White paper (in response to the call for white papers for the Decadal Survey on Biological and Physical Science (BPS) Research in Space 2023-2032 (BPS2023) conducted by The National Academies of Science, Engineering and Medicine)

Topical: Studying dusty/complex plasma under reduced gravity condition – COMPACT – A Complex Plasma Facility for the ISS

Primary Authors:
Uwe Konopka, *Auburn University, Alabama, USA*
Telephone: 334-844-4248, Email: uzk0003@auburn.edu

Christina Knapek, *DLR – German Aerospace Center, Wessling, Germany*
Telephone: +49-8153-281994, Email: christina.knapek@dlr.de

Co-Authors:
Hubertus Thomas, DLR – German Aerospace Center, Wessling, Germany
Inseob Hahn, Jet Propulsion Laboratory, Passadena, CA, USA
Lenaic Couedel, University of Saskatchewan, Canada and CNRS, France
Andre Melzer, University of Greifswald, Germany
Markus Thoma, University of Giessen, Germany
Evdokiya (Eva) Kostadinova, Auburn University, Auburn, AL, USA
John Goree, University of Iowa, Iowa, USA

Introduction / Background

Complex, or dusty plasmas are systems where small particles are suspended in a plasma environment. The particle size can range from nano- to millimeters. Due to plasma interaction the particles acquire a typical negative net charge that scales with the capacitance of the particle and thus the dust size. As a result particles interact with each other via a strong Coulomb interaction that is partly screened by rearrangement of the charge carriers (electrons and ions) in the plasma background. These systems are ubiquitous in nature. They can be found in planetary rings, comet tails, interplanetary and interstellar clouds, on Moon and Mars, as well as in the Earth's Mesosphere and thunderstorm clouds, or in the vicinity of artificial satellites and space stations. Further, they have impact in industrial fields such as fusion research and plasma-based manufacturing processes.

Complex plasmas can also be regarded as model systems for classical condensed matter physics, that can be easily generated in a laboratory. One of their unique features is that the systems are optically thin. In the laboratory, imaging can be used to track ensembles of micron-sized particles, measuring their individual coordinates and velocities. All time scales relevant for the system dynamics can be easily resolved. Complex plasma therefore builds a bridge between single particle dynamics over mesoscopic systems to fully statistical systems and allow to investigate condensed matter physics on multiple scales. Fundamental physics topics from statistical many-particle physics, nonlinear phenomena and phase transitions can be investigated using the particles as proxy "atoms" in a virtually undamped system – complementary to strongly damped colloidal systems.

Gravity strongly affects the behavior of complex plasmas due to the high mass of the particles. Within the main plasma volume of a laboratory setup, there are no forces such as buoyancy that can offset gravity, and the virtually undamped system of microparticles sediments into 2D, quasi-2D and stressed 3D systems close to the lower plasma boundary (the plasma sheath), where electric forces levitate the particles against gravity as shown in figure 1. To study homogeneous and isotropic, 3D systems, particles have to be confined in the bulk plasma, calling for experiments in a stable microgravity environment provided for example by the International Space Station (ISS).

To overcome the gravitation induced restrictions, a longstanding microgravity program started in 2001 with the complex plasma facility PKE Nefedov (the first natural science experiment installed on board the ISS) [1], followed by the PK-3 Plus facility in 2005 [2]. Sample representative results from the studies performed with these facilities are the discovery of the coexistence of different 3D lattice structures [1], and of electrorheological complex plasmas [3] that can serve as a model system for smart materials. Currently, the PK-4 facility [4] is operated on the ISS, with direct involvement of multiple US science groups funded by several NASA and NSF grants, as an international collaboration. With more than 120 scientists involved worldwide up to now and over 130 peer reviewed publications, the former and currently operated dust experiments on the ISS have proven very successful. Some sample publications are [5-9].

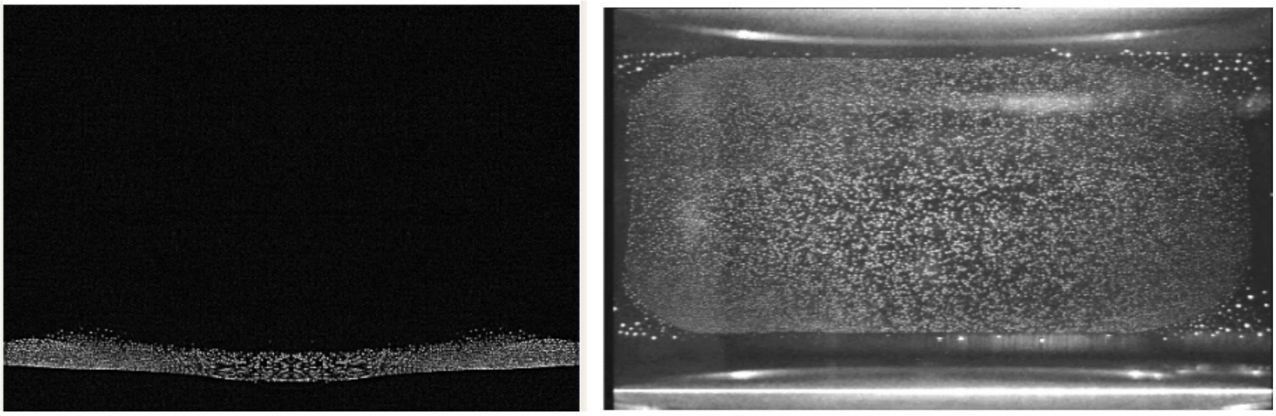

Figure 1: Complex/Dusty plasma are subject to a strong gravitational influence. Dust particle levitation takes place mainly where the weight is compensated by electric field forces. Experiments in the lab (left image) are therefore strongly affected by sedimentation leading to compressed, thin systems, while under free-fall conditions as on the ISS (right image taken with the former ISS based experiment PK-3 Plus [2]) the full volume of the discharge chamber can be occupied.

The advent of new imaging technologies, novel machine-learning based (image) analysis tools as well as newly developed plasma techniques for generating near-equilibrium dust clouds call for the next-generation experimental facility for the ISS, COMPACT.

Scientific Motivation

COMPACT is envisioned to address many open questions in a variety of scientific disciplines either by being studied in its own right or when utilized as a general model for many body systems, studied down to the dynamics of the individual "atom", the individual particle. An international science definition team guided by the input of the broader scientific community during two workshops in 2021 collected and compiled the most important scientific topics to address with COMPACT by utilizing a stable microgravity environment such as given by the international space station (ISS). The most prominent topics, selected also to be included in the science requirement document for COMPACT, include questions related to:

- statistical physics (e.g. transport properties, non-equilibrium thermodynamics)
- phase transitions (e.g. solid-liquid phase transition, supercooled liquids, glass transition)
- nonlinear dynamics (turbulence, nonlinear waves)
- active matter (ordering, mode dynamics, rheology, statistical properties, collective behavior)
- planetary physics (dust charging, mitigation, dust collisions and coagulation, formation of ice particles)

Highlighted research objectives within the categories above cover fundamental topics of broader, interdisciplinary interests that are discussed right now in highly rated journals, including:

- Exploring the long-time statistical behavior of phases in the absence of a flow, such as a supercooled liquid near the glass transition
- Revealing the connection between microscopic particle-particle interactions and large-scale nonlinear, turbulent flows
- Studying the emergence of the collective behavior of self-propelled particles from the energy input on the single-particle level

The anticipated investigations are expected to give new insights into fundamental physical properties of matter, and have the potential to advance applications in industrial plasma processing, e.g. etching, plasma coating, safety of fusion devices, or planetary exploration. COMPACT will enable studies of the above scientific objectives and beyond that are not accessible using existing instrumentation on ground or in space (for example aboard the ISS). It is anticipated to serve a broad, international scientific community that has been also consulted in 2021 on two dedicated workshops to define the core scientific mission for COMPACT. A possible collaborative operation model could follow the example of PK-4.

Proposing a next generation ISS based complex plasma facility, COMPACT

The proposed COMPACT (Complex Plasma Facility) for the ISS will be designed to offer a wide experimental parameter range to cover the experimental requirements to answer the large number of science objectives from the above mentioned areas and topics beyond. Former, pre-development studies (PlasmaLab, Ekoplasma) already provide valuable hardware components, that can be utilized for this purpose giving the development of COMPACT a head start. Based on the expert knowledge available in the international scientific community, complex plasma research can be extended into new regimes that were not accessible so far with any prior ISS based complex plasma experiments.

COMPACT will support a novel concept of a plasma chamber [10] with considerably larger volume than previous experiments (10 times larger that the PK-3 Plus chamber), allowing to study large 3D systems that are on the edge to overcome the gap to continuous media (particle systems equivalence in number of atoms to an Aluminium grain of several micro-meter in diameter). The chamber volume is designed to be flexible, i.e. systems can be compressed/expanded to induce internal pressure and thus e.g. crystallization by changing the ratio of the inter-particle energy to the thermal energy, the coupling ratio. Further, novel capabilities for plasma and particle manipulation will extend the accessible plasma parameter range and the user control of the experiment. Techniques proposed include using pulsed plasma, multi electrode systems with individual radio frequency, ac and dc power control. Also the individual phases between the electrodes will be under user control. Figure 2 shows a potential facility design, the experimental core device – the discharge chamber – and several potential plasma operational modes using a set of 4 individual addressable electrodes. Further, advanced diagnostics (e.g. stereoscopy) will be used to obtain real-time 3D particle trajectories for the first time in an ISS complex plasma facility. Data analysis procedures utilizing artificial intelligence (AI) and machine learning algorithms will improve the experiment real-time control, help to handle the large amount of data and ultimately improve the science outcome. While the core design of the facility is already finished, several potential modifications are still under discussion to support a wider scientific community. Potential modification or additions include:

- Adding specific dedicated particles (such as super-paramagnetic, ferromagnetic, elongated and/or active particles of different kinds)
- Adding one or multiple Helmholtz coil pairs to manipulate the particle interactions and plasma behavior with low field (~10 Gauss) magnetic fields.
- A temperature control system to manipulate particle distributions and/or to potentially handle ice particle growth. It is possible that the latter will not be included at this time as handling of ice particles involves the risk to strongly degenerate plasma quality which would affect other experiments. On the other hand it would open up a new field of studies related to astrophysical and atmospheric environments.

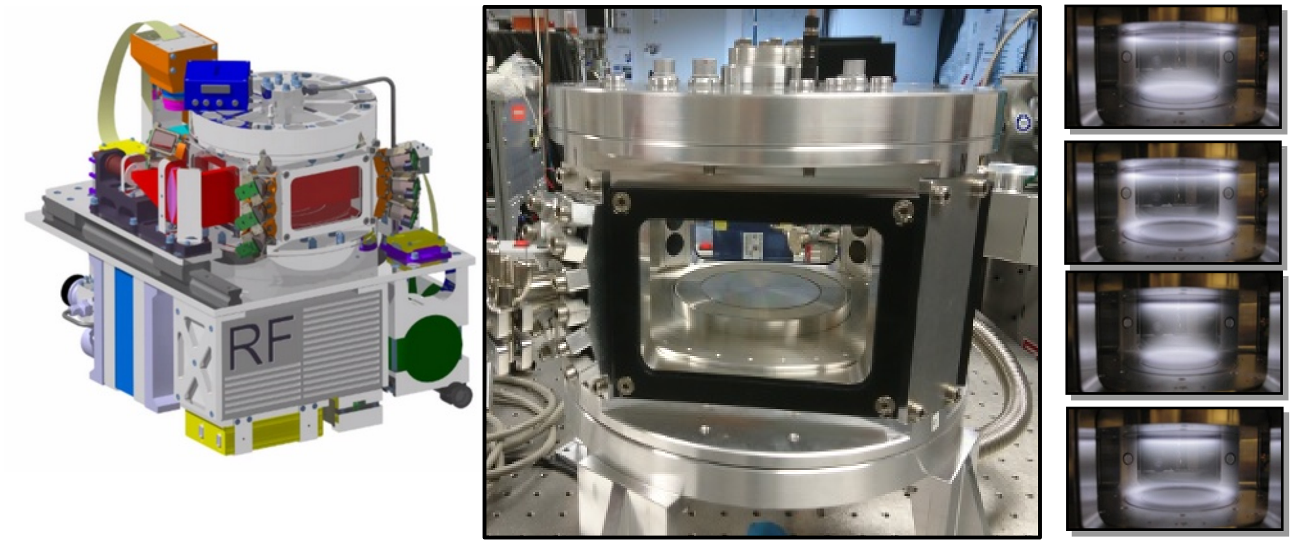

Figure 2: Left: CAD design of the composed building block structure of COMPACT. Included, mounted to a base plate, are the gas-support system, experiment electronics and the core of the setup: the plasma generation, matching networks, central vacuum vessel, optical diagnostics and particle dispenser system. Center: The core plasma vessel supports a double, parallel plate electrode system, where each electrode consist of a center and a ring electrode. The electrodes are individually driven by their own rf/ac/dc power systems, all of which are phase and amplitude controlled with respect to each other. A variety of plasma generation modes can therefore be realized with this system. Example plasma configurations already demonstrated during parabolic test flights are shown on the right. While changing phases and amplitudes of the rf signal a variety of plasma modes can be archived. A very important feature, described in detail in the recently published description of the Zyflex chamber (the breadboard chamber for COMPACT) [10] is the electrode motion system that allows to compress the complex plasma in a running experiment.

Necessity for complementary studies

Complementary to the development and operation of COMPACT on the ISS, studies will be needed on other microgravity platforms, such as parabolic flights or sounding rockets. Especially, topics from planetary physics might require dedicated equipment (e.g. electrode cooling, water injection) that can be realized using initially a parallel experimental setup for parabolic flights and on the long term get own experimental inserts in follow up experiments to COMPACT. Ground based research will include advanced plasma diagnostics and simulations and help to develop and implement new machine learning techniques that represent a mandatory tool not just for data analysis, but also for automated experiment control and data acquisition.

Proposed mode of operation

COMPACT is intended to be a multi-purpose, multi-user facility with international accessibility and the involvement of a large science community to reach beyond the complex/dusty plasma community: the worldwide community that will utilize this unique facility consists of leading groups in America, Europe and Russia and multiple other groups distributed all over the globe. The international coordination of science access could be organized via similar arrangements as put in place for the ongoing PK-4 operation which is overseen by an international facility science team, operated by a national core group and made available via an experiment proposal process to the international community. COMPACT is not yet funded but is otherwise supported by multiple international agencies:

- NASA and NSF (USA)
- DLR (Germany)
- ESA (Europe)
- ROSCOSMOS (Russia)

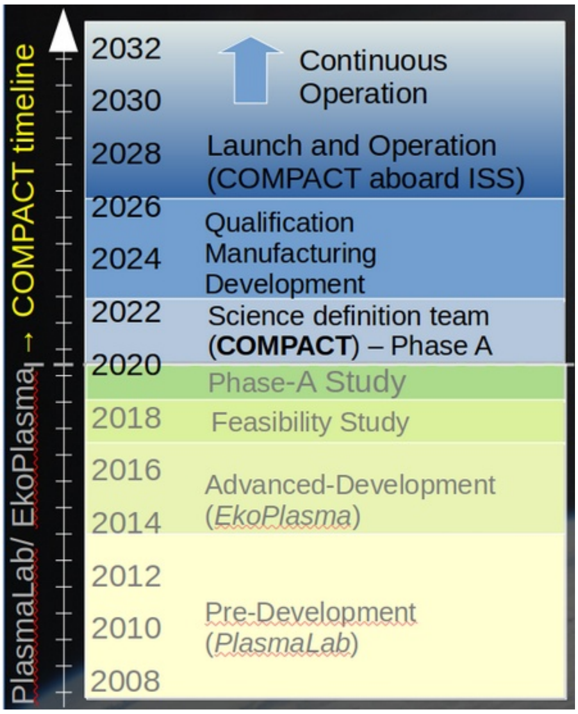

Figure 3: The roadmap of COMPACT as anticipated including the pre-development activities (PlasmaLab and Ekoplasma) that define the new complex plasma facility COMPACT.

If fully supported, we expect that the experiment will follow the here sketched timeline of figure 3 with a phase-A study in 2022, development and manufacturing in 2023-2024 and qualification for flight in 2025-2026. A launch could be realized potentially in 2026-2027. As can be seen, the expected operational time of COMPACT would require that the international community of agencies (including NASA) would allow to operate the ISS beyond 2028.

References:

[1] A. P. Nefedov. G.E. Morfill, H. Thomas, T. Hagl, A. Ivlev, M. Zuzic, B. Klumov, A.Lipaev, V. Molotkov, O. Petrov, Y. Gidzenko, S. Krikalev, W. Sheppard, A. Ivanov, M. Roth, H. Binnenbruck, J. Goree, Y. Semenov, *PKE-Nefedov: plasma crystal experiments on the International Space Station*, New J. Phys. 5(1), 33 (2003). https://doi.org/10.1088/1367-2630/5/1/333

[2] H.M. Thomas, G.E. Morfill, V.E. Fortov, A.V. Ivlev, V.I. Molotkov, A.M. lipaev, T. Hagle, R. Rothermel, S.A. Khrapak, R.K. Suetterlin, M. Rubin-Zuzic, O.F. Petrov, V.I. Tokarev and S.K. Krikalev, *Complex plasma laboratory PK-3 Plus on the International Space Station*, New J. of Physics 10, 2008. https://doi.org/10.1088/1367-2630/10/3/033036

[3] A.V. Ivlev et al., *First Observation of Electrorheological Plasmas,* Phys. Rev. Lett. 100, 095003 (2008). https://doi.org/10.1103/physrevlett.100.095003

[4] M. Y. Pustylnik, M. A. Fink, V. Nosenko, T. Antonova, T. Hagl, H. M. Thomas, A. V. Zobnin, A. M. Lipaev, A. D. Usachev, V. I. Molotkov, O. F. Petrov, V. E. Fortov, C. Rau, C. Deysenroth, S. Albrecht, M. Kretschmer, M. H. Thoma, G. E. Morfill, R. Seurig, A. Stettner, V. A. Alyamovskaya, A. Orr, E. Kufner, E. G. Lavrenko, G. I. Padalka, E. O. Serova, A. M. Samokutyayev, and S. Christoforetti, *Plasmakristall-4: New complex (dusty) plasma laboratory on board the International Space Station*, Rev. Sci. Instrum. 87 (9), 093505 (2016). https://doi.org/10.1063/1.4962696

[5] S. A. Khrapak, A. V. Ivlev, G. E. Morfill and H. M. Thomas, *Ion drag force in complex plasmas*, Phys. Rev. E 66 (4) (2002), https://doi.org/10.1103/PhysRevE.66.046414

[6] A. V. Ivlev, M. Kretschmer, M. Zuzic, G. E. Morfill, H. Rothermel, H. M. Thomas, V. E. Fortov, V. I. Molotkov, A. P. Nefedov, A. M. Lipaev, O. F. Petrov, Y. M. Baturin, A. I. Ivanov and J. Goree, *Decharging of complex plasmas: First kinetic observations*, Phys. Rev. Lett. 90 (5) (2003), https://doi.org/10.1103/PhysRevLett.90.055003

[7] A. M. Lipaev, S. A. Khrapak, V. I. Molotkov, G. E. Morfill, V. E. Fortov, A. V. Ivlev, H. M. Thomas, A. G. Khrapak, V. N. Naumkin, A. I. Ivanov, S. E. Tretschev and G. I. Padalka, *Void closure in complex plasmas under microgravity conditions*, Phys. Rev. Lett. 98 (26) (2007), https://doi.org/10.1103/PhysRevLett.98.265006

[8] K. R. Sütterlin, A. Wysocki, A.V. Ivlev, C. Räth, H.M. Thomas, M. Rubin-Zuzic, W. J. Goedheer, V. E. Fortov, A. M. Lipaev, V. I. Molotkov, O. F. Petrov, G. E. Morfill, H. Löwen, *Dynamics of lane formation in driven binary complex plasmas*, Phys. Rev. Lett. 102, 085003 (2009), https://doi.org/10.1103/PhysRevLett.102.085003

[9] Khrapak, S. A. et al., *Freezing and Melting of 3D Complex Plasma Structures under Microgravity Conditions Driven by Neutral Gas Pressure Manipulation*, Phys. Rev. lett. 106 (20), 205001, 2011. https://doi.org/10.1103/PhysRevLett.106.205001

[10] Knapek, C.A., Konopka, U., Mohr, D.P., Huber, P., Lipaev, A.M. and H.M. Thomas, *„Zyflex“: Next generation plasma chamber for complex plasma research in space*, Rev.Sci.Instrum., **92**, 103505, 2021. https://doi.org/10.1063/5.0062165