White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***20 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	
• Interactions of plasmas and waves	P
• Plasma self-organization	
• Statistical mechanics of plasmas	

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	Direct observation of particles as they interact with waves in dusty plasmas under microgravity conditions
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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 particle-wave interaction observed at the level of individual particles. This is done by exploiting dusty plasmas. Gravity is a limiting factor for the experiments, however, so that is attractive to use the International Space Station (ISS).

The importance of this challenge arises from the difficulty of observing individual electrons and ions. In most plasmas, waves can only be detected by measuring quantities, such as number density or magnetic field, that lack information about individual particles. Imaging discrete particles as they move in the presence of a wave would greatly improve upon this situation, providing particle-level data with a richness that is usually seen only in simulations. Such imaging is possible with dusty plasmas [1-4], and less commonly with pure ion plasmas [5].

Dusty plasmas are a mixture of electrons and positive ions, plus an unusual component: solid microspheres. These so-called dust particles are microns in diameter, making them large enough to image directly, as seen in the Figures. These particles are electrically charged, so that they participate in waves, the same as ions and electrons. The most common wave is a compressional mode excited by ion flow, known as the dust acoustic wave, which is like an ion acoustic wave.

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

Experimental methods for dusty plasmas are new. They started in the early 1990s. So far, most experiments have been done in low-temperature glow discharges, which do not melt the dust particles.

Imaging makes these experiments special. Dust particles are big enough to image directly with simple video cameras, with laser beams to illuminate them. This imaging diagnostic allows measuring the positions and velocities of individual particles as they move, so that the experimenter obtains data not just for continuum quantities, but also for *discrete particles*. For the study of wave-particle interactions, a wave diagnostic that tracks the motion of discrete particles is a game-changer.

Gravity is a limiting factor. Unlike electrons and ions, micron-size dust particles are so heavy that they settle to the bottom of the plasma chamber. A vertical electric field is required to levitate them, and this is indeed now a common practice. However, the mass that can be suspended is limited, so that ground-based experiments are done in a small volume, with dust occupying only a two-dimensional horizontal layer, or filling only a three-dimensional volume that is so small that only a few wavelengths fit within it, as seen in Figure 3. A larger 3D volume requires eliminating the effects of gravity.

Microgravity conditions will advance the frontier. Microgravity can be achieved either with parabolic trajectories in aircraft or with spacecraft. Dusty plasma experiments have been done in parabolic flights (Figures 1 and 2), but the time duration of the microgravity is limited, and vibration levels are high enough to disturb the waves. The International Space Station (ISS) greatly improves upon this situation, making it ideal for dusty plasma experiments. So far, dusty plasma experiments on ISS have been performed by a German-Russian group, using the recently retired PK-3 and PK-3 Plus instruments [6]. They yielded a rich scientific output, including a large number of Physical Review Letters and thousands of citations. As impressive as that program was, it only scratched the surface of what is possible, because PK-3 and PK-3 Plus were limited in their imaging capability, their size, and their manipulation tools.

The Dusty Plasma Physics Facility (DPPF) is a more capable instrument now being considered by NASA, to fulfill U.S. leadership in the exploitation of the ISS. Because its imaging diagnostic will yield data at the level of discrete particles, DPPF is perfect for wave-particle interaction studies. Topics that can be studied include wave-particle trapping, wave breaking [1], nonlinear synchronization of modulated waves [2-4], and merging of wavefronts due to nonlinearity.

Aside from waves, transport processes will be another major topic for plasma research on DPPF.

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

An impact on plasma science is the exploitation of a discrete-particle diagnostic to observe wave-particle interactions in a way that is not practical in other kinds of plasma experiments.

A societal benefit is the utilization of the International Space Station for physical science. The ISS generates considerable public interest. Presently, most science performed on ISS is health science, involving the crew members. Because of the rarity of physical science experiments on ISS, and the visual nature of its main diagnostic, dusty plasmas on ISS have an unusual capacity to intrigue non-scientists.

References (Maximum 1 page)

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2. W.D. Suranga Ruhunusiri, and J. Goree
   "Synchronization and Arnold tongues for dust density waves"
   Physical Review E Vol. 85, article no. 046401, April 2012 PDF

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5. Daniel H. E. Dubin and T. M. O'Neil
   "Trapped nonneutral plasmas, liquids, and crystals (the thermal equilibrium states)"
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   "Complex plasma laboratory PK-3 Plus on the International Space Station"
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7. O. Arp, J. Goree, and A. Piel
   "Particle chains in a dilute dusty plasma with subsonic ion flow"
   Physical Review E, vol. 85, article no. 046409, April 2012 PDF

Figures (maximum 1 page)

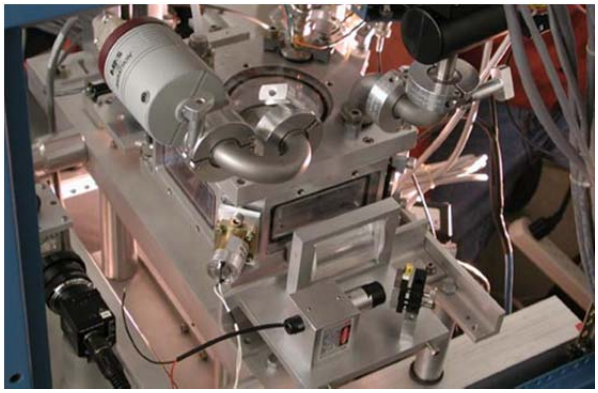

Fig. 1 Dusty-plasma scientific payload for the author's KC-135 parabolic flights. A plasma is ignited by applying radio-frequency high voltages to parallel-plate electrodes inside the chamber. Polymer microspheres are then injected into the plasma with a solenoid-powered shaker. The dust is illuminated by thin sheets of laser light and imaged through the windows using video cameras.

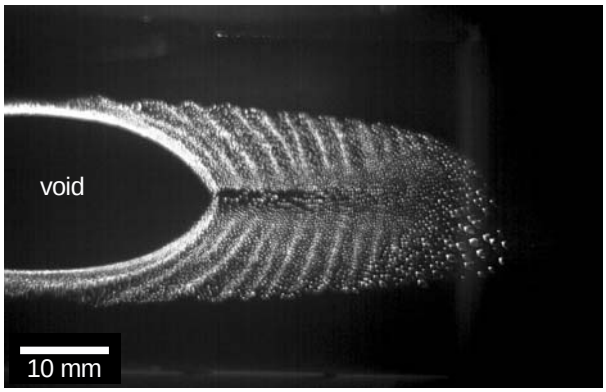

Fig. 2 Cross-sectional image of 6.8 micron polymer microspheres suspended in a plasma in a parabolic flight. A video camera is filtered so that it detects only laser light scattered by the dust. Individual dust particles are visible. The dust acoustic wave (DAW) excited by ion flow, grows to nonlinear amplitudes. It is easily seen in the images. The void is a dust-free region due to the Coulomb collisional drag force imparted by flowing ions. Image from [7].

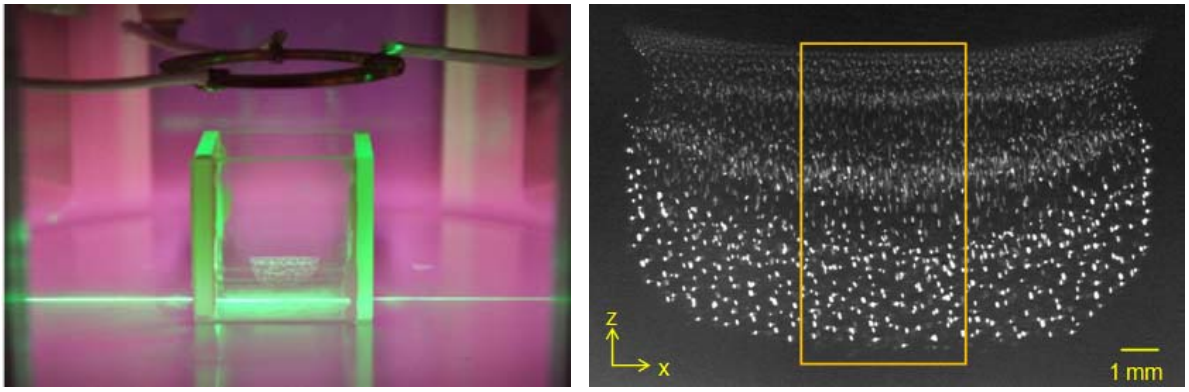

Fig. 3. Ground-based experiments allow sub-centimeter-size studies of nonlinear wave phenomena such as synchronization and wavefront merging. Dust particles are illuminated by green laser light. Gravity limits the size of experiments, causing particles to settle to the bottom. Images from [3].

Fig. 4. The International Space Station (ISS). will house the Dusty Plasma Physics Facility (DPPF). Remotely controlled experiments of significant size and time duration will be possible, with direct imaging of discrete particles. Image from NASA.