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Plasma diagnostics for complex plasmas under microgravity and on ground

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Abstract. Complex plasmas are low-temperature plasmas containing micron-sized particles (microparticles) such as dust grains. These are present in astrophysical systems (comets, molecular clouds, et al.) and in technological applications (microchip production by plasma etching, deposition of solar cells, et al.). Complex plasmas are also of interest in basic science because these are often used as models for many other strongly coupled many-body systems in solid state, fluid, or plasma physics. Since gravity has a strong influence on the microparticle component, experiments under microgravity (parabolic flights, sounding rockets, International Space Station (ISS)) are performed. Interaction between microparticles depends on plasma parameters such as ion density or ion temperature. Also, the presence of microparticles may change the properties of background plasma. Therefore, the background plasma needs to be characterized to provide adequate interpretation of the microgravity experiments. For this purpose a dedicated high-speed diagnostic system has been set up.

1. Introduction

Complex or dusty plasmas are ionized gases containing micron-sized particles of solid matter, e.g. dust grains (Fortov et al. 2005; Morfill and Ivlev 2009). Hence, they belong to the class of soft matter in which mesoscopic components are embedded in a dispersive medium such as colloids, aerosols, or emulsions. In contrast to atoms, the mesoscopic components are strongly affected by gravity. Therefore, an unperturbed investigation of such systems is only possible under microgravity conditions where sedimentation and gravity-driven convection are negligible.

It should be noted that there are alternatives for compensating gravity by applying, for example, a temperature gradient enabling the levitation of microparticles by thermophoresis (Rothermel et al. 2002). This method has, however, the disadvantage that only microparticles of one size can be suspended at a given temperature gradient and convection in the background gas caused by the temperature gradient can disturb microparticles. Problems of a similar nature do not allow for the simultaneous levitation of microparticles of different materials in case of a magnetic trap.

The possibility of a strong coupling of microparticles in complex plasmas was predicted by Ikezi (1986), who estimated the Coulomb coupling parameter,

$$\Gamma = \frac{Q^2}{d\,k_\mathrm{B}T} \tag{1.1}$$

for microparticles immersed in a typical laboratory, low-temperature plasma. Here Q is the particle charge, d is the interparticle distance (typically few hundred μm), and $k_\mathrm{B}T$ is the thermal energy of microparticles in the plasma. Ikezi (1986) showed that in complex plasmas the coupling between microparticles can become so strong that they may form a Coulomb crystal (Fig. 1). This was experimentally proved later (Thomas et al. 1994).

The charge Q is accumulated on the surface of a microparticle due to equilibration of electron and ion fluxes. Due to higher mobility of electrons, the charge is always negative unless other charging mechanisms, e.g. photo-, thermionic, or secondary emission, start to play a role. Hence, the surface of microparticles may represent a sink as well as a source of plasma species (Mitic et al. 2009), therefore leading sometimes to a significant shift of ionization balance in the discharge. This complex process has not been completely understood so far.

In addition, the background plasma is coupled to a microparticle subsystem via quasineutrality condition. Assuming only singly charged ions in the plasma, the latter can be expressed as follows:

$$n_\mathrm{e} - n_\mathrm{i} + \frac{Q}{e} n_\mathrm{d} = 0, \tag{1.2}$$

where n_e, n_i, and n_d are the electron, ion, and microparticle densities, respectively.

The electrostatic potential of the interaction between microparticles can be well approximated by the screened Coulomb potential (Konopka et al. 2000; Kompaneets

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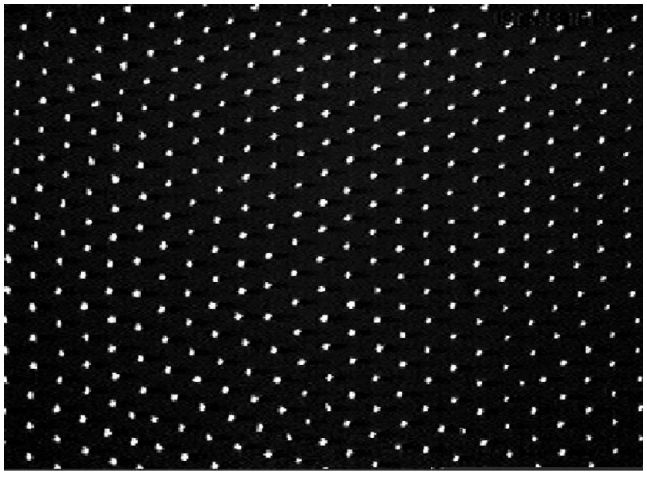


Figure 1. Top view of a plasma crystal. The white dots are the microparticles illuminated by a laser sheet and recorded by a video camera.

et. al. 2007):

$$V(r) = \frac{Q}{r}\, e^{-r/\lambda_D}. \tag{1.3}$$

Although the physics underlying the screening length λ_D in particular experimental situations is under discussion, in the simplest linear approximation for an isotropic bulk plasma it is just the Debye length:

$$\lambda_D = \left(\frac{4\pi e^2 n_e}{k_B T_e} + \frac{4\pi e^2 n_i}{k_B T_i} \right)^{-1/2} \tag{1.4}$$

with T_e and T_i being electron and ion temperatures, respectively.

Equations (1.1)–(1.4) indicate that the behavior of individual particles as well as the interaction between microparticles are in general self-consistently connected to the background plasma. Therefore, for the correct interpretation of complex plasma experiments it is desirable to have as much as possible information on the background plasma.

Due to great difference in the nature of the electron–ion background and microparticles, the diagnostic approaches to both subsystems are also quite different. Microparticles, being small, but still macroscopic objects, can be observed even with a naked eye. In most of the experiments they are illuminated by a laser and then imaged by video cameras. Digital processing of images gives information on their positions and velocities, i.e. full kinetic description of microparticle subsystem. Looking at (1.1)–(1.4), we find only one quantity, which can be reliably measured by the analysis of microparticle dynamics – kinetic temperature T. Although attempts to derive charge, screening length, and plasma parameters from the dynamics of microparticles have been done, they, however, require either special experimental conditions (like in a binary collision experiment (Konopka et al. 2000)) and therefore cannot be applied in general or are based on assumptions or models, and from this point of view are actually estimates rather than measurements (Liu et al. 2010). In other words, the dynamics of microparticles is hardly reliable in obtaining information on the background plasma. The correct procedure is opposite: The behavior of microparticles should be interpreted based on the independently measured plasma parameters.

2. Microgravity experiments

Complex plasmas have a long tradition of microgravity research. Special environmental conditions of a space station and generally of microgravity put serious restrictions on dimensions and weight of the setup, as well as on the use of particular materials or components. Therefore, a researcher willing to do a microgravity experiment is always facing several trade-offs in choosing the final configuration of the experimental setup. From the very beginning of complex plasma research in laboratory as well as in space the main experimental emphasis was on observing the behavior of microparticles. Therefore, the direct diagnostics of background plasmas under microgravity was always sacrificed. However, there is an ongoing step-by-step improvement from one generation of experiments to another (Fig. 2).

First, experiments in long-term microgravity, known as PK-1 (Fortov et al. 1998) and PK-2 (Nefedov et al. 2002), were performed on board of the MIR space station. Being extremely simple, they did not have any diagnostic means for the plasma. Interestingly, the neglect of 'plasma' issues at that time was so strong that, e.g. in PK-1 (Fortov et al. 1998), the authors after estimating the electron density and temperature in their experimental cell did all possible calculations for microparticle charges, but did not make a simple comparison of the Debye length with the dimensions of the cell. However, this comparison, if made, doubts the treatment of the system as a sort of a plasma. PK-2 made use of a classical neon DC discharge in a glass tube. Although this discharge is in principle well known and characterized, the absence of gas flow through the discharge volume led to a strong and uncontrollable contamination of the gas. Interpretation of the experiments was therefore very difficult.

In 2001, a complex plasma experiment facility PKE-Nefodov was put into operation as the first scientific experiment on the ISS (Nefedov et al. 2003). Within thirteen missions with the help of the ISS crew, in total a 65-h experiment time in the Russian segment of the ISS was used until 2005 to gain new insights in the behavior of complex plasmas. Since 2006, PK-3 Plus, also based on a radio frequency (RF) chamber but significantly improved compared to PKE-Nefedov, was launched and is being operated on board of the ISS since then (Thomas et al. 2008). Both the experiments were developed and used in a German–Russian cooperation by the Max-Planck-Institute for Extraterrestrial Physics (MPE) together with the Joint Institute for High

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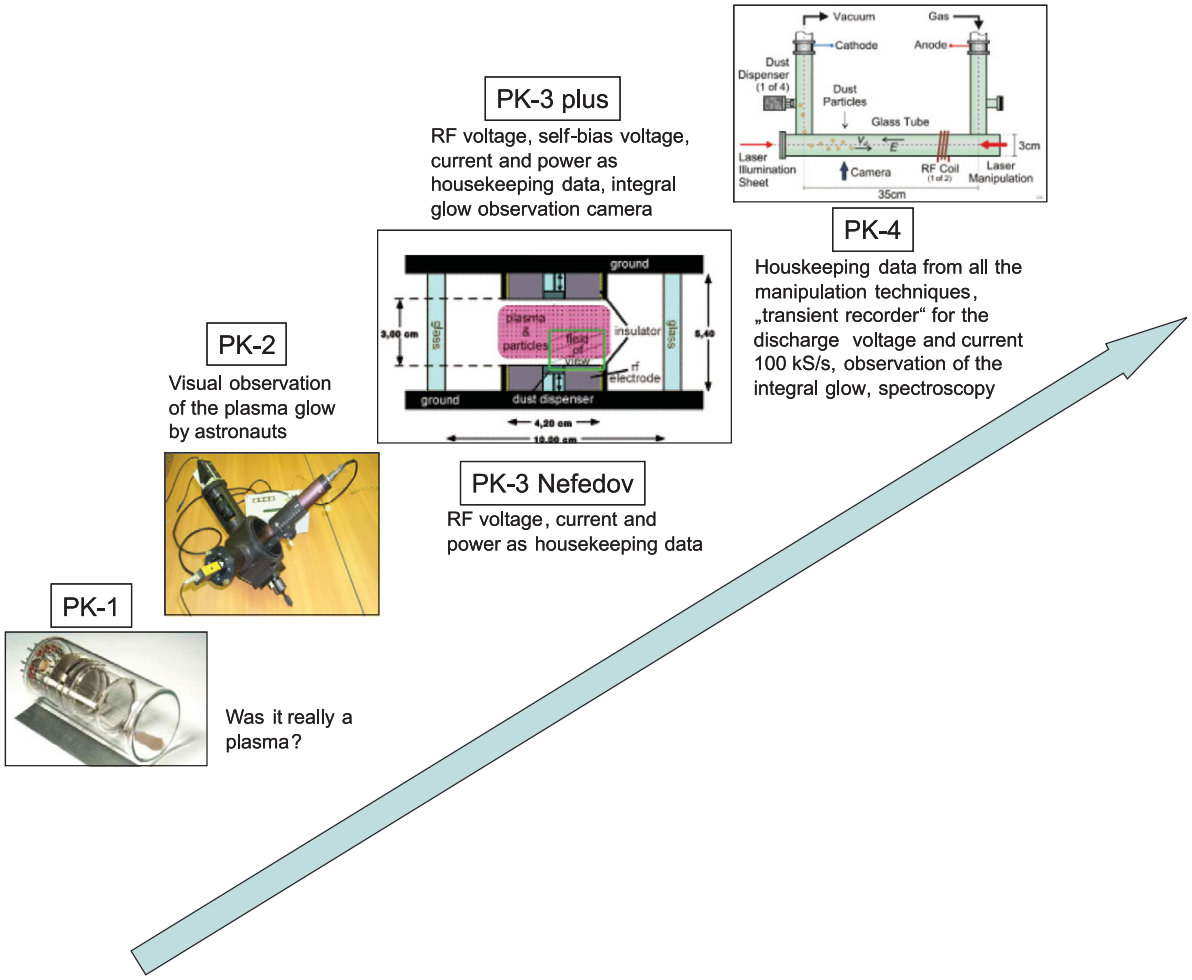


Figure 2. (Colour online) Progress of plasma diagnostics in microgravity complex plasma experiments.

Temperatures (JIHT), Moscow under the support of German Aerospace Center (DLR). These two experiments constituted a big step forward in the technique of complex plasma experiments in space. Also, plasma diagnostics was introduced in a space experiment for the first time. The external parameters of RF discharge (RF voltage and currents, forward and reflected power, DC bias, as well as the pressure) were monitored in real time. In PK-3 Plus, a camera observing the plasma glow was added.

PKE-Nefedov and PK-3 Plus have stimulated further improvement of plasma diagnostics in microgravity experiments due to the discovery of phenomena in which the microparticles and the background plasma cannot be treated independently. An example of such a phenomenon is the so-called 'void' (Samsonov and Goree 1999a; Nefedov et al. 2003), an area of the discharge, which is free of microparticles. On the images, showing only the reflected light from microparticles, it appears as a dark spot in the center of the discharge with a very sharp boundary. It is known that the bulk plasma of an RF discharge does not contain any strong gradients. Such a gradient, however, appears in the presence of microparticles. Another important phenomenon of this kind is the so-called heart-beat instability (Mikikian et al. 2003), which represents a spontaneously excited low-frequency oscillation of the microparticle cloud associated also with dramatic changes in the discharge glow.

The next generation facility for the ISS, PK-4 (Thoma et al. 2007), is presently in the construction phase within a European–Russian collaboration supported by European Space Agency (ESA) and DLR. Its launch is scheduled for 2013. Like PK-2, PK-4 is based on a classical DC discharge in a glass tube. The power supply, however, allows for a much larger degree of flexibility. It provides the opportunity of a low-frequency modulation of discharge current and even a periodic switching of discharge polarity. An additional electrode inside the discharge tube together with external RF coils allow for all kinds of manipulations of microparticles, e.g. trapping or acceleration. PK-4 is the first microgravity complex plasma experiment in which an extensive diagnostics of the plasma is performed on ground. Distributions of electron densities, temperatures, and electric fields along and across the discharge tube are measured with a Langmuir probe (Fortov et al. 2005). For a space setup, along with the housekeeping data from the discharge and all manipulation techniques, it is planned to implement tools for spectroscopic

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measurements. A miniature spectrometer will be included in the setup and filters for selected spectral lines in front of the glow observation camera will be used (Samsonov and Goree 1999b). Supported by a kinetic model of discharge (Zobnin 2009), this will allow to get information on electron density and temperature also under microgravity conditions.

3. Requirements on diagnostics of complex plasmas

The simplest situation from the point of view of relating the measured plasma parameters to the dynamics of microparticles is the one in which a small amount of microparticles is injected into a large volume of plasma. Then the influence of microparticles on the plasma can be neglected and the plasma parameters, measured, e.g. by a Langmuir probe in the absence of microparticles, can be safely used. The problem in many ground-based cases (Konopka et al. 2000; Pustylnik et al. 2006) is that the microparticles levitate in sheath regions where any measurements are hardly possible. Theories of the plasma sheath may help in such cases. Anyway, even measurements of the plasma parameters in the bulk may give at least qualitative understanding of the behavior of microparticles in the sheath. In microgravity the microparticles are located in the bulk areas of the discharge. Therefore, the approach that is going to be used in the PK-4 experiment will provide adequate description of the behavior of a small amount of microparticles.

Recently, however, it has been shown that even a small amount of microparticles may produce a measurable influence on the plasma background conditions. Laser-absorption measurements of metastable atoms showed a significant drop in metastable density even inside a narrow rarefied cloud of microparticles (Do et al. 2008). However, no indication of the influence on the ionization balance has been reported in this case.

In the situation when the influence of microparticles on the plasma cannot be neglected, much deeper insight into the plasma physics is required. A complex plasma is a multi-component and therefore multi-timescale system. The plasma frequency can vary many orders of magnitude for different components. In the case of a plasma with a density of $10^8\,\mathrm{cm}^{-3}$, it is of the order 10^8 Hz for electrons and 10^6 Hz for argon ions. Dust modes have typical frequencies of 10^0–10^1 Hz. Additional timescales originate, for instance, from the charging of microparticles. Typical frequencies of the microparticle charge relaxation are 10^4–10^5 Hz. Although the microparticle component seems to be pretty well detached from others by 3–4 orders of magnitude in timescale, there are nevertheless several kinds of phenomena demonstrating the coupling of microparticles to ion and electron components. For example, in the so-called delayed charging effect (Nunomura et al. 1999; Pustylnik et al. 2006), the finite charging time of a micropatricle leads either to an instability or to an additional damping force. Another recently discovered phenomenon of this kind is the rotation of microparticle clouds under the action of a rotating electric field (Nosenko et al. 2009). Surprisingly, the resonance of the rotation of microparticles occurs due to interplay between the ion drag and electrostatic force at the frequency of the rotating electric field of the order of 10^4 Hz.

Moreover, recently phenomena in which the microparticles are also coupled with the electron component have been found. One of them is the response of levitating microparticles to high-voltage pulses of nanosecond duration (Pustylnik et al. 2009). It has been shown that in spite of the short duration (20 ns) of disturbance, the microparticles exhibit significant dynamics in response to repetitive pulses. The relaxation of complex plasma after the pulse is of course much longer than 20 ns, but the important point is that the initial disturbance is so short that only the electrons can respond to it. Therefore, the energy pumped specifically into the electron subsystem may go down through orders of magnitude in timescales and be partly transferred to the heavy microparticles as well.

An example of the opposite influence, i.e. when the static microparticles affect the steady-state electron kinetics, has also been observed. It was reported (Hübner and Melzer 2009) that the evolution of radiation of the discharge if resolved over the RF period is influenced by the presence of microparticles. The intensity can either increase or decrease with respect to the microparticle-free discharge depending on the size of immersed microparticles. The radiation of the plasma is the result of the electron impact excitation of neutral atoms and is therefore a direct indication of electron kinetics. The observed variation of the intensity has been attributed to the interplay of electron loss due to electron capture by microparticles and the increase of electron average energy to compensate the loss.

The above examples clearly demonstrate that in order to obtain a deep insight into the microparticle–plasma interaction, the plasma has to be monitored at all timescales from steady state to that of electron kinetics. Also, since very local influences have been reported, it is desirable that diagnostics should be space-resolved.

Another issue concerns the invasiveness of diagnostics. Although the Langmuir probe is regarded as the most reliable and direct measuring instrument of plasma diagnostics, the presence of microparticles in complex plasmas makes its use practically impossible. Attempts to use special probe tip biasing and cleaning techniques (Klindworth et al. 2007) do not remove the issue of disturbance produced in microparticle clouds. The probe, being an invasive instrument, always produces a disturbance in the plasma. It is, however, not clear whether these disturbances are similar in dust-free and dusty regions. Complex plasmas therefore should be diagnosed preferably by non-invasive means.

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Figure 3. (Colour online) Electronics rack (left) and optics rack (right).

4. High-speed plasma diagnostic system

In order to comply with the above requirements, MPE in collaboration with the industrial partner Berner & Mattner Systemtechnik GmbH (B&M) built a high-speed plasma diagnostic system (PDS). This project was financially supported from general funds of the Max-Planck Society. The emphases of the system are spectroscopic measurements. Therefore, the main elements of the system are the imaging spectrometer iHR550 from Horiba Scientific and an ICCD camera iStar 740 from Andor. The spectrometer has a focal distance of 550 mm and has two outputs. On one of the outputs the camera is installed, whereas another output is equipped with a photomultiplier (PMT). While the camera is to be used for imaging experiments, the advantage of the PMT is its ability to work in real time, i.e. to detect unrepeatable events (e.g. fluctuations in the incoming light). The minimum gate width of the video camera is 2 ns and the bandwidth of the PMT electronics is 150 MHz. The camera can be detached from the spectrometer to perform usual two-dimensional imaging as well.

The PDS is accommodated in two racks (Fig. 3): one for optical components, and another for electronics, including a computer for control and data acquisition. A positioning system allows for the precise motion of optical axis of the system in vertical and horizontal directions. The spectrometer is placed on a pneumatic plate, which self-levels the spectrometer plane and isolates optical elements from vibrations.

In addition, the PDS has a data acquisition system from National Instruments with several digitizing cards (maximum bandwidth available 300 MHz) and function generators. Therefore, it can be used not only for diagnostics but also for controlling the experiment.

Although the PDS cannot be used under microgravity conditions (parabolic flights, ISS) due to its size and mass, it will be very helpful for the analysis of microgravity experiments with complex plasmas. For example, in the case of PK-4, the plasma diagnostics from the plasma glow observation and the miniature spectrometer on the ISS will be verified, improved, and supplemented by the use of the PDS for the science reference model of PK-4 on ground.

Microgravity-related plasmas and, more general, complex plasmas are only one of the possible applications of the system. The whole system is transportable and can be brought to any laboratory within MPE. There is a great demand of diagnostics of plasmas for biomedical applications, e.g. in plasma devices for disinfections and wound healing (Kong et al. 2009), which are currently developed at the MPE and applied in hospital tests. The system would also allow to benchmark the simulation of plasmas on the level of electron kinetics, which is a very important and often missing step in the development of simulation codes.

The system was delivered to MPE in June 2010 and final tests and calibrations have been completed. Results of current measurements of various low-temperature plasmas used for complex plasma research and plasma medicine will be reported elsewhere.

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