Plasma Research on the ISS – Fundamental New Discoveries and Benefits on Earth

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Abstract

Plasma research on the International Space Station – why would one want to do that? The environment is difficult, the travel to the plasma laboratories is laborious, the experiments must be carried out by trained specialists – the cosmonauts, with voice and video contact to the scientists on Earth delayed by huge distances, data rates are low, reaction times are slow etc… However, if the experiments require microgravity, if the physics is not well established and requires real time human intervention, if the research field is new and has a research scope requiring hundreds of different set-ups – then all the difficulties are an incentive rather than a hindrance towards achieving the desired goals. This is the case in the special plasma physics regime studied on the ISS since the beginning of regular operation. In this report, I will touch on different areas of fundamental physics (starting with plasma crystals, liquid plasmas including "atomistic" studies of the melting transition, shear flows, shock waves, plasma rheology, super-coagulation and self-organization) and then follow this with spin-off advances made on Earth (medicine, hygiene, agriculture and odor control). With so many different discoveries and advances, I cannot, of course, delve deeply into the different subjects – interested readers may follow this up by looking at the cited original articles.

Introduction

Plasma Research under microgravity began seriously with the start of the first crew to the International Space station on November 2nd 2000. Before that there were some activities on parabolic flights, sounding rockets and on MIR, however, these were small tests to learn and acquire skills for a planned major effort with a versatile laboratory, operated by humans in Space – the Cosmonauts. This laboratory, named simply PKE (for "Plasma Kristall Experiment"), was an amazing cooperation between Germany and Russia, involving the Max-Planck Society, DLR and Kayser-Threde GmbH in Germany and the Russian Academy, ROSCOSMOS and Energia Corporation in Russia. Little did we know at that early time that the cooperation would continue over two decades – and that it would become a most successful research effort in fundamental physics, with technology spin-offs on Earth in medicine, hygiene, agriculture, and odor control – to name only a few applications.

At this point I must first give my sincerest thanks to my friend and colleague, Professor Vladimir Fortov, who unfortunately died on 29th of November 2020 as a result of a Corona infection. Without Vladimir none of what I report here would have happened – and it is sad that he is not here to witness the benefits for humans that have been developed as a direct consequence of what was learnt in Space. Second, I must thank the Cosmonauts, who trained on Earth with copies of the new Plasma Laboratories (first PKE, followed by PK3-Plus and then PK4) and then performed complex experiments under weightlessness in Space. Again, without these fine experimenters none of what I report here would have happened.

"Plasma" – the fourth state of matter (the other states are "solids", "liquids" and "gases") – is recognized as the most disordered state. A plasma consists of electrons and ions, overall charge neutral. The particles interact via weak electrostatic forces, hence there can be no strong coupling. This was regarded as common knowledge. Nevertheless, many famous physicists had been intrigued by the concept of strongly coupled plasmas, possibly even leading to "plasma crystals" (Landau, Wigner, Wilson, deGennes, Kosterlitz, Thouless…) – and some ended up with the Nobel Prize for some other exceptional discoveries. It became a major surprise in the physics community, therefore, when we published our first results that "plasma crystals" could actually be produced and self-organize in the laboratory (Thomas, Morfill et al. 1994).

The way to produce "plasma crystals" is in principle quite easy – once one knows how… By increasing the charge on the plasma particles to 1.000 - 10.000 elementary charges, the interaction strength is increased by 1 – 100 million, which implies strong electrostatic coupling. How to introduce highly charged plasma particles? By loading micro-particles into the plasma, one can achieve that. The microparticles are automatically charged up to these high values – and they become the dominant charge carriers in these "colloidal plasmas". These colloidal plasmas consist of negatively charged microparticles and positive ions, with a small component of electrons present and some neutral particles. Since the system is dissipative (i.e. electrons and ions recombine on the microparticles) energy must be constantly supplied to maintain the plasma crystal.

At this point microgravity starts being important. The microparticles (diameter a few microns) have a mass of ~ 10^9 atoms. They are heavy! That means that on Earth such a structure has to be supported against gravity – so that only very flat systems are readily produced. This is also interesting, of course, for studying the dynamics of membranes at the individual particle level in real time and space. Under microgravity, it is possible to produce 3-dimensional structures and to extend the research from surface dominated to bulk properties – a really exciting prospect, as we will see.

The microparticles can be easily visualized by illumination with a laser and microscopy. Due to the heavy mass, their motion is slowed down drastically (compared to the motion of atoms, thermal velocities at the same temperature scale as $1/\sqrt{m}$) and the background neutral particles provide practically no damping. This means that basic processes can be followed in “slow motion” and analyzed – something not possible with atoms (the motions are too fast) or with colloidal suspensions in liquids (the damping of the fluid is too strong).

In this sense, “colloidal plasmas” have opened another door for researching fundamental science topics – complementary to “colloidal fluids” and “many particle simulation studies”.

Sergei Krikalev with the plasma laboratory PKE (Plasma Kristall Experiment) just after receiving it on the ISS. Nefedov et al., New Journal of Physics, 2003

Now to some nomenclature:

In „**complex fluids**“ (a term for “colloidal fluids” coined by the Nobel Prize Winner Pierre-Gilles de Gennes) the fluid provides significant damping to the immersed colloidal particles, so that fast processes at the most relevant Debye or Einstein frequencies cannot be experimentally studied.

In “**complex plasmas**” (a term for “colloidal plasmas” introduced by G. Morfill and his colleagues in analogy to de Gennes nomenclature) the rarefied plasma provides practically no damping, so that the experimental investigation of fast kinetic processes at the single particle level is possible for the first time.

It is self-evident, that the ability to study basic physical processes at the “atomistic level” resolved in real space and time will provide research opportunities and new knowledge for many years to come – provided the opportunity exists to study 3-dimensional systems at that level in Space, as well as 2-dimensional systems on Earth.

Fundamental science studies

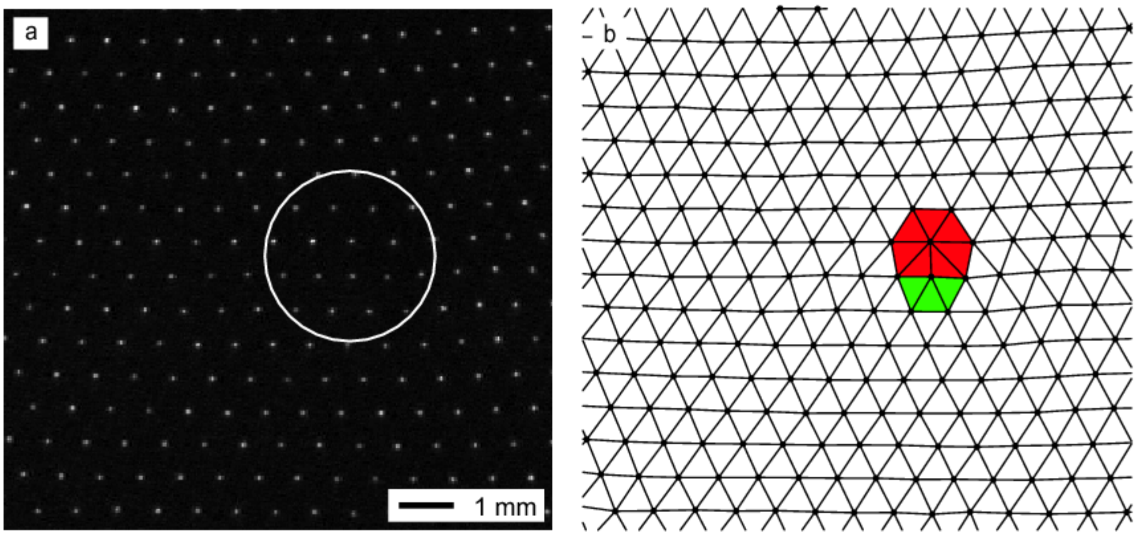
Fundamental science studies – aimed at increasing our knowledge generally about the physics of the world we live in – have opened a range of new insights and discoveries using these "colloidal or complex plasmas", e.g. plasma crystals, liquid plasmas including "atomistic" studies of the melting transition, shear flows and turbulence, shock waves, plasma rheology, critical point, super-coagulation and self-organization, to give only a few examples.

Here we briefly touch on some of these topics.

Plasma Crystals

- **First some 2-dimensional results from studies on Earth.**

These discoveries were of intrinsic interest in themselves (the ability to observe the dynamics of such systems in real time and space at the single particle level without overdamping was not possible before).



In this Fig. We show the typical crystal lattice of a monolayer plasma crystal. Also shown is a typical dislocation. What we see is the following:

- *The „ground state" of a 2D crystal is a hexagonal structure.*
- *An edge dislocation is a crystallographic defect where an extra half-line of microparticles is "inserted" into a crystal.*
- *The dislocation core is represented by an isolated pair of 5- and 7-fold defects in an otherwise hexagonal lattice.*

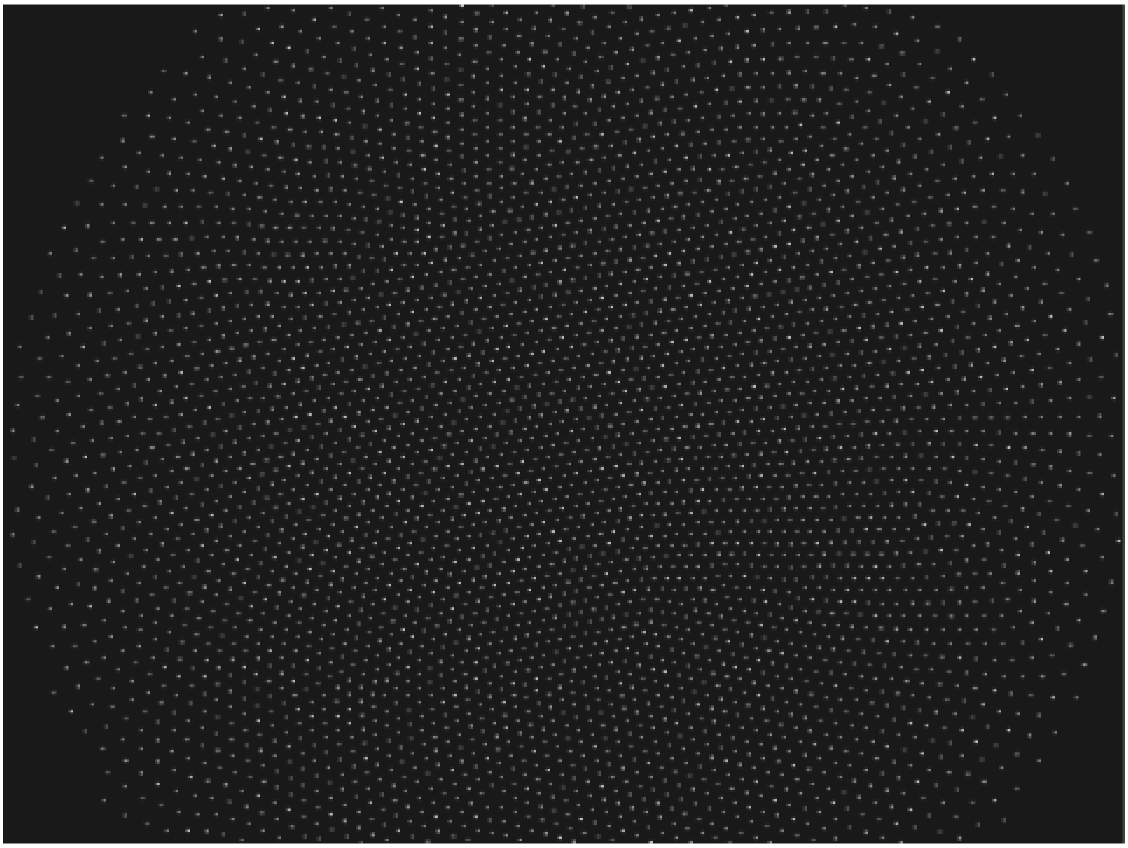
These observations are not surprising – the equilibrium structure confirms what has been observed before with complex fluids, and is theoretically supported.

Of much greater interest is the question of the speed of propagation of such crystal defects. This was a controversial subject at the time:

The common wisdom was that a gliding edge dislocation cannot surpass the sound speed of shear waves C_T, as the energy radiated by a dislocation becomes infinite at C_T.

However, Eshelby predicted a long time ago (Eshelby, Proc. R. Soc. London 1949) that an edge dislocation can glide at a particular speed of √2 C_T without any radiation at all.

To resolve this controversy, numerical simulations have been performed, but the issue remained -can this be observed experimentally at the "atomistic level"?

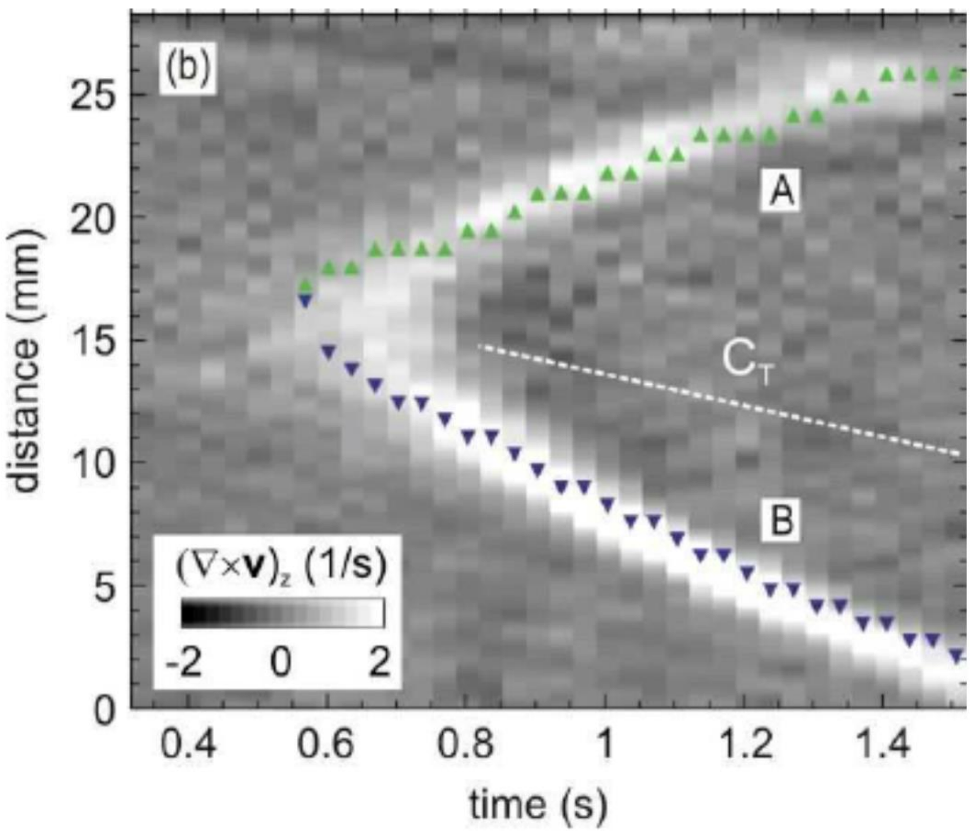


V. Nosenko, S. K. Zhdanov, and G. E. Morfill, Phys. Rev. Lett. ***99****, 025002 (2007)*

The measurements require very large two-dimensional plasma crystals as well as individual particle tracking in time. The summary of the research results is:

"Experimental results on the dislocation dynamics in a two-dimensional plasma crystal are presented. Edge dislocations were created in pairs in lattice locations where the internal shear stress exceeded a threshold and then moved apart in the glide plane at a speed higher than the sound speed of shear waves, C(T). The experimental system, a plasma crystal, allowed observation of this process at an atomistic (kinetic) level. The early stage of this process is identified as a stacking fault. At a later stage, supersonically moving dislocations generated shear-wave Mach cones."

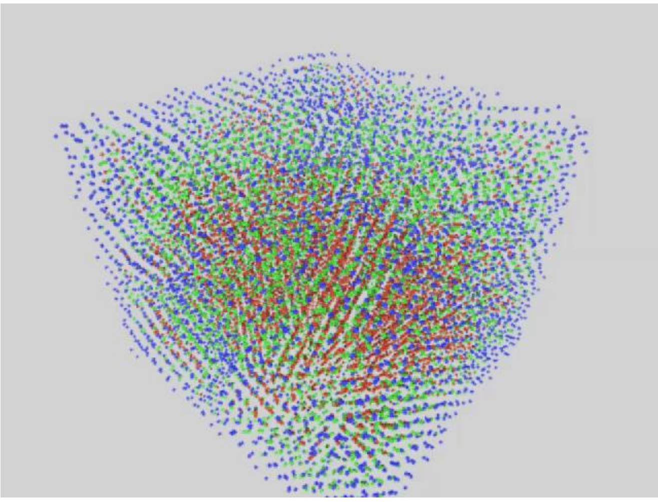
"Dislocations that move supersonically create a distinct signature, i.e., a shear-wave Mach cone, shown in the Figure below. A Mach cone is a V-shaped wake created by a moving supersonic disturbance. Mach cones obey the Mach cone angle relation sin μ = C/U, where μ is the cone's opening angle, C is the speed of sound, and U is the speed of the supersonic disturbance. From their Mach cone angles, we derive the relative speeds of dislocations A and B in the Figure, U_A = 1.7 C_T and U_B = 1.9 C_T. The local sound speed is also indicated (dashed line)."



V. Nosenko, S. K. Zhdanov, and G. E. Morfill, Phys. Rev. Lett. ***99****, 025002 (2007)*

- **Next some 3-dimensional results from Space:**

The figure below shows 3-dimensional plasma crystal as measured in Space under microgravity. A laser sheet was stepped through the cloud of particles and positions were recorded with a microscope. The crystal structure contains more than 15.000 particles.



P. Huber – colour coded real complex plasma measurements, taken with PK-3Plus in 2007

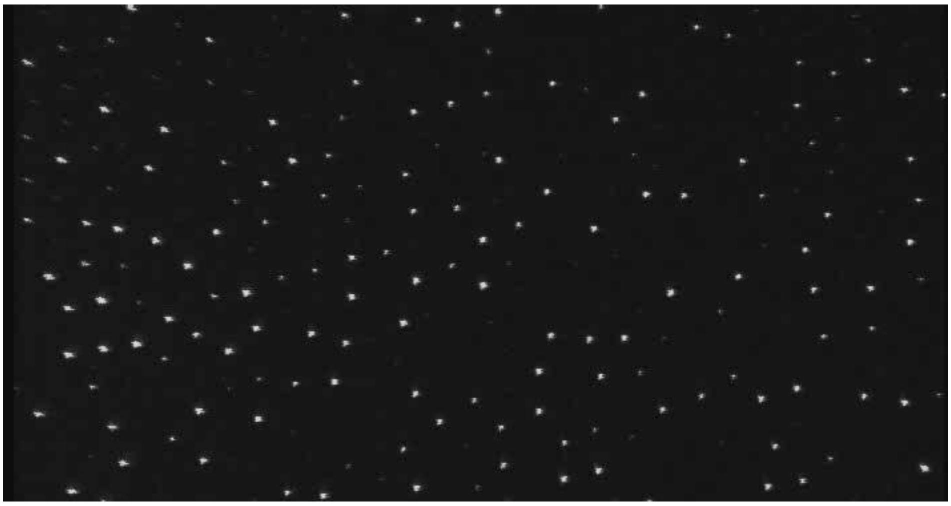
Color coding: Red points FCC (face Centered Cubic)
Green points HCP (Hexagonal Close Packed)
Blue points Fluid – no structure

The interesting point with this example of a (comparatively) macroscopic structure is the fact that on the outside the order is lost – we still have strong coupling, but the system is more fluid-like. In the interior we have regimes of HCP and FCC crystal structures, which are formed as a result of the self-organization taking place. And unexpected

By disturbing the crystal (e.g. by changing the electric field impulsively) we can observe how the self-organization proceeds slowly from the inside to the outside via phonons, which redistribute the energy.

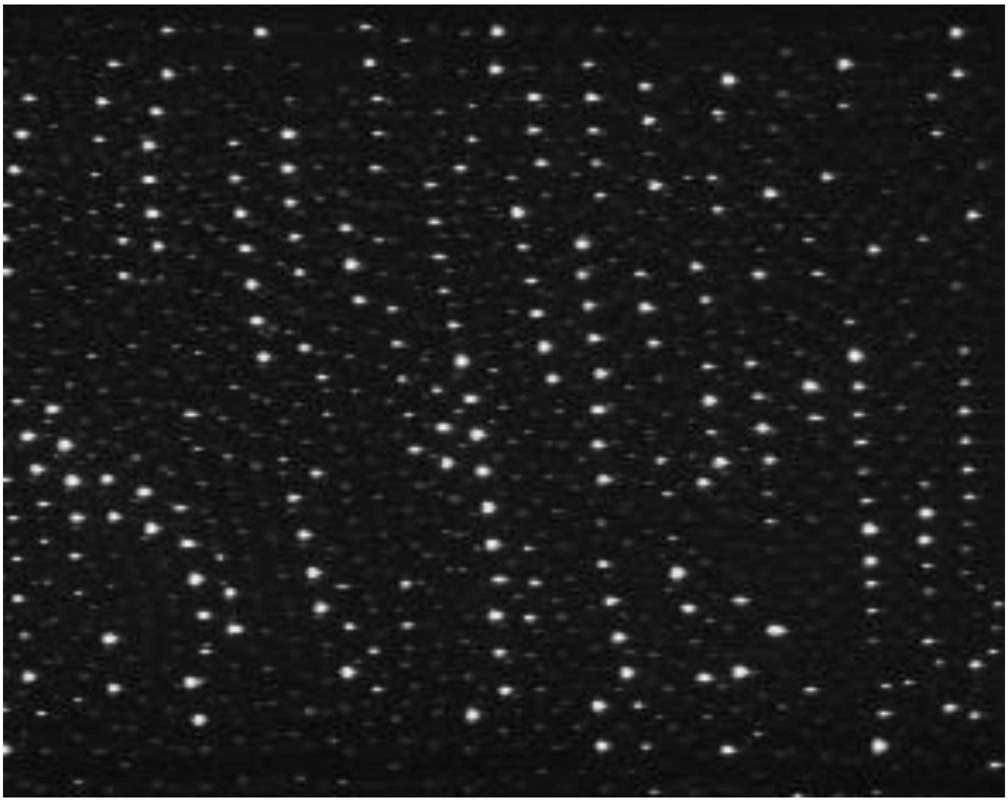
Plasma rheology

An interesting and surprising discovery was made by Thomas Reiter (ESA Astronaut) and his Russian colleagues (M. Turin, and P. Vinogradov). They observed a new phenomenon for the first time – the self-organization of a complex plasma fluid into a “string plasma” – where the particles all align along a certain direction. The first picture below shows the complex plasma in its fluid phase.



Sequence with small modulating AC amplitude (26 Volts p-p) showing the characteristic complex plasma isotropic fluid phase. PK-3Plus, Th. Reiter (2006)

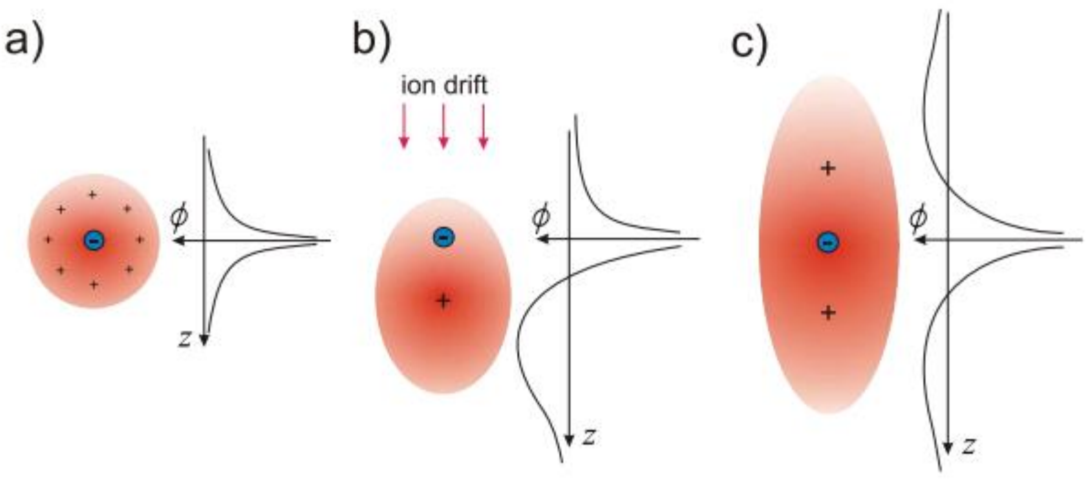
‘‘Conventional’’ electrorheological (ER) fluids consist of suspensions of microparticles in (usually) nonconducting fluids with a different dielectric constant. The interparticle interaction, and hence the rheology of ER fluids, is determined by an external electric field, which polarizes grains and thus induces additional dipole-dipole coupling. The electric field plays the role of a new degree of freedom that allows us to ‘‘tune’’ the interaction between particles. This makes the phase diagram of ER fluids remarkably diversified.
So far, colloidal suspensions have been the major focus for ER studies, providing a wealth of information. The discovery that complex plasmas also have electrorheological properties adds a new dimension to such research—in terms of time or space scales and for studying new phenomena: Ensembles of microparticles in complex plasmas can act as an essentially single-species system with very weak damping. This is very different from colloids (it is a consequence of the fact that the neutral gas density in complex plasmas is about 10^6–10^8 times smaller than the fluid density in colloids). Therefore, complex ER plasmas cover new physics and enable us to investigate previously inaccessible rapid elementary processes that govern the dynamical behavior of ER fluids—at the level of individual particles. In particular, such investigations may allow us to study critical phenomena accompanying second-order phase transitions.



Sequence with high modulating AC amplitude (66 Volts p-p). The first observation of the phase transition of an isotropic complex plasma fluid to an electrorheological ´string plasma´.PK-3Plus, Th. Reiter (2006)

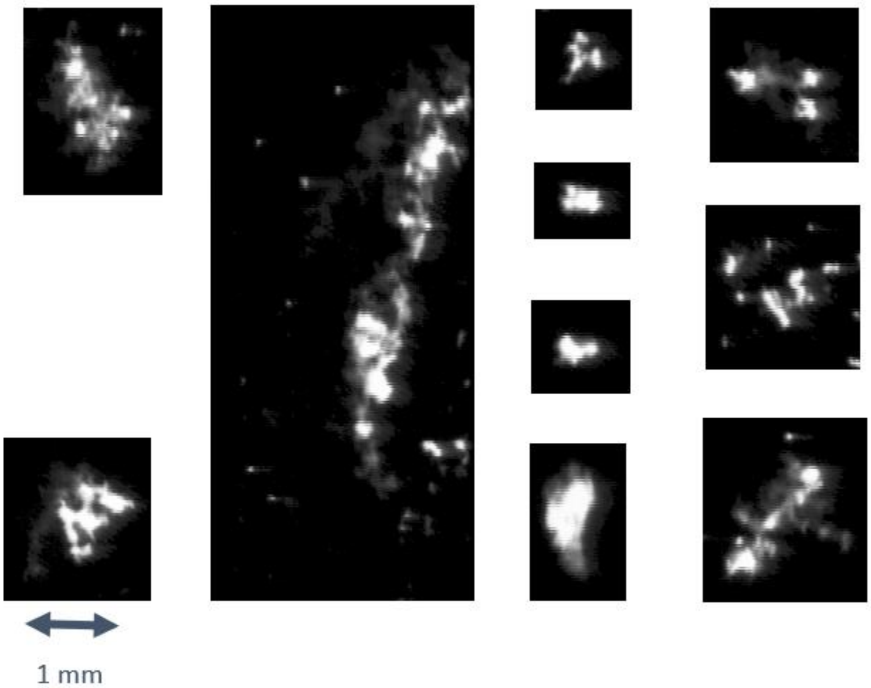
First Observation of Electrorheological Plasmas, A. V. Ivlev, G. E. Morfill, H. M. Thomas, C. Räth, G. Joyce, P. Huber, R. Kompaneets, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, T. Reiter, M. Turin, and P. Vinogradov, PRL 100, 095003 (2008).

The physical process, which produces an asymmetric coupling between the particles and ultimately leads to string formation is schematically depicted below. The external AC field which is applied across the complex plasma cloud distorts the local charge cloud surrounding the microparticle as depicted in c) – provided that the frequency of the AC field is sufficiently high to influence the lighter ions, but not the heavy microparticles. When this is chosen correctly, we get electro-rheology.



Super-coagulation

Another unexpected and surprising discovery was made by Yuri Baturin. In a large sequence of experiments, he discovered „super-coagulation" – a process where thousands of microparticles joined into an agglomerate within seconds! We have named this discovery the "Baturin Effect".



The figure above shows several examples of large agglomerates of microparticles. From the size, it is clear that these structures must contain 10s of thousands and up to a million microparticles!

Charge-induced gelation of microparticles, Konopka U., Mokler F., Ivlev A.V., Kretschmer M., Morfill G.E., Thomas H.M., Rothermel H., Fortov V.E., Lipaev A.M., Molotkov V.I., Nefedov A.P., Baturin Y.M., Budarin Y., Ivanov A.I., and Roth M., NEW JOURNAL OF PHYSICS 7, 227

This super-coagulation process could not have been discovered on Earth, because gravity would have removed the particles and prevented a detailed analysis.

➔ **Quite possibly, without this process we might not even exist!**

The reasoning is as follows: In stellar nucleosynthesis condensable elements are formed. These are ejected (with H, He) in the stellar winds. The expanding wind cools, leading to conditions where solids may condense. Small dust particles are formed and transported into the interstellar medium (where we see them as so-called "dark clouds", since the dust absorbs the starlight – and re-emits it in the infrared).

The physics of dusty plasmas is of paramount importance for the thermodynamics, the chemistry and evolution of the interstellar medium. This is particularly true for star formation. New stars are born in interstellar clouds. These clouds consist of gas (H,He...) and dust particles (typically 1% by mass). The dust is essential for cooling the cloud, so that gravitational collapse can set in – the dust therefore may be regarded as the star formation „trigger". The dust then ends up in the star or it survives in the planets.

For the formation of planets, dust coagulation is the initial most important process. The larger coagulated particle agglomerates can settle into the midplane of the circumstellar dust/ gas cloud faster and produce further instabilities that lead to planetesimals and finally planets.

Obviously, if the super-coagulation process discovered on the ISS by Yuri Baturin also operated in the early solar system cloud, then planet formation could proceed faster and the likelihood of a “solar system” as we know it becomes more feasible. It is all a question of time scales – planets have to be formed before the star (sun) develops a strong stellar (solar) wind, which disperses the circumstellar (circumsolar) cloud.

Other important discoveries on the ISS include the physics of shear flows, structure and thickness of shock fronts, new types of wave phenomena, critical phenomena, phase transitions, phase separation processes – altogether too much to refer here. I hope I have been able to transmit some of the excitement and awe, which the 20 years of research on the ISS have given us.

The interested reader is invited to look at some of the original publications in the reference list.

Applications on Earth

The applications on Earth derive from the technology advances that were necessary to carry out research into colloidal plasmas. The microparticles used for these studies should be as uniform in size as possible, so that their electric charge (which in equilibrium is proportional to the particle radius) should be similar. Of course, there will be statistical variations, but these effects are small if the number of elementary charges on the microparticles is large. The microparticles used are polymers, and they have a low melting point. Thus, for these particles to survive in the plasma environment, the plasma has to be "cold" – room temperature is sufficient.

Technologically this means that plasma sources must be developed that provide a sufficient supply of charged particles whilst at the same time ensuring that the ions are at a low temperature and the electrons at a high temperature – so-called "cold plasmas".

Cold Atmospheric Plasmas (CAP)

If the plasma production takes place in air – i.e. Cold Atmospheric Plasmas – we have basically three components of relevance: Oxygen, Nitrogen and Water vapor. The plasma production in such an environment is definitely more complex than in a noble gas. Altogether, there are over 600 chemical and physical reactions that take place!

Negative particles:	e, O^-, O_2^-, O_3^-, O_4^-, H^-, OH^-, NO^-, N_2O^-, NO_2^-, NO_3^-
Positive particles:	N^+, N_2^+, N_3^+, N_4^+, O^+, O_2^+, O_4^+, NO^+, N_2O^+, NO_2^+, H^+, H_2^+, H_3^+, OH^+, H_2O^+, H_3O^+
Neutrals:	N, N*, N_2, N_2*, N_2**, O, O*, O_2, O_2*, O_3, NO, N_2O, NO_2, NO_3, N_2O_3, N_2O_4, N_2O_5, H, H_2, OH, H_2O, HO_2, H_2O_2, HNO, HNO_2, HNO_3

Of particular interest for many applications are the Nitrogen and Oxygen Modes. The Oxygen Mode (also called Ozone Mode – since Ozone is the most abundant molecule created in the plasma chemistry process) also connects strongly to the water chemistry. Basically we have:

- Ozone mode (silent discharge; low input energy)

$$e + O_2 \rightarrow O + O$$
$$O + O_2 + M \rightarrow O_3 + M$$

- Nitrogen oxides mode (discharge poisoning; high input energy)

$$\left.\begin{aligned} N + O_2 &\rightarrow NO + O \\ N_2(v) + O &\rightarrow NO + N \end{aligned}\right\} \text{NO generation}$$

$$\left.\begin{aligned} O + NO + M &\rightarrow NO_2 + M \\ O + NO_2 &\rightarrow NO + O_2 \end{aligned}\right\} \text{O quenching}$$

$$\left.\begin{aligned} O_3 + NO &\rightarrow NO_2 + O_2 \\ O_3 + NO_2 &\rightarrow NO3 + O_2 \end{aligned}\right\} O_3 \text{ quenching}$$

This abundant chemistry can be utilized – if it is possible to design (or control) the specifics of the plasma production – for various applications. One of the most interesting is the design of a "medical plasma" – one that is capable of inactivating bacteria and viruses, whilst at the same time accelerating wound healing. For this purpose, a start-up company was created in 2013 – a spin-out from the Max-Planck Society. The name of the company – terraplasma – was chosen to emphasize that its place of operation is on and for Earth, although some of the developed products could be very useful in human space flight, too – at least this is what the cosmonauts have been telling me!

Plasma wound treatment

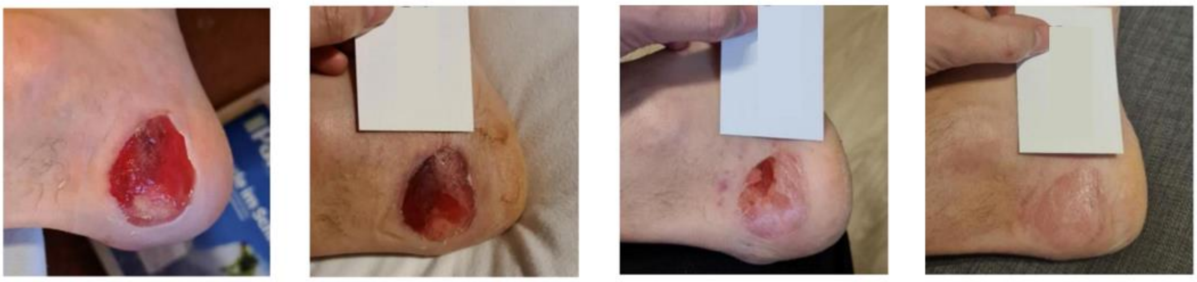
The first medical plasma device developed (in a daughter company – terraplasma medical) is shown below. It is a hand-held inductively rechargeable device, which requires a treatment time of 60 seconds per day in order to ensure infection-free wounds and improved wound healing. To be able to do this, the plasma care device has been designed to produce first a strongly bactericidal effect, followed by a second phase of tissue regenerating ability.

plasma care at charging station

plasma ring during treatment

plasma care spacer
sterile single-use add on

An example of wound treatment is shown below.



Initial situation | After 1 CAP Treatment | After 2 CAP Treatments | After 3 CAP Treatments

Complete wound closure after only 1 week (Treatment: 3 times every 2nd day for 2 minutes) – wound due to a skiing injury by a fit young male person (courtesy of terraplasma GmbH).

Plasma hygiene

Hygiene standards differ greatly across the world. About 15% of all deaths worldwide are due to infectious diseases. This being said, there is another growing and significant threat – antibiotically resistant bacteria. Here an excerpt from a recent international report:

The global rise in antibiotic resistance poses a significant threat, diminishing the efficacy of common antibiotics against widespread bacterial infections.

"The 2022 Global Antimicrobial Resistance and Use Surveillance System (GLASS) report highlights alarming resistance rates among prevalent bacterial pathogens. Median reported rates in 76 countries of 42% for third-generation cephalosporin-resistant E. coli and 35% for methicillin-resistant Staphylococcus aureus are a major concern. For urinary tract infections caused by E. coli, 1 in 5 cases exhibited reduced susceptibility to standard antibiotics like ampicillin, co-trimoxazole, and fluoroquinolones in 2020. This is making it harder to effectively treat common infections.

Klebsiella pneumoniae, a common intestinal bacterium, also showed elevated resistance levels against critical antibiotics.

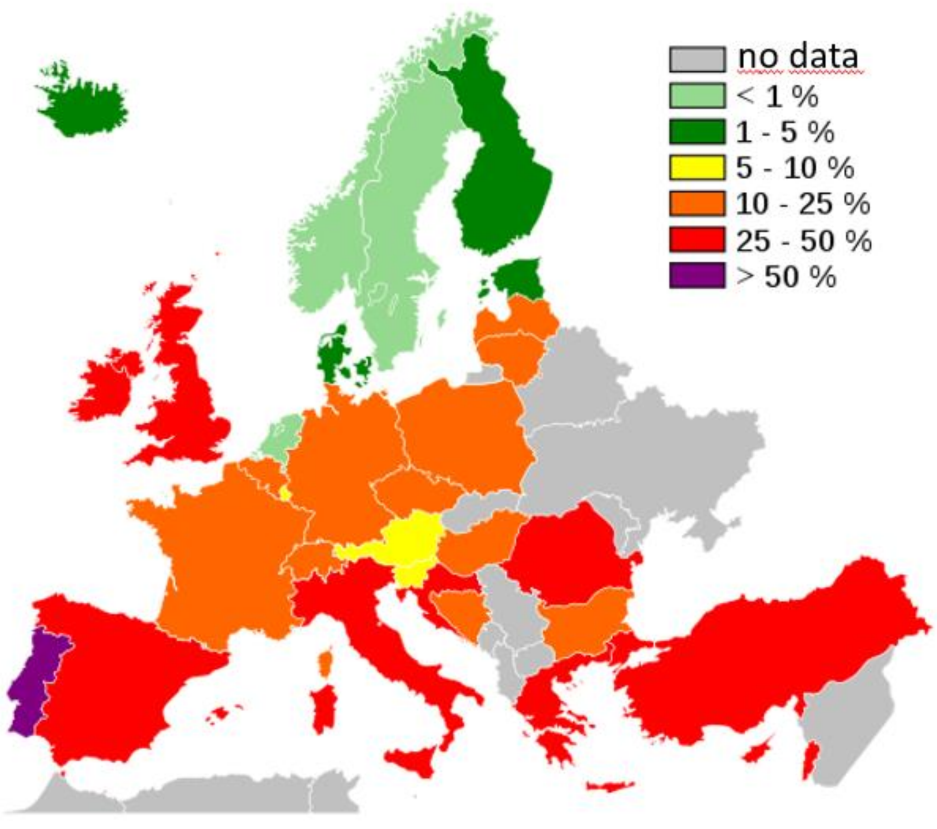
The emergence and spread of multi-drug resistant Candida auris, an invasive fungal infection, is of particular concern. Development of WHO's Fungal Priority Pathogens List includes a comprehensive review of fungal infections and drug-resistant fungi globally."

Antimicrobial Resistance Collaborators. (2022). Global burden of bacterial antimicrobial resistance in 2019: a systematic analysis. The Lancet; 399(10325): P629-655. DOI: https://doi.org/10.1016/S0140-6736(21)02724-0

https://www.who.int/news-room/fact-sheets/detail/antimicrobial-resistance

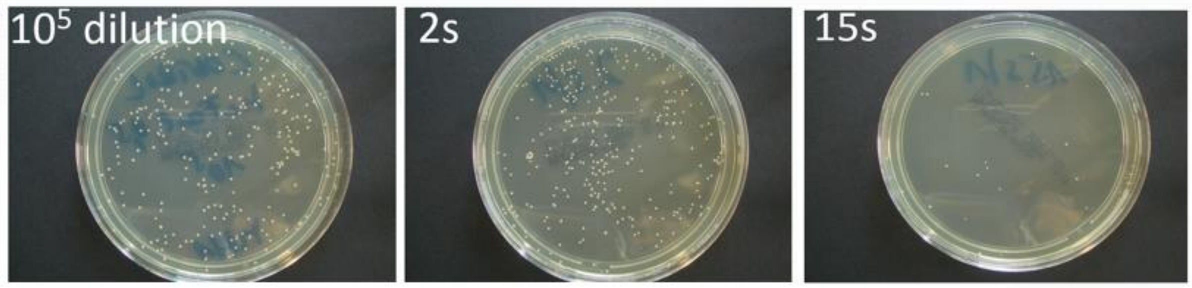
Of particular concern are hospital Acquired Infections. In Europe (map of 2008) the situation was as seen in the figure below:

Hospital acquired infections – incidence of MRSA (2008)



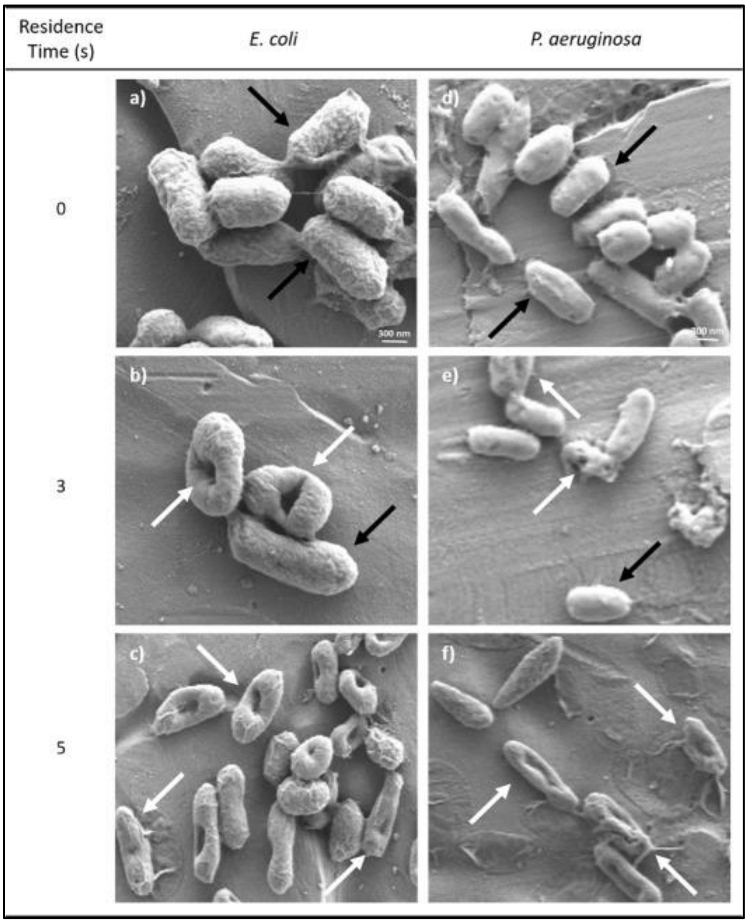
Whilst there has been some improvement since then, the situation is not remarkably improved.

How can Cold Atmospheric Plasma help?



In the figure above results are shown for the effect of CAP on MRSA – a highly antibiotically resistant bacterium. Within 15 seconds of plasma treatment all of the originally 10 Million bacteria were inactivated. SMD (Air) results for MRSA

Cold Atmospheric Plasma attacks bacteria (and viruses) in different ways – mechanically, electrically, thermally, and chemically. Due to this multitude of processes, it is very difficult – if not impossible – to develop resistance against the plasma treatment. In addition, since the plasma is gas-like, it can access small regions (e.g. of the skin) where ointments and salves cannot penetrate. Also, there are no side effects known. Below we show the damage inflicted on bacteria by plasma treatment.

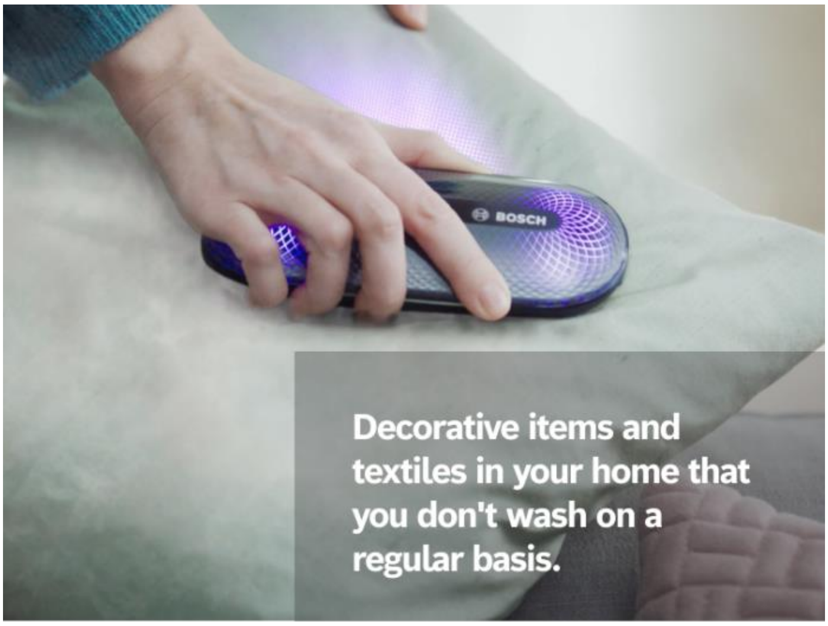


SEM pictures of E. coli (a, b, c) and P. aeruginosa (d, e, f) before and after plasma treatment
pictures (a) and (d) are untreated controls
pictures (b) and (e): bacteria after 3 sec plasma treatment
pictures (c) and (f): bacteria after 5 sec plasma treatment
L. Patinglag et al., Water Research, Volume 201, 1 August 2021, 117321

Cold Atmospheric Plasma can therefore help in many ways – surface hygiene, water hygiene, food hygiene, air hygiene are all areas of current research – and initial applications in progress.

Clothes refreshing and disinfection.

Finally, just a brief excursion into the world of commerce. A plasma device for removing odor from clothes was developed by terraplasma in cooperation with the German company Bosch. This device just needs to be switched on and then gently moved across the clothes (or any fabrics) and after a few strokes all the odors that were embedded in the material have been eliminated – not concealed (as in most chemical aerosol odor treatments) – the odor molecules are picked out by the plasma and broken up.



This device – so the Cosmonauts tell me – would be very welcome on the ISS, too.

Again, as in basic research, the plasma application is much broader. There is a lot of research going on: in plasma agriculture – enhancing plant growth without polluting the ground water with fertilizers, in water treatment – harnessing solar energy to disinfect and produce good quality drinking water, in cancer treatment – selectively inactivating cancer cells without affecting healthy cells, - in plasma enhanced drug action – improving the efficacy of topical drugs… etc.

Summary

I hope that with this brief excursion into the plasma world I have achieved two things – first, to emphasize how research in Space can not only increase knowledge of fundamental processes, but also provide unexpected insights and benefits for all of us on Earth – and second, in doing so have triggered the reader´s curiosity as well as provided a fitting memory to one of the world´s most remarkable scientists – Vladimir Fortov.

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