White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***July 22, 2015***

Indicate the primary area this white paper addresses by placing "P" in right column.
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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• 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:	Seeking convergence of experiment and theory for strongly coupled 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.**

Strongly coupled plasmas are dominated by Coulomb collisions, so that they often behave differently from the more common weakly coupled plasmas [1,2]. Previously this area of research was mainly theoretical, but new experimental methods began twenty years ago.

The frontier is to develop new classes of theories suitable for nonuniform conditions with multiple charge species, as is common in experiments, while improving the experiments themselves.

Strongly coupled plasmas have particles with either a high density, high charge, or very low temperature. The metric for coupling strength is $\Gamma = E_c / kT$, which is the ratio of interparticle potential energy $E_c = q^2/(4\pi\, \varepsilon_0\, r)$ and the thermal energy, for particles with a typical spacing r. When $\Gamma \sim 1$, the plasma is said to be "non-ideal", with roughly equal contributions from collisional and non-collisional processes [1]. A plasma with $\Gamma \sim 1$ is roughly analogous to a non-ideal gas. Neutron star crusts [3], white dwarf stars [4,5], and giant planet interiors [6,7] are natural examples of a non-ideal plasma. Inertial confinement fusion [8,9] and other high-energy-density experiments with warm dense matter [10] are examples of laboratory-made non-ideal plasmas. Much larger values of Γ are uncommon in astrophysics, but attainable using dusty plasmas and pure ion plasmas. For $\Gamma \sim 10$ to 100, a particle responds greatly to its nearest

neighbors, and cannot easily move past them; Vlasov theory fails under these conditions. Such a plasma with $\Gamma \sim 10 - 100$ is analogous to a liquid, except that the constituent particles are all free and charged, so that they respond to electric and magnetic fields. A plasma with $\Gamma >> 100$ forms a Wigner crystal.

The theoretical literature for strongly coupled plasmas is much older than the experimental literature. The theory mostly considers a single polarity of charge, using the so-called one-component plasma (OCP) model, and it mostly considers uniform conditions. Typical problems that are investigated this old way are equations of state and structural arrangement of particles.

The newly developed experimental tools include ultracold plasmas, dusty plasmas, pure ion plasmas, and warm dense matter made with high energy pulsed beams. In these experiments, the plasmas are finite in size so that there are often large gradients, and charge separation as well. They exhibit phenomena such as transport, waves, instabilities, shocks, expansion, and separation of charges that cannot be modeled using a homogeneous OCP-based theory.

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

The experimental tools, which are recent in their development, are dusty plasmas [11-13], ultracold plasmas [14], pure ion plasmas [15], and high energy density plasmas [10]. Strong coupling occurs in dusty plasmas due to a high charge, in ultracold and pure ion plasmas due to low temperatures, and in high energy density plasmas due to high densities. All these plasmas are finite in size so that they have significant gradients. Except for pure ion plasmas they have multiple charge species which can move separately to create large macroscopic fields that can dominate the particle motion. Pure ion plasmas are even more extreme, in the effect of macroscopic electric fields, because there is no particle of opposite polarity to cancel macroscopic fields at all. These experimental plasmas already indicate needs for new kinds of theories, yet the experiments themselves are far from mature, so that there is considerable opportunity to improve their capability and the range of physical topics that are explored. Typical topics envisioned in this frontier include transport, waves, and instabilities arising from gradients and charge separation.

Existing theoretical tools, such as the old OCP approach, and newer innovations such as density functional theory, tend to assume uniform conditions and not account for macroscopic fields. Simulations that account for two or more charge species are promising, but these are still uncommon because the physics of a second charge species is often simplified by assuming it merely shields the first charge species, without any macroscopic gradients or drifts, so that the simulation assumes a Yukawa or Debye Huckel potential and tracks the motion of only one charge species, i.e., an OCP model. New theoretical tools, both analytic and simulations, are needed that can account for gradients as well as multiple charge species. As an example, for transport one promising analytic approach is based on potentials for near-equilibrium conditions [16].

A plasma physicist who works primarily with weakly coupled plasmas might find this frontier to be surprising, because in weakly coupled plasma research it has almost always been common to recognize the experimental significance of gradients and separate behavior of different charge polarities. For strongly coupled plasmas, however, a lack of experimental observations until recently has allowed theories to develop less than we now envision.

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

Seeking convergence of theory and experiment in a wide class of problems is fundamentally how science should develop.

Strongly coupled plasmas are relevant to plasmas in astrophysics, controlled fusion, and weaponry. Strongly coupled plasmas also exhibit much in common with the field of soft condensed matter physics, and in particular colloidal suspensions, which have micron-size charge particles plus ions of two opposite polarities [17]. Commercial examples of colloidal suspensions include paint.

References (Maximum 1 page)

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