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

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

Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	
Poster	
Either Oral or Poster	X
Will not attend	

Title:	Bringing experiments to the field of statistical physics, using dusty 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 research frontier is to carry out experiments to study the dynamical underpinnings of statistical physics at the microscopic level, using individual particles in a dusty plasma as analogs for atoms and molecules. For the purpose of the Frontiers Workshop categories, this frontier is not limited to the realm of statistical physics – it is also connected to collisional transport.

The importance of this challenge arises from the dilemma that statistical physics at the level of particles is primarily a theoretical area. Experiments are lacking because atoms and molecules are too small to allow tracking their motion.

A mesoscopic experimental system is needed, one that is large enough that video imaging can track the motion of the particles, yet small enough to allow at least thousands of particles to interact. The individual particles in this mesoscopic system can serve as an analog of atoms and molecules.

An older mesoscopic experimental system, used in the area of condensed matter physics, is the colloidal suspension, consisting of microspheres immersed in a liquid solvent [1]. Experimenters image the micron-size particles of solid matter by video microscopy, and track their motion, allowing the

experimental study of such phenomena as two-dimensional melting. When desired, the colloid particles can be charged electrically by providing two kinds of ions in the solvent, so that the micron-size particles interact not just by touching but also at distances of microns. A disadvantage of colloids, however, is that the solvent is so massive that the microsphere motion is overdamped, and its thermal contact with the microparticles makes it impossible to vary the kinetic temperature of the microspheres much, as compared to room temperature.

A frontier in experimental statistical physics is the use of a newer mesoscopic experimental system: dusty plasma. Like a colloid, a dusty plasma contains micron-size particles of solid matter. These particles are large enough that they can be imaged by video microscopy, so that their motion can be individually tracked. As in colloids, the micron-size particles are electrically charged, and the medium that fills the volume between them has two kinds of free charges, which are electrons and positive ions in the case of the dusty plasma. Unlike colloids, however, the medium that fills the volume between the particles has a very low mass – it is a rarefied gas, so that the motion of the microparticles is not overdamped, and it is possible to vary their kinetic temperature.

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

The exploitation of this new analog system as a tool for experimental statistical physics has just begun. Most of the present generation of dusty plasma experiments make use of a partially-ionized plasma at low temperature, with ionization of a background gas that is sustained under steady conditions by a radio-frequency or DC electric field, without large magnetic fields. Polymer microspheres are injected into this plasma, where they each gain negative charges of thousands of electrons so that they repel one another strongly. They are illuminated by laser beams and imaged by commercial video cameras with a macro lens. Presently, most experiments rely on simple two-dimensional imaging, and they track the motion of the microparticles using image analysis techniques like those used by colloid experimenters.

Some of the statistical physics topics that have been studied so far, using this method, include:

- experimental validation of the popular Green-Kubo theory for transport coefficients [2],
- experimental observation of localized heating due to viscosity [3],
- experimental measurements of viscoelasticity based on individual particle motion [4],
- experimental verification that the theoretically popular Tsallis velocity distribution for nonequilibrium thermodynamics can be observed at the level of individual particle motion.

Future research topics will likely include nonequilibrium transport and fluctuations, observed at the level of individual particles.

Future exploitation of this experimental approach can be advanced by improving the instrumentation. Most experiments are presently performed on the tabletop, in PI laboratories, and this will likely continue in the future, but further opportunities can be unlocked by the special capabilities of user facilities:

- One US-based facility is the new Magnetized Dusty Plasma Experiment, which has the prospect of enabling experimental observations of superdiffusion transport, for example.
- Another US-based facility is the Dusty Plasma Physics Facility, a project that is waiting for approval for the International Space Station. It will exploit weightless conditions in space to avoid sedimentation of dust particles to the bottom of a plasma chamber, so that three-dimensional physics can be studied, not just two-dimensional physics.

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

Dusty plasma research is highly interdisciplinary:

- Dusty plasmas occur not just in laboratory experiments, but also in interstellar space, planetary rings, and comet tails.

- The mitigation of dust contamination is a key problem for fusion energy. The first walls of magnetically confined fusion reactors erode, due to plasma exposure, yielding dust that accumulates hazardous quantities of tritium fuel.

- Dusty plasmas are often compared to ultracold plasmas, which is a new area of experimentation. In both of these plasmas, Coulomb collisions have a dominant effect, so that collisions govern not just transport but also waves and instabilities. In other words, both plasmas are experimental tools for the study of *strongly coupled plasmas*, a research area that previously lacked adequate experimental methods.

- Dusty plasma are also compared frequently to the field of soft condensed matter, which includes colloids [1].

The main societal benefit of fundamental research is a greater understanding of nature.

References (Maximum 1 page)

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   Charged colloidal suspensions and their link to complex plasmas
   AIP Conference Proceedings, vol. 1397, p. 201 (2011) PDF

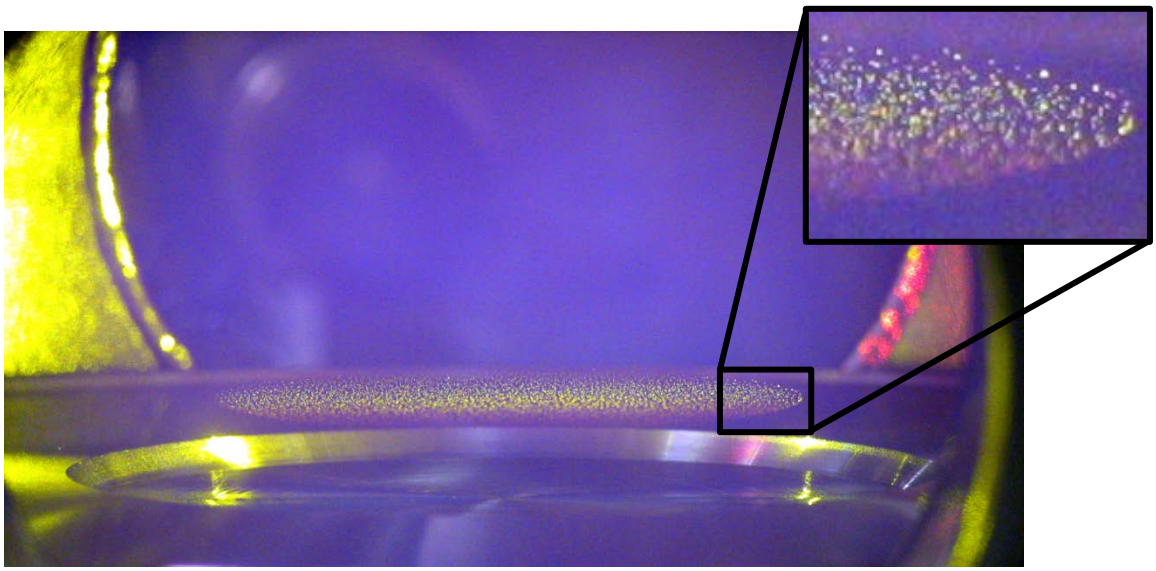
2. Yan Feng, John Goree, Bin Liu, and E.G.D. Cohen
   Green-Kubo relation for viscosity tested using experimental data for a two-dimensional dusty plasma
   Phys. Rev. E, vol. 84, article no. 046412 (2011) PDF

3. Yan Feng, J. Goree, and Bin Liu
   Observation of temperature peaks due to strong viscous heating in a dusty plasma flow
   Phys. Rev. Lett., vol. 109, article no. 185002 (2012) PDF

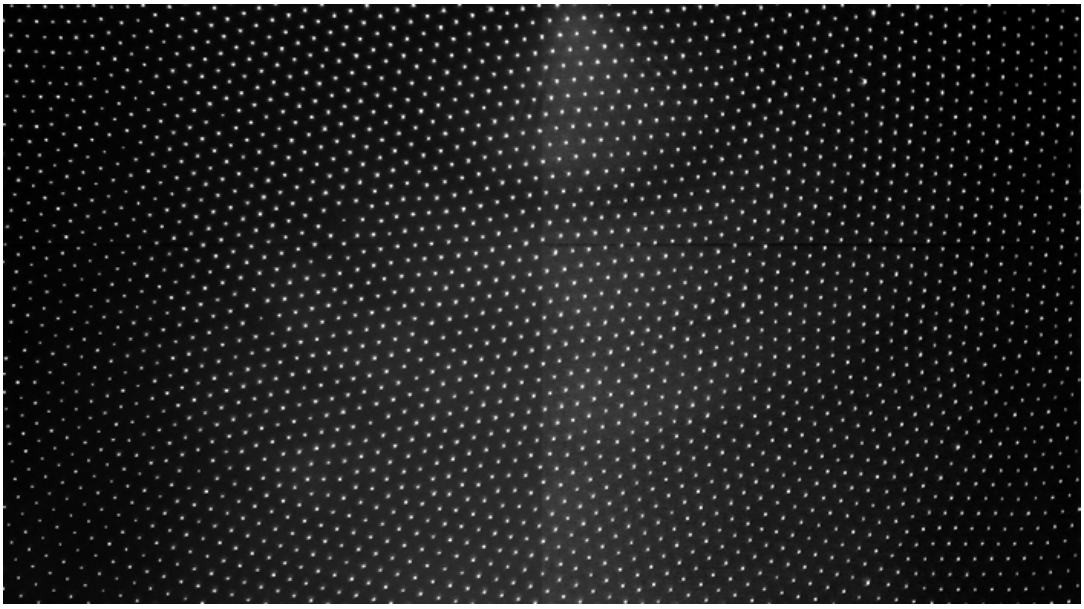
4. P. Hartmann , M. C. Sándor, A. Kovács, and Z. Donkó
   Static and dynamic shear viscosity of a single-layer complex plasma
   Phys. Rev. E, vol. 84 article no. 016404 (2011) PDF

5. Bin Liu, J. Goree, and Yan Feng
   Non-Gaussian statistics and superdiffusion in a driven-dissipative dusty plasma
   Phys. Rev. E, vol. 78, article no. 046403 (2008) PDF

Figures (maximum 1 page)



1. Side-view photograph of a single-layer dust cloud consisting of polymer microspheres. It is levitated a few mm above a lower electrode in an rf argon plasma, which is seen as a purple glow. A horizontal sheet of yellow laser light illuminates the dust particles. The dust cloud has only a single layer due to gravity; this is avoided in experiments on the International Space Station.



2. Top-view image. This is a single video frame, as recorded by a video camera. Thousands of dust particles are seen, separated by ~0.5 mm. The particles move slowly enough that they can be tracked precisely using image analysis software. Random thermal motion, as well as drifts and waves, can be observed in great detail. The sample shown in this image is self organized in a crystalline pattern; the dust particles act as a *strongly coupled plasma* due to their large electric charges. The crystal can be melted by applying laser manipulation. This experimental system allows the study of the statistics of individual particle motion in equilibrium or in flows.