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PK-4 –COMPLEX PLASMA RESEARCH ON THE INTERNATIONAL SPACE STATION

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ABSTRACT

The International Space Station (ISS) is the outpost of mankind in low-Earth orbit, and has been permanently manned by three to six astronauts since the end of 2000. It is the world's biggest international project yet, bringing together partners from Russia, America, Europe, Japan and Canada. It was built following a political decision after the Cold War and provides a platform for fundamental research in life and physical sciences, for Earth observation and astronomy. Recently it became the platform for preparing the next steps in the quest for longer deep-space manned missions to the Moon and Mars.

PK-4 is an active laboratory for fundamental research in the field of complex plasmas and part of the European Columbus Module. The project is a bilateral European-Russian collaboration. Scientists from Europe, Russia and also other nations worldwide benefit from this project. They participate in experiments, the analysis of resulting data and contribute to theoretical and numerical modelling. Experiments with PK-4 are carried out in frequent campaigns on the ISS. In 2019 three such campaigns totalling 12 experiment days were performed, producing about 9 TB of high quality scientific data.

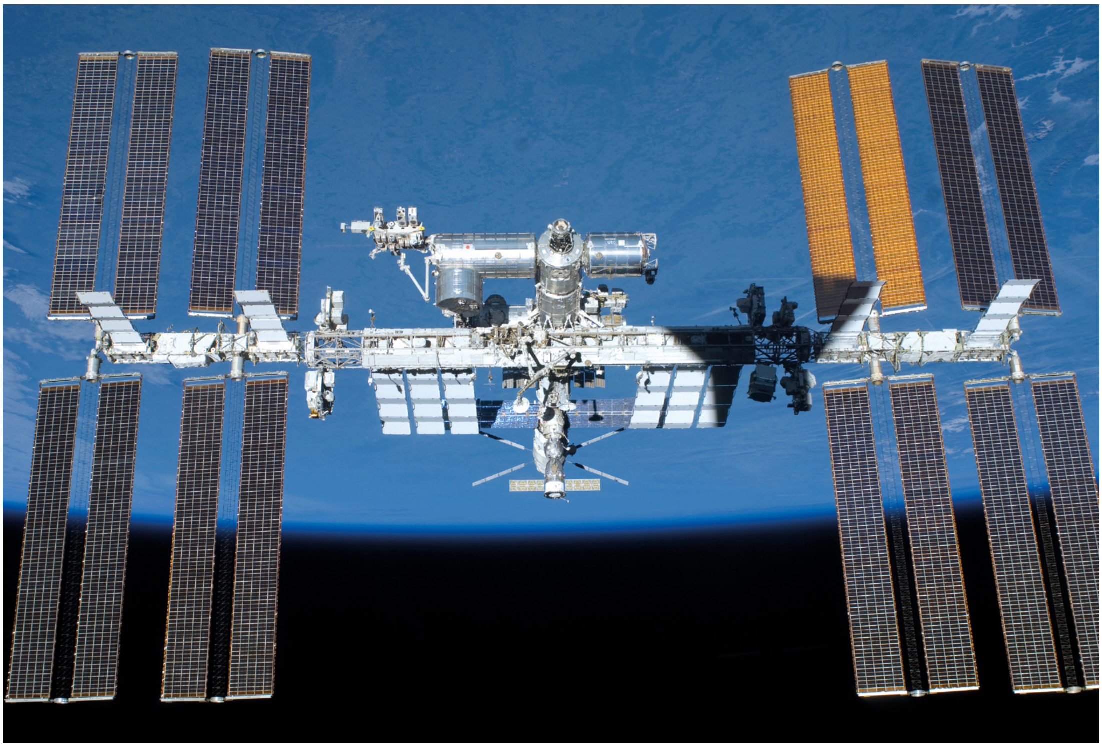

Fig 1: The International Space Station (ISS) outpost of humankind in space.

COMPLEX PLASMA RESEARCH

Complex plasma research is quite a young field that evolved with the discovery of crystalline structures in laboratory dusty plasmas in 1994. It combines all four states of matter – solid, liquid, gaseous and plasma – opening up a very broad field of interdisciplinary research. Complex plasmas consist of micrometer-sized particles embedded in ionized gas. These systems make up a new form of soft matter the study of which is interesting in itself. Under some conditions, on the other hand, complex plasmas can be regarded as classical model systems of fluids and solids offering insights into the dynamics of these systems on the individual particle level with the microparticles in complex plasmas acting as proxy atoms. Complex plasmas thus provide a new experimental approach for fundamental studies of strong coupling phenomena. In nature as well as in man-made plasmas dust can appear naturally, forming so called "dusty plasmas". Fundamental knowledge gained from complex plasma research is easily transferrable.

Plasma is a (partially) ionized gas with free electrons and ions. 99% of the visible matter of the universe is in the plasma state. It can be found for example in the interior of stars, in star forming regions, interstellar clouds or the atmospheres of planets. Thus Earth has a (plasma)-ionosphere a few hundred kilometres deep formed due to the interaction of charged solar wind particles and UV/X-ray photons from the Sun with the gas in the upper atmosphere. This region filters the Sun's life-destroying rays and reflects radio signals, making long-distance communication possible.

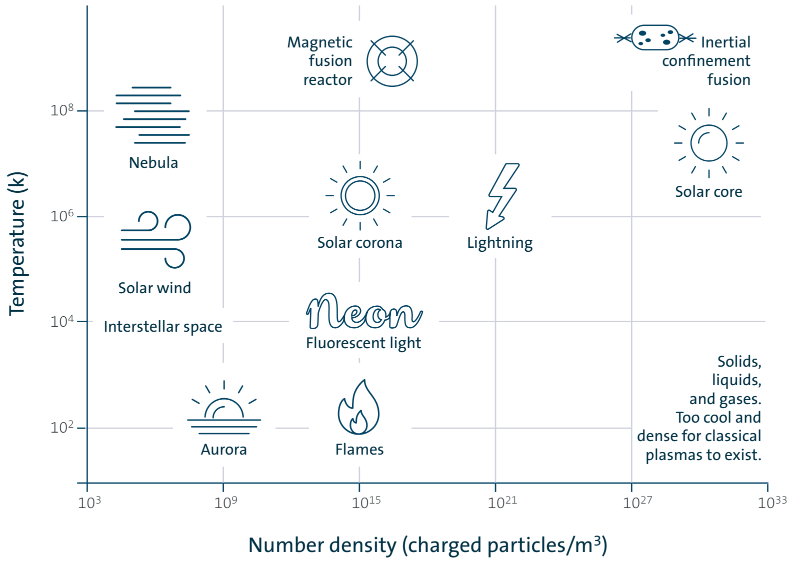

Fig 2: *Plasma temperature versus number density diagram. The region of man-made cold plasmas is indicated by the yellow box. Adapted from Ref. [1]*

Looking at the natural occurrence of plasmas it is obvious that the plasma state covers a very broad parameter range in charged particle number density (electrons and ions) and temperature (Fig. 2). There are very low-density and low-temperature plasmas like Earth's aurora but also very hot and dense plasmas like the interior of the stars.

Since plasma is ubiquitous in our universe it also interacts with the other states of matter, e.g. in star or planet forming regions, supernova outbursts, or on airless bodies like our Moon. In most cases this matter appears in the form of solid dust particles from nanometre to centimetre sizes. The dust is charged by the plasma components through direct collection of electrons/ions on its surface or indirectly by secondary electron emission.

Basic processes of dusty plasmas like charging of dust particles, their levitation and trapping in plasma and their transport are investigated in laboratory experiments complemented with theoretical and numerical models. This is important to understand for example the levitation and transport of dust clouds over the Moon. This dusty plasma was first observed by the Surveyor lander missions as horizon glow (Fig. 3).

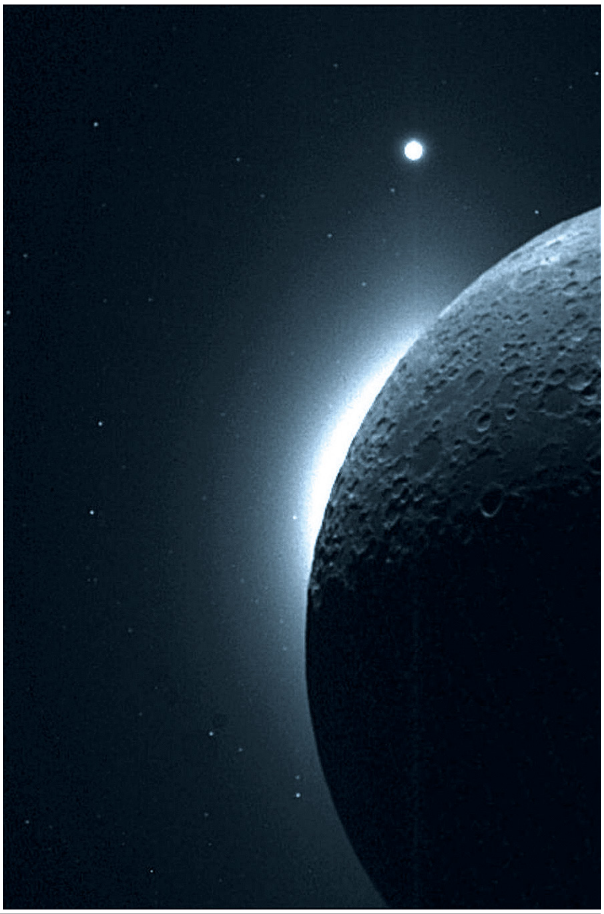

__Fig 3:__ The Moon's horizon glow, a dusty plasma effect leading to transport of dust without wind.

In natural dusty plasmas the dust can have any shape and size, making the interaction with the plasma very hard to predict. Complex plasmas are man-made dusty plasmas where the properties of dust are well defined. In most cases monodisperse, spherical particles of micrometre sizes, so-called microparticles, are used. Only then can the interaction of neighbouring microparticles lead to strong coupling, showing fluid and even solid-like behaviour.

The fundamental properties of complex plasmas are:

- Observation of individual particles (proxy atoms) in solid and liquid phases on the most fundamental, the kinetic level.
- Large mass of particles slows down the processes and enables easy observations with state of the art optical diagnostics.
- Classical interaction due to screened Coulomb interaction – quantum effects are negligible.
- Large distance between neighbouring particles allows easy three-dimensional measurement of particle positions and trajectories.
- Low damping of microparticle motion in the background gas/plasma allows the investigation of virtually undamped processes.

These properties make complex plasmas a perfect classical condensed matter system, ideal for a new approach to studying generic and scale-invariant processes like melting or crystallisation.

Besides the positive effect of slowing down processes under investigation the large mass of the microparticles – many billions of times heavier than atoms - has a very important drawback: gravity influences the microparticles. The complex plasma therefore needs gravity compensating forces on Earth or microgravity conditions.

Only under microgravity conditions can large, three-dimensional complex plasma systems be formed and investigated. This was realised from the beginning and such volume-force free experiments have supplemented the research under gravity conditions since 1996. First short-term parabolic flight experiments have been performed followed with two sounding rockets in 1996 and 1998. The resulting six minute long microgravity conditions allowed a glimpse of the new experimental area. The results paved the way for the long-term laboratories PKE-Nefedov and PK-3 Plus on the Russian segment of the ISS, operational from 2001 to 2005 and from 2006 to 2013, respectively.

The results from these two ISS labs were printed in over 100 scientific publications, covering basic topics like charging or de-charging of microparticles in plasma, the ion drag force or the agglomeration of positively and negatively charged microparticles, processes from fluid and solid state physics like crystallisation and melting of 3-dimensional complex plasmas, string formation in electrorheological plasmas, wave and shock wave propagation in liquid systems, lane formation and phase separation in binary mixtures consisting of two different particle sizes etc.

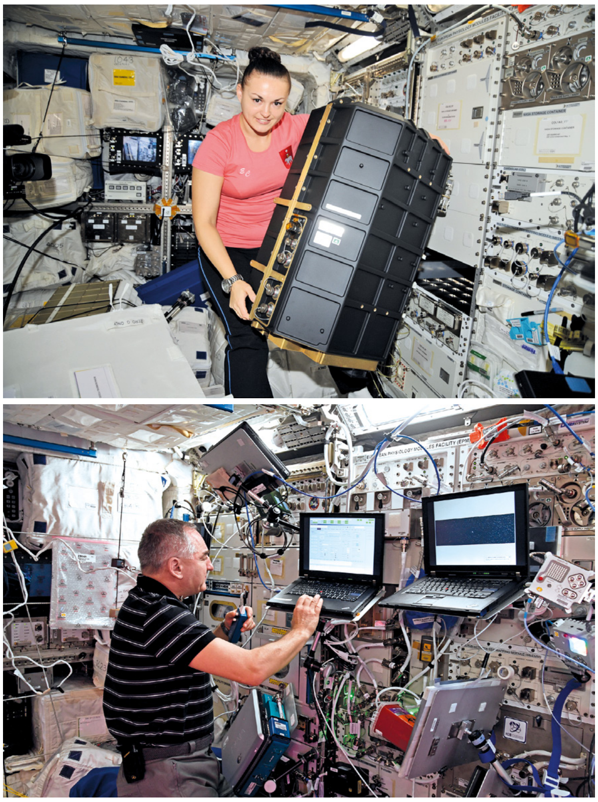

Fig 4: *Cosmonaut Elena Serova installing the PK-4 experiment container in the European Physiology Module of the Columbus Laboratory of the ISS in November 2014 (top). Cosmonaut Alexander Skvortsov performing an experiment with PK-4 on the ISS in November 2019 (bottom)*

PK-4 LABORATORY SET-UP AND RESULTS

PK-4 is the follow-up laboratory on the ISS installed in the European Columbus module in November 2014 (Fig. 4, top). The lab was designed and built at the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, in cooperation with OHB-Munich (former Kayser-Threde GmbH) as prime contractor for ESA. PK-4 is operated as a multi-user and multi-purpose facility by a core team of scientists from the Joint Institute of High Temperatures of the Russian Academy of Sciences and the DLR Institute of Materials Physics in Space at its Oberpfaffenhofen site. It is open to a worldwide community of more than 60 scientists performing basic and dedicated experiments.

PK-4 allows the study of a broad portfolio of phenomena in classical condensed matter and plasma physics. The main interest lies in the investigation of the liquid phase (Fig. 6) and flow phenomena of complex plasmas for which PK-4 is especially suited thanks to a DC-discharge and its geometry (elongated glass tube with a large observational access as shown in Fig. 5).

The experiments can be divided into three classes of fundamental questions:

1. Microscopic properties of complex plasmas: This category comprises charging of the particles, external forces on the particles (e.g. ion drag), fundamental interactions between the particles, agglomeration, and particle growth.
2. Macroscopic properties of complex plasmas: Part of this category are hydrodynamics (e.g. viscosity), thermodynamics (e.g. equation of state) and non-equilibriums aspects (e.g. lane formation, self-organisation) of complex plasmas.
3. Generic properties of classical many-body systems: Studying various problems of strongly coupled many-body systems in solid state physics, fluid physics, plasma physics, nanotechnology and even fusion physics.

The setup is specially designed to fulfil the goals mentioned above. Therefore the heart of the experiment is a dc-discharge tube as shown in Fig. 5. Typical images are shown in Fig. 6.

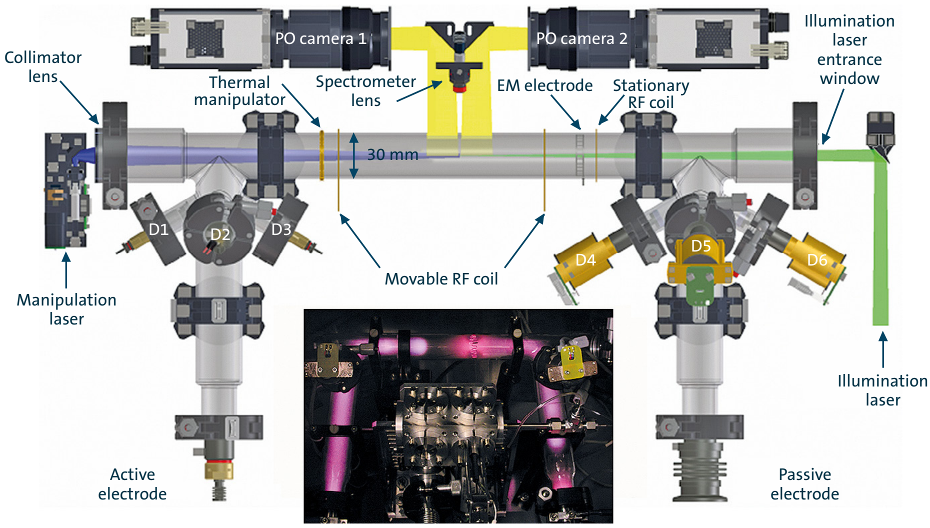

Fig 5: Schematic of the PK-4 experiment. The main working area occupies about 200 mm along the middle part of the 30 mm diameter glass plasma tube. Six microparticle dispensers (D1-D6) are mounted on the two side tubes. Each of the side tubes has an electrode on its edge. Between these electrodes the dc discharge can be ignited (the image insert shows the purple glow of a combined dc and rf discharge in argon gas). The working area of the plasma chamber is illuminated by a laser sheet and observed by the two particle observation (PO) cameras. Both cameras can be moved along as well as across the plasma chamber axis. Several manipulation devices may be used to manipulate the microparticles in the working area. Among them – stationary and movable – rf coils, thermal manipulator, manipulation laser (Fig. 6), electric manipulation (EM) electrode. Adapted from [3].

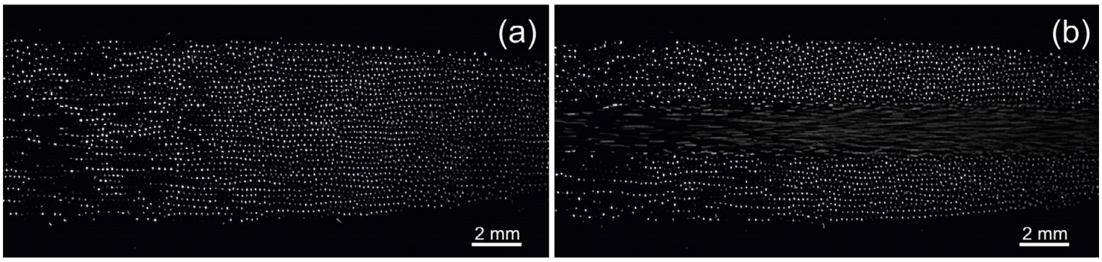

Fig 6: Video images of a cloud of 3.38 μm diameter microparticles (a) without the influence of the manipulation laser and (b) under the influence of the manipulation laser. The manipulation laser obviously creates a flow of microparticles inside the cloud. Adapted from [3].

PK-4 has been operational since 2015 but due to a leakage in the gas flow system that increased over the years and disturbed the microgravity conditions the full experimental programme could only be started after refurbishment of the flight module in July 2018. The lab has since been utilised regularly, performing three experimental campaigns per year, controlled from the control centre CADMOS based in Toulouse, France. The experimental runs are controlled from the ground station via telescience with direct connection to the flight module where the cosmonaut on the ISS supports the progress of the experiment; crew time is one of the Russian contributions to the joint ESA-ROSCOSMOS PK-4 programme. As the time delay between sending and receiving commands to/from the ISS is about 10 seconds cosmonauts assist the ground crew in running experiments, particularly so when prompt intervention becomes necessary. Processes like trapping of flowing particle clouds can only be controlled directly by the ISS crew (Fig. 4, bottom).

Results from the PK-4 laboratory have already been published in a series of papers [3-12] and cover description of the instrument [3], fundamental measurements like charges on microparticles [12], waves and instabilities [5, 7-9], special data analysis techniques dedicated to PK-4 [4, 11] and other topics [6, 10].

One aspect of the interaction of a dense microparticle cloud with surrounding plasma is the appearance of dust density waves as shown in Fig. 7, left. While a gas flow was continuously passing the microparticle cloud the response of the wave behaviour by the change in direction of the electric field was investigated [7, 9]. Following the waves over time, especially during the electric field reversal, has led to the following observations: 1. The direction of the wave propagation does not change after the polarity reversal, most probably driven by the gas flow; 2. waves exhibit large amplitudes and bifurcations, leading either to the birth or death of wave crests (Fig. 7, right, space-time plot). Dust density waves are supposed to be excited as a consequence of the ion-streaming instability associated with the electric field. Here we have measured the influence of a weak gas flow on the wave structure and propagation.

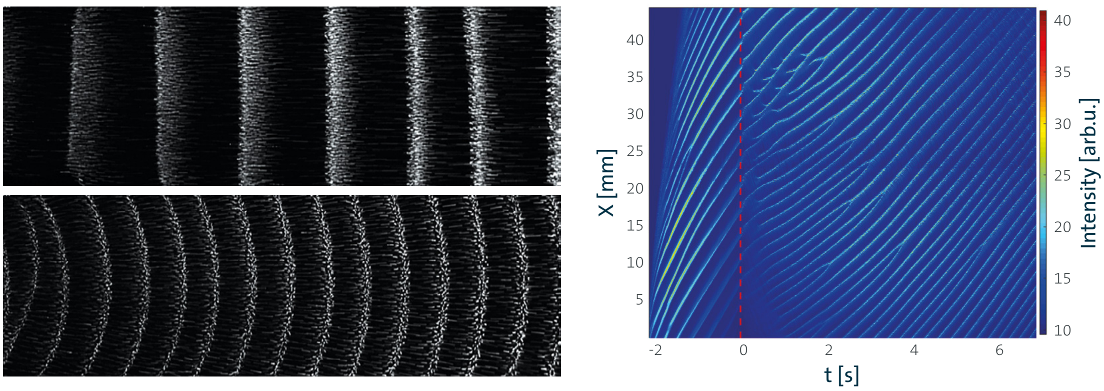

Fig 7: *Left: Original images of self-excited waves before (upper) and after polarity reversal (lower). Right: Spatiotemporal pattern of the image intensity, corresponding to wave crests, constructed using the original images. The polarity reversal (at dashed line t=0) leads to an easily visible change in slope of the wave crests. Adapted from [7].*

One of the recent highlights of the research with PK-4 concerns investigation of phase transition from an isotropic fluid to a so-called string fluid well known from electrorheological fluids. The transition is initiated by applying an alternating electric field. Due to dipole interactions the particles align along the tube axis, forming the strings shown in Fig. 8. With the help of PK-4, it was possible for the first time to observe the development of this transition on the basis of the three-dimensional distribution of the microparticles. This result will be published soon.

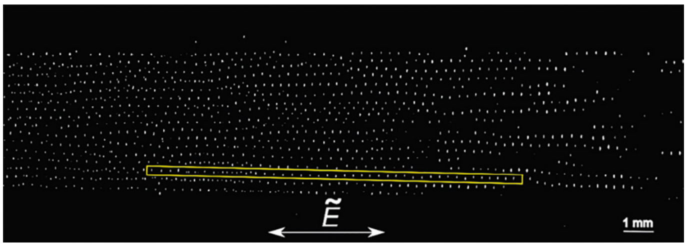

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Fig 8: Formation of long string fluids in an alternating electric field. Central axial view of the microparticle cloud illuminated with a thin sheet of laser light.

SUMMARY AND OUTLOOK

PK-4 operation has been guaranteed until end of 2022. This will allow the scientific community to finalise the full programme as planned. The timescale will even allow for reactions to unexpected results trying out ideas for new experiments. Every phenomenon observed under microgravity conditions adds new insights into the physics of complex plasmas and therefore enhances textbook knowledge on the future of complex plasma physics, natural dusty plasmas, plasma physics in general, classical condensed matter physics and multiple-particle physics.

In addition to the increase in fundamental knowledge in the field of physics, the technical know-how gained through the design, building and operation of the space plasma laboratories may be of great importance. This know-how has, for example, been made available to the new and fast growing field of plasma medicine. This field in particular has benefited from the necessity to miniaturise and functionalize large ground-based laboratories requiring particular attention to crew safety in manned space flight. It has helped optimise cold atmospheric plasma (CAP) sources for hygiene and medicine [13]. As a result of this knowledge transfer from space to ground applications, the involved scientists were able to perform the first clinical study worldwide using CAP in plasma medicine. It was an important milestone for this interdisciplinary research, connecting plasma physics and plasma chemistry with microbiology and medicine.

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Mikhail Pustylnik obtained his physics diploma from Moscow Engineering Physics Institute in 2000 and his PhD from the Joint Institute for High Temperature RAS in 2003. He was working at Nagoya University (2004-2006) and at MPI for Extraterrestrial Physics (2006-2013). Since 2012, he became a project scientist of the PK-4 ISS experiment and is continuing this activity at DLR since 2014.