

PK-4 (or Plasma Kristall-4) is a Russian/German development designed to study in particular the liquid phase of complex plasmas. It is a dc plasma chamber combined with movable rf external manipulators that allow compression, wave excitation, soliton production, the introduction of flow constrictions, thermal excitations etc. Laser manipulation enables the generation of shear flows as well as other patterned flow structures, thermal excitation gradients etc., allowing a large and

Fig. 9: Laboratory prototype of the PK-4 plasma experiment, showing the dc cylindrical plasma chamber, the rf manipulators and the diagnostics. Pre-development (in Russia and Germany) is financed by DLR, MPG and the Russian Academy of Science.
varied class of experiments to be performed. PK-4 (laboratory prototype) is shown in Fig. 9.

**IMPF/IMPACT**

The International Microgravity Plasma Facility is one of the two facilities of the ESA cornerstone Laboratory IMPACT (International Microgravity Plasma, Aerosol and Cosmic dust Twin). It is designed as a modular facility consisting of sub-units for easy accommodation. IMPACT, as the master facility, delivers the rack structure, power, vacuum, cooling, experiment control via laptop and/or telescience, data storage etc. The experimental inserts are defined by the scientific community on evaluated proposals. For IMPF two kind of different plasma chamber inserts are foreseen: an rf-IMPF insert and a dc/rf combined insert, both very different in their set-up and scientific goals. The rf-IMPF insert consists of a parallel plate plasma discharge, similar to the PKE-Nefedov and PK-3 Plus experiment. This insert is foreseen to investigate strongly coupled plasmas in the crystalline state mainly. The second insert consists of a long dc-tube discharge with rf-coils or electrodes used for manipulation and trapping. This set-up will open up a new field of research under microgravity, the liquid complex plasmas. PK-4, as a precursor for the latter, is again a Russian/German cooperation. The hardware is developed at IHED and MPE jointly, funded by the national space agencies. The project is currently in the pre-development phase and is foreseen to replace PK-3 Plus in 2007/8 after the operational phase is ended.

The IMPF facility proposal was one of the outcomes of an ESA Announcement for Opportunities AO 1998 (Principal Investigator or Team Coordinator G. Morfill) with participating scientific groups from 13 international institutions. In the subsequent review process, the proposal was given the highest rating “outstanding”. Since then the Institute (MPE) has been working on the implementation, partly financed by DLR and ESA, supported by an international advisory board and the space industry.

In a second International AO 2000, the ISS related agencies called for experiments for existing or planned facilities. From a total of over 100 proposals worldwide, five received the top grade “outstanding”, and three IMPF proposals took the first three places in the ranking. The proposal “Investigation of Yukawa Clusters” by the proposer of the project group was one of these three. Additionally, three more proposals with team-coordinators from the MPE were rated “highly recommended” (Ivlev et al., “Waves, shocks and solitons in complex plasmas” and Zuzic et al., “Thermodynamics, phase transitions, and defects in plasma crystals”) and “recommended” (Morfill et al., “Fluid behaviour of complex plasmas”). The above mentioned proposals are attached in the Annex for further information. These successful proposals form the second scientific basis for the project group. The cooperative work within the scientific teams and with ESA and the space industry to develop the scientific inserts and to guarantee that the support system provided by IMPACT serves the scientific requirements is a very demanding and time consuming task, which nevertheless is important and essential so that the science community will be provided with the best science possibilities under microgravity conditions.

**IMPF FACILITY DESCRIPTION**

The IMPACT Laboratory consists of an electronic and mechanical support system which delivers the rack structure, power, gas and vacuum, cooling, control, data storage etc. and two experiment inserts, one for the scientific field of complex plasmas and another one for the field of dust and aerosol physics resulting from two independent proposals for facilities (see additionally Fig. 10, which shows the sketch of the IMPACT laboratory). For further information, see [http://www.mpe.mpg.de/theory/plasma-crystal/](http://www.mpe.mpg.de/theory/plasma-crystal/).

**SELECTED SCIENTIFIC RESULTS: LABORATORY RESEARCH**

The discovery of the crystallisation of complex plasmas triggered the interest in laboratory complex plasma research from the fundamental side. Plasma crystal features like defect migration, the melting but also wave propagation in the crystalline and liquid phase were investigated in detail and showed the special properties and possibilities of complex plasmas mentioned above [17-25]. Two recent laboratory investigations, both performed in the apparatus designed for the microgravity experiments, will be presented here.
as examples for the special properties of complex plasmas. The first concerns the investigation of the crystallisation process of a large 3-D plasma crystal [26]. The second is related to the transition from a laminar flow of a complex plasma around an obstacle to a turbulent flow [27].

Under special conditions (e.g. very small microparticles) it was found that the small microgravity plasma chamber can be used to produce significant 3-dimensional plasma crystals even under gravity conditions [28]. The special field lines, the symmetry and the direct coupling of the rf-voltage to both electrodes symmetrically are responsible for that (s. Fig. 7).

In the first example we studied the kinetics of the crystallisation process in real time [26]. A plasma crystal is first melted into a disordered liquid-like phase (by a short pulse of increased discharge power). Afterwards, the system starts re-crystallizing. Sometimes, this results in a homogeneous nucleation, but often this occurs in the form of a crystallization front. Figure 11a shows colour-coded particle traces observed in the experiment during $\approx 1$ s (side view), which give an impression of the particle temperature. The crystallization front is fairly narrow (about 3-4 interparticle distances). The temperature drop across the front is about a factor of a few. This indicates that the observed condensation is strongly non-equilibrium. One can also see the interface between different crystalline domains, which has a narrow width (2-3 lattice planes) and a substantially higher temperature than the crystal domains themselves – direct evidence for interfacial melting. Figure 11b shows molecular dynamics simulations of the crystallization front, also revealing the qualitative features observed in experiments. The front has a well developed fractal structure, with an abrupt temperature drop within the transition layer (blue) from the liquid/gaseous (green-yellow) to the crystalline (black) phase.

Figure 11. (a) Crystallization wave observed in the experiment (particle positions are colour-coded from green to red, i.e., cooler particles appear redder, hotter are multicoloured) [26]. (b) Crystallization wave in molecular dynamics simulation (particle temperature is colour-coded, temperature rises from black to yellow).

Figure 12 (molecular dynamics simulations) shows how the temperature (kinetic energy, red line) of microparticles decays with time during the crystallisation. Initially, when the system is in a gaseous-like phase, the temperature $T$ exceeds or is about equal to the energy of electrostatic interaction. At this stage, $T$ decreases rapidly due to neutral gas friction, and the slope of the decay obeys the pure Epstein drag law for an individual particle. However, as $T$ decreases further and consequently the coupling parameter $\Gamma_{ES}$ grows, the decay becomes much slower. In the crystalline regime, when $\Gamma_{ES}$ exceeds the critical value corresponding to the “solid-liquid boundary” (see phase diagram shown in Fig. 3), the sequence of transitions from one (metastable) configuration of particles to another (lower energy level) can take from a few seconds to dozens of minutes. Energy and structure relaxation at this stage is solely governed by transport properties of the crystal itself.
The second experiment presented here was performed in a slightly modified space chamber with a temperature gradient adjusted over the plasma chamber producing a thermophoretic force to levitate the microparticles against gravity [29] but introducing a flow pattern of the complex plasma. This is particularly suitable for the kinetic investigation of elementary processes in fluids [27]. The importance of the thermophoretic force and its quantitative effect was discovered in experiments performed on the ISS [29].

Under microgravity conditions the typical static and dynamic behaviour of complex plasmas is illustrated in Figure 14 b). This figure shows a 3 second trajectory fragment of the microparticles, color coded from red to blue. The dominant features which can be investigated here are:

1. a microparticle free “void” in the centre of the system for most experimental parameters.
2. a sharp boundary between the void and the complex plasma.
3. demixing of complex plasma clouds formed by microparticles of different sizes.
4. crystalline structures along the central axis.
5. vortices in different areas away from the central axis.

All of the above mentioned features have been investigated in detail over the last three years. These and other effects are published in a series of papers [16, 30-43].

1. The void: The microparticle free centre between the electrodes can be explained by the equilibrium of all forces acting on the particles. Since the dominant force on earth, gravity, is reduced by orders of magnitude the weaker forces can be investigated in detail. These forces (see Fig 14 a)) are the electrostatic force $F_Q$ arising from an electric potential with a maximum in the centre, which decreases radially and axially, and the ion drag force $F_{id}$. The latter is due to the acceleration scales. The microscopic driving mechanism for the observed instability is identified as a Rayleigh-Taylor instability inertially driven by (large-angle-scattering) collisions between particles. This also has been confirmed by molecular dynamics simulations. Comparison in terms of similarity parameters – Reynolds and Mach numbers – suggests that the liquid complex plasmas are remarkably like conventional liquids, e.g., water – observed at the molecular level. This suggests that we have a powerful new tool for investigating fluid flows on (effectively) nano-scales, including the all-important transition from collective fluid behaviour to individual kinetic behaviour, as well as nonlinear processes on scales that have not been accessible for studies so far.
of the positive ions along this electric field out of the centre and the resulting friction force on the particles. According to the well known formula by Barnes at all [44], the ion drag force is too low to overcome the electrostatic force to form the void. A major result of the microgravity experiments is that the ion drag formula of Barnes et al. has to be modified, so that the experimental results agree with the theoretical ones [31]. Since this ion drag is of great importance in many physical situations and problems, the new insights gained from these experiments on the ISS have been considered as a major achievement.

The void can be closed under special experimental conditions. These conditions are neutral gas pressures below 0.5 mbar and the lowest possible rf-voltages, close to the plasma-off condition. At these parameters the plasma density is so low and the electric field is so weak that finally the electrostatic force dominates over the ion-drag force, and the particles are pushed to the centre.

2. Void/complex plasma boundary: The equilibrium of the above mentioned (opposite) forces gives the radial position of an isolated microparticle. In a particle cloud, there are pressure forces, too. The sharp boundary cannot be explained by the equilibrium position alone. It was discovered that the complex plasma changes the potential distribution in such a way that a sheath with a so-called double layer is formed. This double layer produces a change in the sign of the electric field and can explain the sharp edge [32]. This phenomenon, well known to occur in plasma-wall interactions, is apparently present, even if the “wall” is extremely porous (in our case only about 10⁻⁴ of the surface is “solid”).

3. Demixing of different particle sizes: The forces shown in Fig. 14 a) are all size dependent. \( F_Q \propto a \) and \( F_{id} \propto a^2 \), where \( a \) is the radius of the particle. This results in an equilibrium position of smaller particles closer to the centre than bigger ones, easily explaining the observed demixing of the different sizes. The new physics is therefore not the fact of demixing – it lies in the way how de-mixing proceeds in strongly coupled plasmas. This topic is being actively pursued with new dedicated experiments on the ISS. For now it is sufficient to mention that the approach to final equilibrium passes through a new universal process (a non-equilibrium coordinate space phase transition) not known previously – a process peculiar to strongly coupled systems.

Fig. 14: a) Shown is the electrode system (grey) including the microparticle dispensers (red) and the plasma area in between. The self-generated electric potential has a maximum in the centre, decreasing radially and axially outwards. The radially symmetric forces on the particles are the electrostatic force \( F_Q \) dragging the negative particles into the centre and the ion-drag force \( F_{id} \) acting in the opposite direction. b) Structure and dynamics of a complex plasma containing particles of two different sizes (3.4µm and 6.8µm diameter) under microgravity conditions. The trajectories of the microparticles are shown colour coded from red at the beginning to blue at the end of the trajectory (over the rainbow colours) for an exposure time of 3 sec.
4. Plasma crystal formation: Along the main chamber axis the complex plasma can crystallise and form the so-called plasma crystals (see Fig. 14 b) and 15) [16]. A plasma crystal is an ordered and stable system of charged microspheres interacting via their screened Coulomb potentials, which can occur in different structures (fcc, hcp, bcc etc.) depending on the energetic status of the system (s. Fig. 16). The crystalline structure can be different in local areas, even the transition to the fluid phase occurs.

5. Vortices: In the boundary regions the trajectories of the particles show a vortex like motion. This is caused by strong electric fields which occur at the boundaries of the electrodes to the ground shield and of the electrodes to the dispensers. They disturb the homogeneity of the electric field and therefore cause a change in the (purely radially acting) forces $F_Q$ and $F_d$. In reaction to these local electric potential maxima the particle cloud starts a convective-like motion. For future experiments (see PK-3 Plus below) the plasma chamber and electrode assembly have been changed so that a much better symmetry and homogeneity of the electric field between the electrodes is achieved and therefore the vortex motion does not occur. Nevertheless, it provides interesting insights into the kinetics of shear flows – some of the phenomena observed will therefore become subject of special investigations in the future.

Beside the above described features of complex plasmas under microgravity conditions we observed interesting new phenomena not foreseen. Just to mention two of those, this is the decharging [35] of the microparticles after the plasma source was switched off and the agglomeration of microparticles after injection into a neutral gas [30].

In the "decharging experiment" the rest charge on the microparticles was measured after the plasma was switched off (s. Fig. 17). To measure this, the particles were exposed to a sinusoidally varying electric field (at low frequencies around 0.5 Hz) and – if they remain charged – one can simply determine the charge from the oscillation amplitude shown in Fig. 18.
Fig. 17: Decharging experiment on the ISS. In a) a single image of the complex plasma is shown. Marked are the central axis (dashed-dotted line) and the periphery. The microparticles are exited by a low frequency modulation on the upper and the lower electrode. After the plasma is switched off (b), the microparticles are no longer strongly coupled, but still they react on the low-frequency electrical signal, showing the rest charge on the particles which is kept for a long time. Beside the electrical signal a temperature gradient of about 1K produces a thermophoretic force pushing the particles upwards towards the upper electrode. In c) the particle distribution is shown at a later time.

Fig. 18. a) shows the particle motion upwards separately for particles in the periphery and the centre. The time when the plasma is switched off is shown in the graph. Subtracting the thermophoretic from the oscillatory motion we receive the oscillation amplitude in b).

On Earth such a measurement is practically impossible – the particles fall down too quickly and charge measurements are consequently very difficult to perform. This decharging experiment showed that the particles are not totally discharged after the plasma is turned off. They freeze a charge after the plasma electrons and ions disappeared. This is a new insight of complex plasma physics and might be important for many other processes.

The second interesting experiment was performed on the ISS – accidentally. In this experiment microparticles were injected into the neutral gas (the plasma was accidentally not switched on). The big surprise was, that there was very rapid coagulation – at a rate about 100 000 times in excess of the expected geometrical coagulation rate. In fact, coagulation was so rapid, that it showed all the signs of being a gelation phase transition – an unknown phenomenon up to this point. Again, microgravity made the discovery and detection possible – the final (gel) particle was of mm-size (and contained about 10% of the total injected particles) and would not have remained with the smaller particles on Earth. Gravity would have made this serendipitous discovery impossible.

However, now that we know that conditions can be created to produce this gelation transition, we can, of course, look for possible applications. The premise is, that a new basic process should be put to some use. Fortunately (or unfortunately) there are more than enough problems, for instance, in planet formation it is possible that this process might have played a decisive role, and it would be a significant process for removal of toxic and radioactive nanoparticles.
SUMMARY AND OUTLOOK

The research field “complex plasmas” has seen a tremendous growth in the last 10 years. This is due to the fact that for the first time kinetic (individual particles) studies are possible for a number of critical processes, such as homogenous nucleation, crystal growth, fluid flow self-organisation, physics at critical points, study of nano-fluidics and nano-crystal dynamics etc. and, of course, the fundamental studies of a new state of (soft) matter – the granular plasma state, which shows a plethora of unexpected properties and behaviours. Research is possible on the ground, and for careful studies of universal processes that require stress-free and homogenous environments – in space. Hence it is an essential part of the research strategy, to be able to conduct research continuously under microgravity conditions. A comprehensive programme has been developed (PKE-Nefedov, PK-3 Plus, PK-4 and IMPF/IMPACT) that will serve the growing community worldwide until ~ 2020. It is important for this new and interdisciplinary research field that this programme should be carried out – the scientific and technological yield will be tremendous.

REFERENCES

[26] M. Rubin-Zuzic et al. to be published