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Topical: The Need for International and National Inter-Agency Cooperation for Support of Reduced-Gravity Research in Dusty Plasma

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1. Introduction

Space exploration, searching for life beyond the Earth, and extending the human presence in the Solar System all require an understanding of how fundamental physical processes occur within complex systems operating in low-gravity, microgravity, and free-fall conditions. The field of complex (or dusty) plasma offers the unique capability to study the dynamics and self-organization of such systems from first principles, allowing application of this knowledge both on Earth and in space. Currently, 'reduced-gravity' research within the complex plasma community is organized along two main directions: (i) experiments on the International Space Station (ISS) and (ii) studying the properties of dusty plasma naturally occurring in space. Dusty plasma experiments on the ISS, operating under microgravity conditions, are currently being employed to address major unsolved questions, such as particle charging and dynamics in multi-phase, multi-species matter, the manner in which interaction potentials 'drive' the onset of structural/phase transitions, and the universality of self-organization and pattern formation. Research related to naturally occurring dusty plasmas has already been shown to play an important role in space exploration across such diverse topics as hypervelocity dust impacts (spacecraft safety), structure of cometary tails and planetary rings (astrophysics), and dust mitigation techniques (astronaut safety) for manned missions to the Moon and Mars. Thus, the challenging questions addressed by complex plasma reduced-gravity research align well with NASA's ambitious plans for the future of space exploration.

It has long been known that the most interesting problems of our age (transformative research) are best solved through an interdisciplinary, international approach. The ISS itself is one outstanding example of international research collaboration. The ISS has revolutionized our understanding of science, engineering, and medicine under microgravity conditions. The current 'race to the Moon' is yet another endeavor that would greatly benefit from an international collaborative approach. However, the issues that come with these opportunities require formalized agreements among funding agencies within the countries involved. Although challenging, this approach is not impossible and has proven fruitful in the past, as discussed in the following sections.

2. International / National Interagency Cooperation - Proposed Mechanism

Research in reduced-gravity dusty plasma requires collaborations, both interdisciplinary and international in scope, sponsored through hard funding and/or in-kind support by the funding agencies representing each of the countries involved. To date, international partnerships of this sort have been focused across specific topics, such as processes occurring on the lunar surface or microgravity research on the ISS. A more efficient mechanism would be an umbrella program designed to unite and manage international efforts across all areas of reduced-gravity dusty plasma research. Although challenging, NASA has already successfully managed such a multi-decade experience in the ISS program, which is arguably the biggest and most complex international collaboration ever attempted among an multi-national group of space agencies.

The establishment of a comprehensive program for dusty plasma research in reduced gravity would greatly benefit from new international partnerships that combine some or all of the following features: (i) collaboration between NASA and one or more international agencies, (ii) a strong focus on interdisciplinary topics, (iii) long-term support for cross-institutional research teams, and (iv) increased numbers of partnerships between NASA and other US funding agencies. *To support the needs of the dusty plasma community, a logical first step would be to establish an international partnership between NASA and the German Space Agency, DLR. Two additional choices for such* *partnership are the European Space Agency (ESA) and the Russian Space Agency (Roscosmos).* The three foreign agencies proposed here have been US partners in the ISS program as well as strong supporters of microgravity dusty plasma research. Such international agency-driven cooperation would provide additional access across a wide range of microgravity / reduced-gravity environments, including current and future experiments on the ISS, studies planned for Artemis and future missions to the Moon and access to sounding rocket, parabolic flight, and drop tower campaigns. Further partnerships between NASA and other US national funding agencies could also support parallel ground-based activities and post microgravity experimental data analysis that often have only limited support within the current proposal environment.

The present paper highlights several successful programs already in place, which can serve as examples for a proposed international partnership in reduced-gravity dusty plasma. Additionally, a proposed mechanism focused on the establishment of a comprehensive domestic program for microgravity dusty plasma experiments is also briefly mentioned.

A. Representative examples of successful international collaborations

One representative example of a successful partnership, both interdisciplinary and international in scope, is the *United States-Israel Collaboration in Computer Science (USICCS)* [1], which is a joint program of the United States National Science Foundation (NSF) and the Israel Binational Science Foundation (BSF). The program supports research projects that develop new knowledge in the theory of computing, allowing revolutionary computing models based on emerging scientific ideas. Through this program, the NSF and BSF jointly support collaborations among US-based researchers and Israel-based researchers. US-based researchers receive funds from NSF to support travel to Israel to interact with their Israeli counterparts, while Israel-based and US-based researchers both can receive funds under the BSF program.

Another example is *Surpassing Evolution: Transformative Approaches to Enhance the Efficiency of Photosynthesis* [2], which is a joint activity between the US NSF and the Biotechnology and Biological Sciences Research Council (BBSRC) in the UK. The goal of this effort is to stimulate innovative and transformative research proposals for the enhancement of photosynthetic efficiency. Proposals funded through this opportunity focus on the development of ideas leading to a sea-change in knowledge, rather than simple incremental advances. The program is specifically designed to bring together the best researchers from the US and the UK, allowing the formation of strong transatlantic alliances. These partnerships have resulted in entirely new synergies as well as significant added value for the investments made by both countries.

B. A representative example of a successful US inter-agency partnership

A recent inter-agency partnership between NASA and NSF, in cooperation with its international partners ESA/DLR and Roscosmos, is the Plasmakristall-4 (PK-4) project [3][4], which allowed US researchers user access to the PK-4 microgravity dusty plasma experiment on board the ISS and grant funding to US teams for analysis, instrumentation, and travel. This research is directly coordinated through the joint European Space Agency and Russian Federal Space Agency team operating the PK-4 facility and has produced both world class research as well as entirely new ground investigations within the field of dusty plasma physics.

One representative result from the NASA-NSF PK-4 program is the development of an entirely new diagnostic based on laser induced fluorescence, which has been used to measure the flows of ionized and neutral atoms in a dusty plasma to the surface of ice grains [5]. Since such "icy dusty plasma" systems are assumed to be the material from which stars and planets begin to form, these results are already changing our ideas of how this process occurs. Such results are relevant to improving existing models and expanding our understanding of formation and evolution of planets within and beyond our solar system.

While the NASA-NSF PK-4 partnership allowed first-time direct US involvement in the ISS microgravity dusty plasma experiments, the US research teams participated only as users of the PK-4 device. Although the US teams involved are grateful for this opportunity and recognize that user-based access was the first logical step, the US dusty plasma community is now prepared to increase its involvement through expanded participation in the design and testing of future microgravity dusty plasma facilities. A simple way to maximize return on investment would be for NASA / NSF to become a full partner in the development of the next generation of microgravity dusty plasma facilities. (The most well developed of these currently is COMPACT, which is intended for deployment on the ISS in 2026.) This would require a NASA-NSF interagency partnership through formalized international collaboration with DLR, ESA, and/or Roscosmos.

C. One Example of a New International Partnership Mechanism

The National Science Foundation (NSF) and the Czech Science Foundation (GACR) recently signed a Memorandum of Understanding (MOU) on Research Cooperation [6]. This MOU provides the framework necessary to encourage collaboration between the U.S. and Czech research communities, establishing the principles by which jointly supported activities can be developed. Through a "lead agency model," the NSF and GACR allow collaborating proposers from both countries to write a single proposal that undergoes a single review at the NSF. A single-proposal-single-review approach ensures that in any international collaborative project, all teams involved receive funding support in a coordinated manner. This, in turn, reduces investment risk by facilitating successful accomplishments of all proposed objectives.

The NSF-GACR collaborative research opportunity focuses on discoveries and innovations in the areas of artificial intelligence, nanotechnology, and plasma science. Proposals are accepted for collaborative research in each of these areas at the intersection of GACR's Call for Proposals and participating NSF programs. Proposals are expected to adhere to the research areas, funding limits, and grant durations for participating NSF/GACR programs from which funding is sought. Since this international partnership already includes plasma physics as a topical area, it could easily be expanded to include other US agencies and/or countries. This could become a viable mechanism for accomplishing the goals of this white paper.

3. Research Topics that would Directly Benefit from the Proposed Approach

A. Fundamental Complex Plasma Questions

As mentioned in the introduction, the research topics discussed here can be roughly organized into two categories: (i) fundamental research on the ISS and other microgravity facilities and (ii) fundamental research of naturally occurring dusty plasmas. Below we list a few representative topics of current interest. It is important to note that this is by no means an exhaustive list of potential research directions.

<u>i. Critical point physics</u> (see white paper by M. Thoma et al. [7])

The critical point on a phase diagram (pressure vs. temperature) represents the conditions at which the liquid and gaseous phases of a substance merge. Beyond this point, a supercritical system exists which has the low viscosity of a gas and the high density of a liquid, thus, showing no clear separation between the two phases. It has been proposed that complex plasma can be used as a macroscopic model system for studying critical point phenomena at the kinetic (individual-particle) level. To accomplish this, the required dusty plasma system must be three-dimensional (3D), and the dust particles must exhibit attractive interactions. Investigation of critical phenomena in extended 3D clouds requires the use of microgravity conditions sustained over long periods of time (minutes or longer), which is currently only possible on the ISS. The attractive potentials needed for the existence of a critical point in dusty plasma can be best achieved with the help of multi-electrode chambers, such as the one developed for COMPACT (discussed below).

ii. Superparamagnetic dusty plasma (see white paper by M. Rosenberg et al. [8])

Previous and current research on the ISS (PK-3 Plus and PK-4 devices) has demonstrated that in the presence of AC or polarity switched DC electric fields, dusty plasmas in microgravity can undergo a homogeneous-to-string structural transition, which likely results from the formation of the electric dipole-like term in the interparticle potential. Study of this phenomena led to the discovery of electro-rheological plasma [9]. It has also been demonstrated that in the presence of an external magnetic field, a magnetic dipole interaction can also be formed in dusty plasmas where the dust grains are superparamagnetic. The resulting magnetic dipole-dipole interaction is usually anisotropic and can be repulsive or attractive depending on the orientation of the magnetic dipole. Unlike electrorheology studied on the ISS, superparamagnetism in dusty plasma has only been explored on Earth and is limited by the size of the dust grains that can be levitated against the Earth's gravity. Since the magnitude of the magnetic dipole effect scales with the size of the dust grain, the ability to use larger grains would both extend the possible parameter space and relax the requirements on the needed magnetic field strength. Thus, microgravity experiments are sorely needed to enable this emerging field of fundamental dusty plasma research.

iii. Charging and dynamics of lunar dust (see white paper by L. Matthews et al. [10])

Lunar dust, best described as a fine powder with sharp edges like glass, can become charged due to conditions on the lunar surface leading to dust lofting and transport. Understanding lunar dust dynamics is not only crucial for the development of effective dust mitigation technology (as discussed in the next section), but also key to understanding natural phenomena, such as the formation of lunar swirls and dust 'storms' at the lunar terminator. Fundamental processes affecting dust charging on the lunar surface include streaming plasma, collisions with energetic electrons, UV radiation, and weak magnetic fields. These charging processes are further complicated by the irregular shapes and composition of lunar dust particles. The problem becomes even more challenging due to the steep temperature gradients across the lunar surface, with maximum temperatures as high as +127 C and minimum temperatures as low as -173 C. Although aspects of lunar dust charging and dynamics have been explored by both domestic and foreign research groups, to our knowledge, there is no single laboratory experiment, numerical simulation, or analytical theory that encompasses the full complexity of this problem. As such, a cross-institutional, interdisciplinary, and international partnership is strongly required, attractive and necessary.

B. Dust Mitigation for Artemis and future missions to the Moon

Lunar dust has been identified as a major 'contamination' issue for lunar missions since Apollo. Charged by various processes on the surface of the Moon, dust affects every aspect of extra-vehicular activities on the Moon, causing vision obscuration, false instrument readings, surface coating and contamination, loss of traction, mechanism and seal failures, thermal control problems, and hazards to astronauts' health. Additionally, dust charging on the lunar surface causes grounding issues due to potential differences, which affect multiple aspects of human activities on the Moon (e.g., measurements of lunar crust properties, drilling and mining activities, habitat building.) Given the primary goal for Artemis is to establish the first long-term presence on the Moon, lunar dust research and mitigation are crucial for mission success. The achievement of this massive goal will require partnerships with international collaborators working on similar topics. Future missions to build settlements, develop mining operations, and/or conduct continuous research on the Moon will also require a well-developed understanding of the dusty plasma environment that exists across various locations on the Lunar surface. This enormous scientific challenge requires international, cross-disciplinary expertise, as well as coordination with other governments currently working on lunar missions. Finally, Artemis has a goal to foster diversity. One aspect of this goal is to land the first woman and person of color on the surface of the Moon by 2024. Cooperative, international partnerships would support this goal while also establishing a more diverse and inclusive science environment.

C. COMPACT dusty plasma microgravity experiment

The discovery of the first two-dimensional dusty plasma crystal on Earth established the scientific basis for 21 years of microgravity experiments on the ISS, where research moved to three-dimensional dusty plasma crystals and liquids. The next generation of dusty plasma experiments on the ISS will enable, among other topics, the study of exotic states of matter (e.g., supercritical systems, liquid crystals and glassy states), superparamagnetism, universality of phase transitions, and pattern formation in soft matter. Dusty plasma labs on the ISS were traditionally developed by German-Russian collaborations. To maximize returns on investments in dusty plasma, the US should seek to become a full partner in the development of COMPACT, the next generation microgravity dusty plasma experiment intended for deployment on the ISS in 2026. Involvement in COMPACT and future microgravity dusty plasma experiments can best be accomplished through establishment of an international cooperative agreement. Such a partnership should include US funding for hardware development, on-ground experiments, theory development and numerical modeling, and microgravity tests (drop towers, parabolic flights, and sounding rockets), all of which are crucial in the design and predevelopment phase of microgravity dusty plasma experiments.

4. Summary

Dusty plasma research in reduced gravity aligns well with a number of NASA's goals. However, this type of research is inherently complex and interdisciplinary, which results in the necessity for cross-institutional projects. An international collaborative approach both minimizes risk and maximizes return on investment, while also fostering a thriving global dusty plasma community. Existing international efforts of the sort proposed have already proven to provide a rich environment for encouraging future scientists, engineers, and educators to take the risks required to pursue the discoveries and new knowledge necessary for success. Such efforts have also been shown to foster excellence in the production of new research and technology while integrating education and research across an international, interdisciplinary platform. This proposal recommends increased funding of the exceptional opportunities which exist for both discovery and creativity, allowing a diverse science community access to research opportunities not otherwise possible.

5. References

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