White Paper for Frontiers of Plasma Science Panel

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Indicate the primary area this white paper addresses by placing “P” in right column. Indicate secondary area or areas by placing “S” in right column

| • Plasma Atomic physics and the interface with chemistry and biology | “P”, “S” |
| • Turbulence and transport | |
| • Interactions of plasmas and waves | |
| • Plasma self-organization | P |
| • Statistical mechanics of plasmas | S |

Indicate type of presentation desired at Town Hall Meeting.

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**Title:** Future research directions for dusty/complex plasmas

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(Limit text to 3-pages including this form. Font Times Roman size 11. 1 page of references and 1 page of figures may also be included. Submit in PDF format.)

- Describe the research frontier and importance of the scientific challenge.

The two fundamental forces that organize matter at macroscopic (to universal) scales are gravity and electromagnetism. For particle-laden plasma systems, it is the competition between electromagnetic and gravitational forces that lead to the static equilibrium and dynamic properties at all temporal and spatial scales. These systems consist of a broad spectrum of physical phenomena ranging from micrometer-sized colloidal systems to light-year spanning planetary nebula that exhibit the full range of plasma phenomena ranging from waves and turbulent phenomena to self-organization and phase transitions. However, to truly understand the physical processes that govern these systems, it is necessary to simultaneously understand both the microscopic and macroscopic processes that occur in these systems. Therefore, the research frontier is the emergence of mesoscopic plasma physics through the competition between electromagnetic and gravitational forces.

Dusty/complex plasma research embodies this concept of “mesoscopic plasma physics”. This field of plasma science lies at the intersection between electromagnetic and gravitational forces and at the
intersection of microscopic and macroscopic phenomena. Research in this field has focused on deconstructing the elements of the dusty plasma to gain insights into processes that govern the system. The future of the field lies in understanding how the dynamics at the microscale (e.g., how the individual grains interact with the surrounding plasma) gives rise to the larger scale, macroscopic phenomena (e.g., how does the collection of electrons and ion by the dust grains impact the density distribution, potential structure, and spatial self-organization of the surrounding plasma). Moreover, as the field expands into new regimes beyond the parameter space of unmagnetized laboratory plasmas, new challenges ranging from understanding how other forces affect sub-micron grains (e.g., momentum transfer from ions and neutrals and thermophoresis) to understanding if and how self-organization will occur in environments dominated by hot plasmas or radiation, it is clear that a multi-scale approach is required to address these issues.

• **Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.**

**Approach:** The central problems of dusty plasma research are charging and screening. In all environments, the dust grains acquire charge due to a combination of the collection of ions and electrons from the ambient plasma and various thermal and radiative processes in the plasma environment. The ambient plasma responds to the depletion of charge through self-consistent screening processes that, in turn, modifies the charging of the grains. A grand challenge remains the development of a single model of dust grain charging and screening that is benchmarked against an unambiguous, in-situ measurement of the particle charge.

From these central challenges, all other areas of dusty plasma research are derived. Figure 1 shows some of the physics topics that comprise this research. Many of these will be described in detail in other white papers. Some selected topics include:

a) Particle growth and breakup – Can a predictive model of how nanometer and micrometer-sized particles form and decompose in cold (laboratory and industrial) and warm (magnetic fusion, astrophysical) plasmas and how do other forces (including momentum transfer from ions and neutrals, thermophoresis, radiation induced secondary emission) along with electromagnetic and gravitational forces contribute.

b) Self-organization – What are the limits under which ordered two-dimensional and three-dimensional structures can be formed beyond the conditions that exist in low temperature laboratory plasmas, e.g., strongly magnetized plasmas, hot plasmas, microgravity conditions, etc.?

c) Thermal properties – What is the flow of energy between the electrons, ions, neutral particles, and dust particles and how does this lead to the observation of enhanced dust temperatures and ultimately contribute to both the self-organization and phase transitions observed in dusty plasmas?

**Resources:** Dusty/complex plasma research is primarily conducted by single investigators with a team of student researchers. This has proven to be an excellent platform upon which to build an active community of researchers. Maintaining this infrastructure is an critical intellectual foundation upon which to begin the exploration of new regimes. The frontiers that extend the range of plasma parameters, electromagnetic environments, and thermal conditions under which dusty plasmas are studied will require collaborative partnerships in order to build and operate mid-scale, multi-user facilities – e.g., the proposed U. S. Dusty Plasma Microgravity Facility, the European Space Agency PK-4 microgravity laboratory, and the Magnetized Dusty Plasma Experiment.
• Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.

Dusty plasma research is an inherently multi-disciplinary activity that impacts many different areas of science. This impact is derived from the ability to simultaneously study the microscopic and macroscopic processes in these systems – enabling a unique insight into complex phenomena. Figure 2 illustrates just a few of the areas that are impacted by the study of complex plasmas. Each radial pair suggests a microscale and macroscale area: for example, fundamental plasma science includes processes primarily dominated by electromagnetic forces such as charging and particle growth, whereas plasma applications, which includes dust contamination in industrial\textsuperscript{17,18,19} and fusion\textsuperscript{21,22,23} plasmas, are driven by both electromagnetic and gravitational phenomena. Additionally, dusty plasmas are a “model system” that can leverage – and possibly make contributions to - adjacent fields such as colloidal physics and soft-condensed matter research.
References

Figure 1: Summary of the physical processes and application of dusty plasmas as an example of mesoscopic plasma physics at the intersection of electromagnetic and gravitational forces. A representation of the microscopic processes (e.g., particle growth, force balance, etc.) that lead to macroscopic phenomena (e.g., waves, self-organization, etc.) which depend upon the interaction between gravity and electromagnetic forces.

Figure 2: A summary of the broad and multidisciplinary impact of dusty plasma research. Each radial pair indicates a microscopic and macroscopic phenomenon as well as indicating topics that cross the boundary between electromagnetic and gravity-dominated phenomena.