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Topical: Mechanism for the Establishment of a National Microgravity Dusty Plasma Program

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I. Introduction

Experiments with dusty plasmas, also known as complex plasmas, have exploited reduced-gravity conditions since 1999 [1]. Many fundamental physics experiments have been conducted since then, not only in space but also in ground-based reduced-gravity facilities.

A dusty plasma is a mixture of micron- to nano-sized solid particles, rarefied gas, electrons, and ions. Unlike colloidal suspensions, for example, this mixture provides no buoyant force to offset gravity in Earth-based experiments. Thus, the solid particles sediment rapidly to the bottom of a chamber, so that under 1-g conditions, it is impractical to perform experiments with particle clouds that fill a three-dimensional volume. For this reason, microgravity experiments have transformed research in dusty plasmas.

A key point is that microgravity completely changes what can be accomplished in an experiment with micron-size solid particles in a dusty plasma. This situation is different from that of many fluid-physics experiments where microgravity only modestly alters the relevant physics. In a plasma, the microgravity condition is crucial as it eliminates the need to apply offsetting forces, which are necessary on Earth where a small solid particle falls like a rock when it is immersed in a rarefied gas. There are no appealing alternatives to microgravity for the study of three-dimensional clouds. In the absence of buoyancy, the only force available to experimenters to offset 1-g acceleration (allowing the dust particles to levitate in the bulk of the plasma), is a thermophoretic force [2]. However, this force requires large-magnitude temperature gradients , which cannot practically be made with the required spatial uniformity.

In coordination with other dusty-plasma white papers, which present compelling arguments in favor of expanding space-based microgravity research, here we explain further needs, in two themes:

- ground-based reduced-gravity facilities, along with ground-based research in preparation of space-flight experiments
- a U.S. National Microgravity Dusty Plasma program, to manage and support space-flight activities including preparation and execution of experiments on-orbit.

This proposal, with its *national* focus, is intended to be compatible with both domestic and international space-flight instruments.

We also note that this proposal complements, and does not contradict, the *international* partnerships proposal discussed by T. Hyde et al. [3], which is endorsed by the authors of the present document.

II. The Need for a National Microgravity Dusty Plasma Program

The preflight stage of any space experiment requires detailed planning, testing, and predictive modeling, which help minimize the risk and maximize the return on investment. Recently, U.S. investment in microgravity dusty plasma research has been made through the NASA-NSF partnership [4], which supported, for the first time, U.S. users of the Plasmakristall-4 (PK-4) experiment, which is on-orbit aboard the International Space Station. This NASA-NSF support met a great need, and was highly appreciated by the funded dusty plasma groups, which enabled them to propose microgravity flight experiments for at least five PK-4 campaigns over the past five years. However, during work for this project, the U.S. research teams also learned important lessons on the limitations of having a "user" status only. Here we emphasize the importance of U.S. involvement in all activities related to current and future microgravity dusty plasma experiments.

Since PK-4 is a facility, designed and operated by a collaboration between the German space agency (DLR) and the Russian space agency (Roscosmos), the PK-4 parameter space and available diagnostics are pre-determined and fixed. This, in turn, poses restrictions on the ideas and topics that can be pursued by the U.S. users. Lack of involvement in the design stage of a device like PK-4 also creates setbacks for the development of device modeling and predictive capabilities. Other challenges arise in data management, distribution, and interpretation. Since experiments using PK-4 are usually conducted by Russian cosmonauts and data are typically handled by multiple foreign agencies before reaching the U.S., it has not been uncommon to experience long delays in accessing experimental results. Such delays not only impede progress on the proposed research goals but also harmfully affect the professional development of U.S. early-career scientists and graduate students working on these projects.

To ensure U.S. involvement in all stages of microgravity dusty plasma experiments, a National Microgravity Dusty Plasma program should be established, which will support these ground-based efforts:

a) ground-based preparatory research (experimental and theoretical) to define physics questions and operating parameters for subsequent flight experiments, as discussed in Section IV below
b) ground-based hardware modeling, design and testing, including parabolic flights as described in Section III
c) flight-experiment planning
d) post-flight work, including data analysis, testing of theories and models, and distribution of major findings.

In addition, this program should allow for training of U.S. astronauts, U.S.-based live communication during experiments, and U.S. involvement in the development of data management plans.

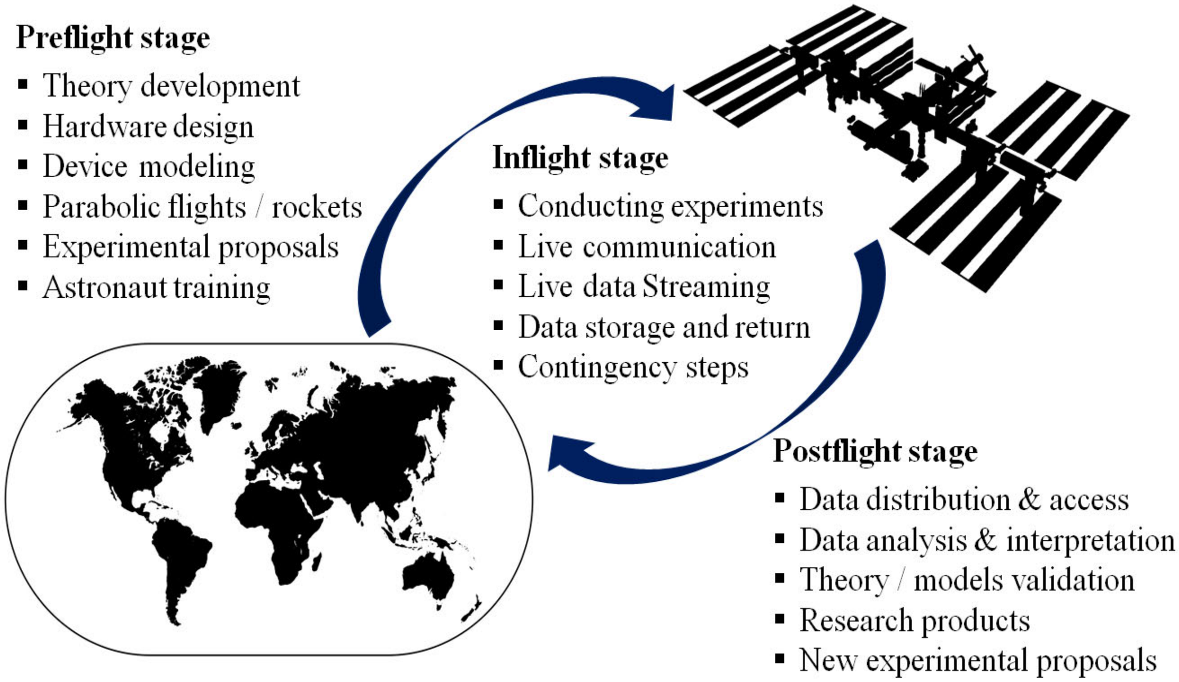

Figure 1.

The scientific effort, for dusty plasma experiments, which can be carried out through a National Microgravity Dusty Plasma Program. These efforts are carried out mostly on the ground, but are centered on space-flight experiments aboard either domestic or international instruments.

III. Ground-Based Preparatory Research

As described in other white papers submitted for BPS2023, the dusty-plasma community anticipates the development of the next generation of spaceflight experiments, which will enable exciting new research topics, including critical points, superparamagnetism, liquid crystal-like phase transitions, glassy states, and other phenomena, which can be best studied in microgravity conditions. Each of these topics requires a carefully prepared experiment, where dust-particle interactions are fine-tuned using multiple electrodes and/or external magnetic fields. The design and diagnostic development for such experiments relies on frequent communication and coordination among various research teams.

Based on the previous experience with the PK missions organized in Europe and Russia, we now realize the importance of ground-based experiments and theory, well in advance of flight experiments. These ground-based efforts help define the physics topic that will be explored, and they also define the operating parameters that are necessary. This is important because dusty-plasma apparatus typically has many adjustable parameters, which can be adjusted with many different sequences in the experimental scripts, so that a large variety of physics topics can be explored.

Theoretical and modeling efforts have proven to be very valuable both before and after experiments. Before experiments, they help define the needed parameter space so that each phenomenon can be observed. Much earlier, during the hardware development, numerical modeling of the device's plasma and diagnostics modeling can speed up the experimental design and improve predictive capabilities for proposed experiments.

Finally, introducing uniform metadata standards is crucial for both accurate and timely interpretation of results, as well as for results reproducibility. The needed analytical, numerical, and experimental expertise is rarely available within one research group. This necessitates the establishment of cross-institutional long-term collaborations. Such collaborations could operate through 5-year, center-like awards. At the national level, such multi-institutional centers can be supported by the proposed US Microgravity Dusty Plasma Program.

The need for measurement reproducibility and validation of proposed hardware functionality in the preflight stage of any space experiment is a crucial lesson that was learned in the European-Russian PK missions. Therefore, multiple experimental groups should be involved in the hardware design for microgravity dusty plasma experiments early on. In addition to developing their own unique diagnostics, these groups should be tasked with the construction of comparative experimental setups, which can be used to benchmark measurements. After a final design for the spaceflight instrument is approved, these experimentalists should unify their setups' design to obtain replica devices. This step is necessary as it allows for the development of contingency plans and quick solutions in case of an issue during the operation of the spaceflight instrument. Additionally, data from such devices is complimentary to the microgravity experiments as it allows to quantify the effect of gravity on the physics guiding the investigated phenomena.

IV. Ground-Based Microgravity Facilities

Since dusty plasmas behave entirely differently under microgravity, as compared to 1-g conditions, it is crucial to conduct numerous ground-based tests with reduced gravity before costly space-flight experiments are carried out.

In preparing flight instruments, such as PK-4 [5], it has been a common practice to employ parabolic flights. Parabolic flights allow the experimenter to fly a prototype of the space-flight instrument, and observe the dust cloud structure and dynamics during short microgravity experiments. Such observations cannot be made in a ground-based laboratory where micron-size solid particles sediment rapidly to the bottom of the chamber (typically in the sheath or pre-sheath plasma), and do not fill a three-dimensional volume in the bulk plasma as they do under microgravity conditions. Parabolic flights also allow observing where the dust cloud moves, whether it is stable, and where a camera should be positioned to observe it. Parabolic flights also allow the identification of weak forces, such as those due to ion-drag effects, attractive potentials, and thermophoretic forces, which can be obscured by 1-g gravitational acceleration.

Parabolic flights that were performed in preparation for PK-4 and previous PK missions were performed mainly under the umbrella of German Aerospace Center or ESA lead parabolic flights campaigns executed by the European Novespace A300 Zero-g Airbus, which allowed the experimenters to observe in person the operational difficulties that needed to be solved before spaceflight. These flights also provided, as a bonus, an opportunity for science results deserving of publication, for example [6-8]. Although U.S. based scientists have participated in the PK-4 space-flight experiments, they did not join the European-only parabolic flights.

We recommend that a U.S. dusty-plasma microgravity program should include multiple parabolic flights before any new U.S. instruments are flown, and again before finalizing a new campaign on an existing experiment in space. This approach allows for the most successful and efficient use of the highly valued microgravity time aboard the ISS.

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