[PHYSICS IN SPACE]

THE PLASMA STATE OF SOFT MATTER

DOI 10.1051/EPN:2008304

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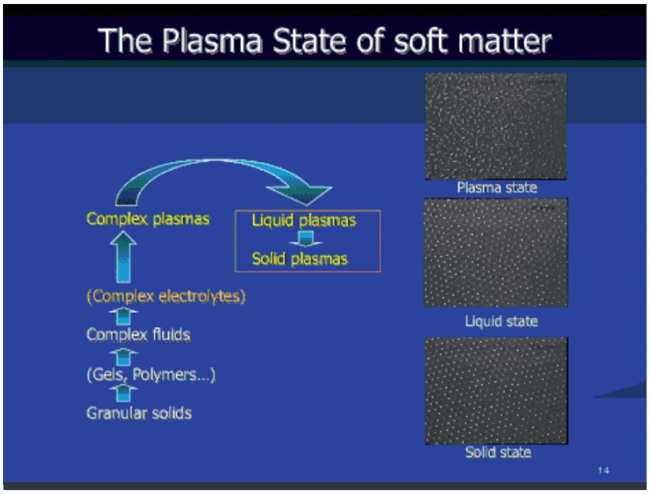
Practically all plasmas contain "dust". This is true for a number of astrophysical plasmas, *e.g.* the solar wind contains dust from the zodiacal light cloud, magnetospheric plasmas may contain dust from planetary rings, interstellar clouds are weakly ionised plasmas containing about 1% of their total mass in the form of tiny dust particles and last, but not least, the planets – our Earth – would not exist if the protoplanetary nebula, out of which we were all formed, did not contain dust. Dust is also found – often as an unwanted by-product – in many industrial plasma applications, notably in plasma vapour deposition (productions of flat screens and panels) and in microprocessor and chip production. In these industrial processes the desire is to eliminate the "dust contamination".

For these and many other reasons it is not surprising that research into dusty plasmas has become the second most important plasma research topic next to fusion. Whilst the original motivation was environmental (*e.g.* understanding the processes that occur in thunderclouds), astrophysical (with the dominant topic the formation of our solar system) and technological (understanding the plasma chemistry, aerosol formation, particle growth and transport) a discovery made in 1994 added a completely unexpected dimension to "dusty plasma research". This was the discovery of spontaneous self-organisation of dusty plasmas (or complex plasmas, as these systems are now called) into strongly coupled crystalline states. [ref 1-3].



▲ **FIG. 1: Schematic illustration of the different states of soft matter. The inserts show three examples of complex plasmas in the "gaseous (plasma)", "liquid" and "crystalline" states. Each white spot is a (supramolecular) microparticle illuminated by laser light and recorded with a CCD camera. In the liquid state the structural disorder is seen and the somewhat higher mobility of the particles. In the disordered (or gaseous) state, the particles move much faster leaving tracks during a single exposure image (from [5]).**

Imagine the most disordered state of matter – plasmas – becoming the most ordered state. Crystals!

Not surprisingly, this discovery led to a huge number of publications aimed at characterising and understanding this new form of matter.

Why the name "complex plasmas"? This name was chosen in analogy to the so-called "complex-fluids", which consist of colloidal particles immersed in a fluid-system which are very important industrially from emulsions, photonics to novel composite materials, and which in addition have been widely used to study basic processes in crystal physics and phase transitions – in particular melting (observed at the individual particle level).

Now, complex fluids are part of the chain which classifies the states of "soft matter" – a name coined by the late Nobel Prize winner Pierre Gilles des Gennes (1991). The definition of what constitutes "soft matter" all but appeared to rule out a plasma state:

Soft matter are *"supramolecular substances which exhibit special properties such as macroscopic softness or elasticity, which have an internal equilibrium structure that is sensitive to external forces, which process excited metastable states and where the relevant physics is far above the quantum level"*.

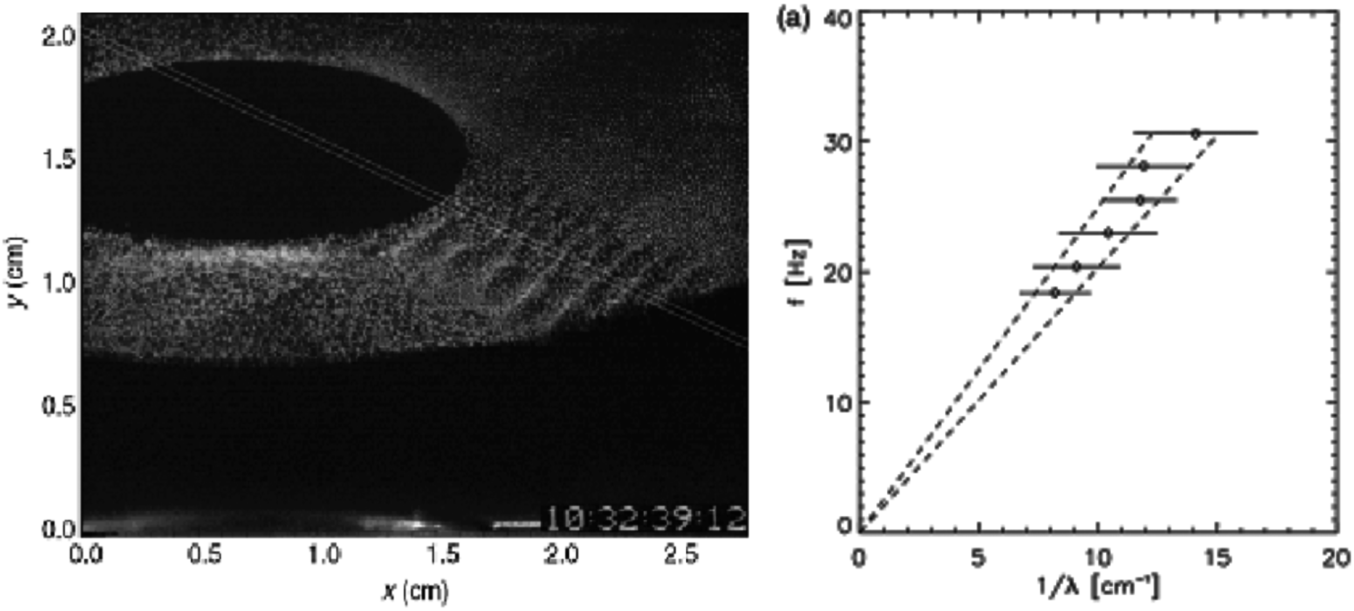
Soft matter comes in a variety of forms, from granular solids, gels, foams, emulsions to colloids (complex fluids). It turns out that, rather surprisingly, complex plasmas also satisfy all these requirements [4] and hence the discovery of plasma crystals in 1994 also marked the discovery of the "plasma state of soft matter". Figure 1 shows the hierarchy of soft matter states – as they appear now.

But what exactly are complex plasmas and why can they become crystalline?

Liquid and crystalline plasmas are supramolecular. This means they consist of atomic (or molecular) components – electrons and ions – as well as microscopic particles (containing 10^{10} to 10^{14} atomic mass units). In usual experiment conditions the microparticles are charged negatively (the same as the electrons), the ions are charged positively and each system is overall charge-neutral (as is usual for a plasma). The charge on the microparticle is large – several thousand electron charges. Such a large charge introduced locally in an electron-ion plasma naturally leads to a spatial rearrangement. Electrons are pushed away, ions are attracted. Overall this results in two things:

First, ions and electrons are captured and absorbed by the microparticle leading to a mean charge which, however, fluctuates statistically due to the impacts.

Second, ions and electrons form a cloud around the microparticle, which screens the charge of the "intruder" over a



▲ **FIG. 2: Wave motion in complex plasma in microgravity. Left: within a three-dimensional dust cloud a thin layer is illuminated by a 150 nm thick laser sheath from the side. A channel of externally excited dust acoustic waves extends from the centre towards the lower right. Right: the dispersion diagram, *i.e.*, the experimentally obtained wavelengths plotted against the excitement frequencies (from [6]).**

characteristic distance (called the Debye length, λ_D named after the famous physicist Peter Debye).

Consequently, the force between such microparticles is electric and it has a limited range of typically a few such Debye lengths. Therefore, if the particles are too far apart, they will not notice one another – the system is said to be "weakly interacting". This is the usual case encountered in nature – *e.g.* in the interstellar medium, in protostellar clouds, in the Zodiacal light cloud, in planetary rings, lightning clouds etc. However, if the particles are close enough, then their motion influences that of their neighbours directly, they become strongly interacting. This is illustrated in the inserts of Fig. 1, where strongly interacting fluid and even crystalline complex plasma states are depicted.

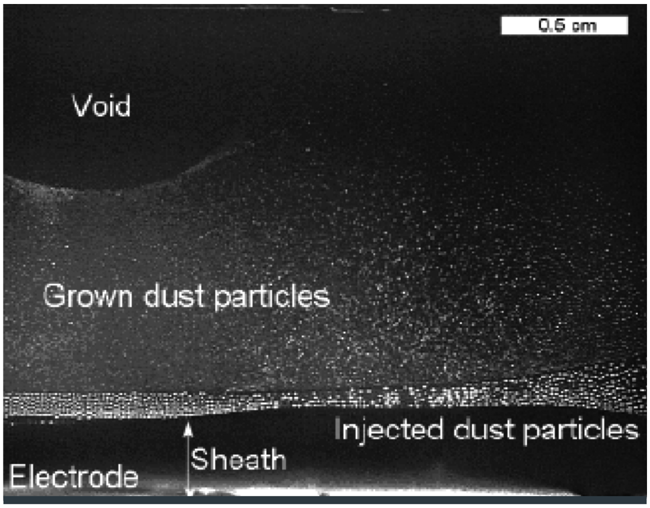
Complex plasmas are fascinating systems for studying generic properties of self-organisation in matter. They are optically thin (this means they can be visualised in three dimensions to typically 1000 lattice planes), the particles can be individually resolved and the large mass of the microparticles (many billion times more than atoms) implies that all relevant time scales (*e.g.* for lattice vibrations, wave propagation etc.) are stretched and are of the order 10's of msec rather than fractions of a microsecond as in natural atomic or molecular systems.

The large mass of the microparticles implies, however, that gravity provides an important constraint for precision measurements. Hence it is natural to propose experiments in Space under microgravity conditions. For the remainder of this paper, we will briefly summarise three experiments performed with our Space Laboratories "Plasma Kristall" (out of a total of about 50 discoveries published to date).

Wave analysis and dispersion relation

Plasmas can support a large variety of wave modes that do not exist in solid, gaseous, or liquid matter. The basic reason is that a plasma contains a mix of particles with different properties such as mass and charge and that those particles can play fundamentally different roles in the wave motion. Also, interaction at a distance via electric and magnetic fields is added to the close collisions of a purely neutral species. In classic plasma physics investigation of the growth, propagation, and damping of waves is therefore an important tool for studying the basic interaction mechanisms through their macroscopic properties.

All this is still true in complex plasmas, but here also the kinetic level of the wave motion can be studied by direct observation of the particle motion. By adding microparticles, new wave modes are added and existing plasma modes are modified. One of the basic new modes are dust acoustic waves, in which the dust grains themselves move and the restoring forces are electric. Although numerous experiments on dust acoustic waves have been made since the mid-90's, problems with experiments in gravity are the occurrence of self-excited waves, and that such experiments are inherently anisotropic due to the electric field necessary to levitate the grains.



▲ **FIG. 3:** Cross sectional image of the particle distribution obtained in the PKE plasma laboratory on the ISS. The "void" (a particle-free zone) is at the centre, the image shows approximately one quadrant. Careful analysis shows two generations of grown particles, the younger (smaller) "fog" located around the void, the older (larger) population further out (from [7]).

In the "Plasma Kristall Experiment" (PKE), on the International Space Station, three dimensional, unmagnetized, isotropic, complex plasmas can be studed at the kinetic level. Figure 2 (left) shows a snapshot from the overview camera of the PKE experiment, in an investigation of dust acoustic waves. This is the first study of dust acoustic waves in the regime of low-amplitude oscillations where comparisons with linear theory can be made. The thin white lines define the strip within which the wave data is taken. The waves were excited by applying an ac electric modulation of variable frequency to the radio frequency electrodes that sustain the plasma. The excitation amplitude was varied with frequency to ensure a sufficiently linear regime of the dust density perturbations. In the right panel the observed wave dispersion is compared with a multispecies dust acoustic wave theory (dashed lines).

Particle growth under microgravity conditions

In plasma reactors usually one observes the formation of fine dust particles. The processes are complicated, they depend on the non-equilibrium plasma-gas chemistry for (initially) cluster formation with subsequent growth due to attachment and coagulation. In principle one would imagine that the gas-phase chemistry and hence the whole nucleation/growth process should not be influenced by gravity in a serious way – however, our experiments carried out in the ANDROMEDA mission on board the ISS showed that gravity does indeed play a role – even if the details are not yet understood. It probably has to do with the overall inhomogeneity of the plasma (sheath, pre-sheath, bulk) and the gravity-induced differences where even small clusters spend most of their time. In this sense results from space experiments could have a profound impact on reactor designs on Earth, *e.g.* for the nucleation, growth, dynamics and transport of dust particles in low pressure cold plasmas for different chemistries (SiH_4, CH_4, CH_4-N_2 and polymer sputtering). In the framework of the PKE program, experiments have been conducted on the formation of dense carbon dust particles, the formation of the central void region and the different self-excited instabilities related to the dust growth. It was shown that the dust particles keep a small residual charge, which can be positive or negative. The distribution of this residual charge was measured. These results are of prime importance for the dust particle transport in the afterglow and thus open the door for many applications where dust particle manipulation is needed.

Particular attention was paid to the dust particle growth mechanisms. The results obtained on the ISS show that the process is a stepwise one, with several generations of grown particles forming, each with their own characteristic size (see Fig. 3).

Discovery of electrorheological plasmas

Electrorheology is a process, whereby an external electric field modifies the structure (rheology) of a given substance in such a way, that the properties are changed (*e.g.* viscosity, elasticity). This effect is well-known in colloids and has significant application potential in photonics, hydraulics and suspensions. During the ASTROLAB mission experiments were performed to test whether electrorheology also occurs in complex plasmas (as it does in complex fluids) [8]. The results are shown in a video on **www.mpe.mpg.de/pke/electrorheology_movie** It is clear that such external electrostatic manipulation makes significant changes to the rheology of (liquid state) plasmas – and correspondingly leads to associated changes in the bulk properties. This discovery will be used for future generic research into the properties of soft matter (or condensed matter generally) and for possible application potential.

In summary, microgravity research of complex plasmas (the plasma state of soft matter) has been enormously successful, with major discoveries that are novel and complementary to research carried out on Earth. ■

Acknowledgements

We should like to thank DLR, BMBF, BMWi, ESA, Roskosmos, RKK-Energia, TSUP, Kayser-Threde GmbH, CNRS for supporting the research described.

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