White Paper for Frontiers of Plasma Science Panel

Date of Submission: 19 June 2015

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 | S |
| • Statistical mechanics of plasmas | P |

Indicate type of presentation desired at Town Hall Meeting.

| “X” |
| Oral |
| Poster |
| Either Oral or Poster |
| Will not attend | X |

Title: Thermodynamic properties of 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.

For over three decades, research into the physics of complex (dusty) plasmas has steadily grown. Dusty plasmas consist of a background of ions, electrons and neutral atoms in which small, charged microparticles, i.e., “dust grains”, are present. In both the laboratory and natural plasma environments, the collection of ions and electrons onto the surface of the dust grains is an important charging mechanism. However, in regions such as the edges of fusion experiments or star forming regions, ionizing radiation, secondary emission, and thermionic emission processes also play important roles determining in the dust grain charge as well as allowing the grains to become a source of ions and electrons to the background plasma. Therefore, a dusty plasma is an ensemble system in which there is a strong, mutual interaction between the charged grains and the surrounding plasma.

Ongoing studies of dusty plasmas suggest that there is an incomplete understanding of the thermodynamics and statistical mechanics of these systems. Some studies – particularly those performed in radio-frequency glow discharge dusty plasmas – suggest that the dust kinetic temperature \( T_d \) can range from a temperature that is comparable to the temperature of the background gas when the dust is in a crystalline state \( (\Gamma = \text{electrostatic energy : thermal energy} >> 1) \) to substantially larger than the electron.
temperature ($T_r$) when the dust is in a weakly-coupled state ($\Gamma \sim 1$). Other studies – notably those performed in dc glow discharge dusty plasmas with $\Gamma \sim 1$ – suggest that the dust kinetic temperature can be substantially larger than the electron temperature ($T_e$). More recently, several studies have focused on the controlled heating and melting of plasma crystals in order to gain new insights into the propagation of thermal energy in the dusty plasma. While all of these studies are providing valuable information, the central questions remain: (1) What is the explanation for the observation of high ($T_d >> T_e$) dust kinetic temperatures? (2) What are the mechanisms that allow energy to flow between the electrons, ions, neutral atoms, and dust particles in a dusty plasma?

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

**Approach:** The use of micron-sized particles in dusty plasmas combined with the relatively long time scales established by their large mass means that dynamics of the charged dust grains can often be directly imaged using standard video imaging technologies. This allows diverse behaviors ranging from single particle motion to self-organization and collective effects to be studied in exquisite detail in these systems. Researchers have developed a wide range of technologies – such as laser light scattering,\(^8,9\) stereoscopic\(^10,11\) and tomographic\(^12\) imaging, digital holography,\(^13\) three-dimensional, lightwave imaging (e.g., using a plenoptic camera)\(^14\) and particle image velocimetry (PIV)\(^15,16,17,18\) – to measure the positions and velocities of the charged microparticles in the plasma. From these measurements, it is possible to extract the velocity space distribution function of the dust component of the plasma and – subsequently – to begin deriving thermodynamic quantities.

The underlying challenges of this work are to understand the fundamental mechanisms that contribute to the dust kinetic temperature and to determine how differences in the experimental configurations contribute to the wide range of experimental results. At the present time, there is no single model that adequately describes the dust self-heating mechanism. For example, works by Quinn and Goree have considered both electric potential fluctuations and dust charge variations as possible mechanisms for heating the dust grains.\(^19,20\) However, their work suggests that neither of these mechanisms may be strong enough to account for the observed temperatures. By contrast, a recent study by G. Norman, et al.,\(^21\) suggests that charge fluctuations may be responsible for inducing vertical oscillations of the dust grains near an electrode that leads to dust grain heating. Additionally, works by Joyce, et al.,\(^22\) and Rosenberg\(^23\) have suggested that ion-dust streaming instabilities may play an important role in dust grain heating and the generation of dust waves, while work by Avinash\(^24\) suggest that thermal electric field fluctuations may be responsible. This wide range of approaches illustrates of the state of understanding – or perhaps, lack thereof – of the thermal properties of dusty plasmas. This area of research remains a rich topic in the dusty plasma community with many opportunities remaining for advancing knowledge. Among the important research issues in this area are:

**Issue 1:** What is the interpretation of a measurement of the dust velocity distribution?

**Issue 2:** Can ion-dust streaming interactions lead to higher dust kinetic temperatures?

**Issue 3:** How do the thermodynamic properties of a dusty plasma evolve in plasma conditions that extend beyond laboratory conditions – e.g., magnetized plasma, microgravity plasmas, warm to hot plasmas, etc.?
Resources: Dedicated laboratory experiments with advanced imaging capabilities – e.g., high speed imaging, access to particle image velocimetry and particle tracking tools, etc. – are the main requirement for this area of research. Therefore, support for the development of new imaging tools, for example, the use of lightfield (plenoptic) cameras to enable single camera, three-dimensional imaging, would make a significant impact in the ability to these measurement. Finally, having access to the a variety of “shared user” facilities such as the proposed U. S. Dusty Plasma Microgravity Facility, the European Space Agency PK-4 microgravity laboratory, and the Magnetized Dusty Plasma Experiment will provide opportunities to extend the range of plasma conditions under which these thermodynamic properties can be investigated.

• Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit.

The potential impacts of this work are two-fold. First, measurements of the velocity space distribution function provides the most fundamental information about the statistical properties of a plasma system. Dusty plasmas are unique in that this measurement can be performed with exquisite detail over wide range of coupling states. This enables highly detailed studies of a fundamental aspect of the physics of plasmas that can provide insight into range of plasma systems, from weakly to strongly coupled plasmas. Second, this work will allow a better understanding of the coupling between the dust and the background plasma and provide insight into the fundamental mechanism(s) for dusty plasma heating that remains elusive.
Figures

Figure 1: (a) Contour plot showing the three-dimensional wave structure of the naturally occurring dust acoustic wave. Plots showing the distribution of (b) thermal energy and (b) energy transport within the dusty plasma system calculated from the measured velocity space distribution function.
References: