White Paper for Frontiers of Plasma Science Panel

Date of Submission:	**June 5, 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	S
• Plasma self-organization	P
• Statistical mechanics of plasmas	S

Indicate type of presentation desired at Town Hall Meeting.

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

Title:	**Laboratory Experiments Relevant to Space, Solar, and Astrophysical Plasmas**
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Importance

It has frequently been presumed by space, solar, and astrophysical (SSA) researchers that laboratory plasmas are irrelevant to SSA plasmas because of the enormous difference in scales between laboratory plasmas and SSA plasmas. However, during the last decade it has been demonstrated that many phenomena relevant to SSA plasmas can in fact be examined in lab plasmas. The advantage of a lab plasma is that it is reconfigurable, controllable, repeatable, and in principle can be studied in infinite detail. Three main issues govern such lab studies, namely (i) making the plasma, (ii) diagnosing the plasma, and (iii) modeling the observations. Using lab plasmas to investigate SSA phenomena is important because these investigations offer a means for understanding phenomena that could not otherwise be understood and as well as a means for testing new ideas and models.

Approach and Needs

The approach is to create lab plasmas governed by the same physics as SSA plasmas, determine what is happening, and then either compare observed behavior to models or use these observations to develop new models. When a good match is achieved between observations and models, confidence is developed in the models and the models can be applied to SSA contexts.

Critical needs include methods to create SSA-relevant lab plasmas and diagnostics for measuring what is going on. For many decades plasma research focused on studying plasmas that were homogeneous

(e. g., uniform plasma in constant magnetic field) or had relatively simple geometries (e.g., toroidal). The plasmas were typically in equilibrium (e.g., described by the Grad-Shafranov equation) or had small perturbations such as waves or instabilities relative to the equilibrium. In contrast, SSA plasmas often have significant inhomogeneities. For example, solar coronal loops have footpoints connected to the solar corona and astrophysical jets originate from accretion disks. SSA plasmas are also often far from equilibrium, examples being erupting solar loops and astrophysical jets. Behavior at an interface between two plasmas having significantly different parameters is often important; an example is the shock that forms when a fast plasma slams into a slow plasma. SSA plasmas are also often far from thermal equilibrium. New research devices capable of creating SSA-relevant inhomogeneous, non-equilibrium, non-thermal plasmas are required. A complementary requirement is new diagnostic capabilities. This latter need is readily seen by comparing improvements in diagnostics during the last two decades to improvements in computers during the same period. Diagnostics have had only incremental improvements whereas computers have improved by orders of magnitude, now having thousands of co-processors, calculating on millions of grid points in fluid simulations, and following over a trillion particles in a PIC code. An equivalent improvement in diagnostics is required. An ultimate capability would be to measure the vector electric and magnetic fields and the electron and ion distribution functions at a statistically large number of locations in the plasma with time resolution faster than the cyclotron frequency and space resolution better than a Debye length. While attaining such a resolution now seems impossible, if it could be achieved, then experiments would tell all there is to know. A realistic goal for the near future would be to develop non-perturbing diagnostics that could measure the vector magnetic field at several thousand locations simultaneously with similar resolution for density and temperature. Furthermore, this new diagnostic should be inexpensive, small, and portable so it could be widely used. Such an improvement would be like going from having a single oscilloscope to having many channels of transient digitizers or like going from having a probe measuring at a single location to having an image.

Three specific needs are (i) lab experiments that simulate the dusty plasmas occurring in space, e.g., the water-ice dusty plasmas that exist in noctilucent clouds on the edge of space, in Saturn's rings, and in astrophysical situations such as accretion disks and molecular clouds, (ii) lab experiments that simulate solar coronal loops, and (iii) lab experiments that simulate astrophysical jets.

Ice dusty plasmas can be created in the lab [1,2]; see Fig. 1 for examples of water ice grains spontaneously formed in weakly ionized plasma. The growth rate, shape, and saturation size of water-ice dust grains can be determined in lab experiments for a wide range of environments. The interaction of the dust grains with background plasma, background neutrals, and electromagnetic radiation could be determined in these lab experiments. Dust particles in accretion disks presumably charge to the floating potential of ambient plasma so all dust particles would have the same polarity and therefore mutually repel. On the other hand, it is thought that dust grains agglomerate to form progressively larger structures until gravity becomes sufficiently strong for the agglomeration to produce planets. It is unclear how same-sign particles would overcome their mutual repulsion and

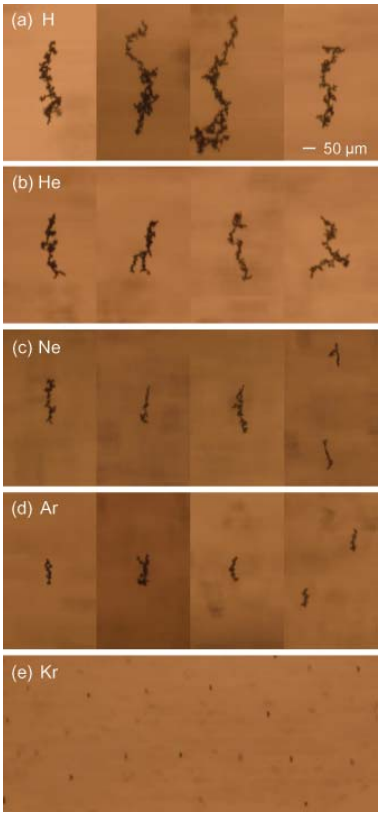

Figure 1 Levitating ice grains formed in plasmas with different background gases (from Ref.[2]).

agglomerate. This could be studied in the lab and would require cooling the background plasma neutrals and ions to cryogenic temperatures to mimic space situations, high speed movie cameras to resolve the dynamics, growth and mutual interaction of micron-size particles, diagnostics to measure the temperature and density of plasmas having ions and neutrals colder than 100 K, means for tracking the trajectories of individual water molecules that agglomerate on water-ice grains in a dusty plasma, and means to study the observed 3D vortex motion of ice dust grains.

Solar corona loops undergo violent eruptions that can be duplicated in the lab [3,4] since the MHD equations have no intrinsic scale; see Fig. 2. The merging of two coronal loops to form a larger loop could be studied in the lab as well as how a loop becomes filled with plasma.

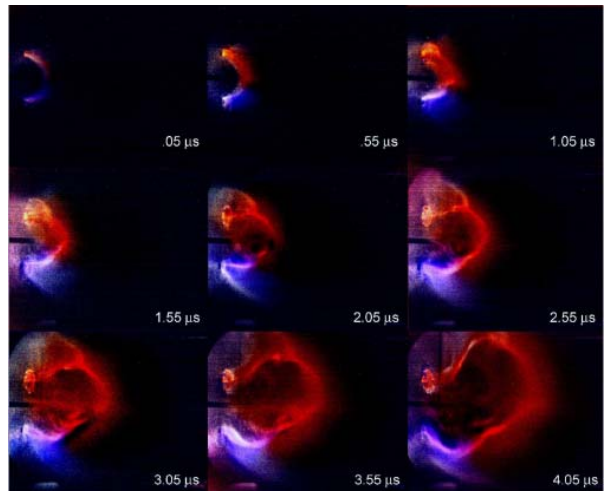

Figure 2 Solar corona loop setup with different gases (hydrogen, nitrogen) injected at the two footpoints to test the hypothesis that jets emanate from each footpoint to populate the loop with plasma.

Astrophysical jets can be duplicated in the lab [5-7] ; see Fig. 3. The mechanism for collimation and the consequences of a jet colliding with a molecular cloud can be studied. The jets can undergo violent kink instabilities resulting in secondary Rayleigh Taylor instabilities that in turn drive collisionless reconnection. These can be studied in the lab and compared to numerical and analytic models.

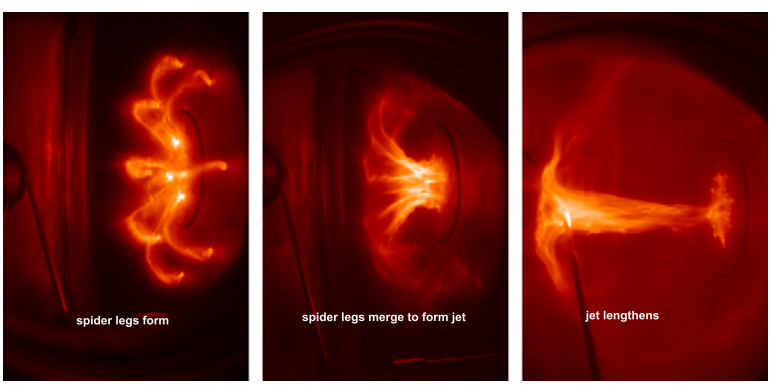

Figure 3 Lab astrophysical jet sequence: First spider legs form, then inner parts of legs merge to form jet, then jet lengthens.

Impact

Understanding the behavior of highly heterogeneous plasmas would reveal what happens in realistic situations. This would show how mass flux from a surface feeds a plasma or how heating and turbulence results when one plasma impacts another plasma. This understanding would have societal impact; for example, solar eruptions can damage power lines, interrupt communications, damage spacecraft, and endanger astronauts. This research would improve understanding of star and planet formation because astrophysical jets and dusty plasmas are intimately related to accretion disks, the means by which stars are formed and planets develop. Understanding how ice dusty plasmas are created and behave will shed light on the formation and behavior of Saturn's diffuse rings, how noctilucent clouds form and interact with radar and optical electromagnetic radiation, and how dust absorbs and polarizes electromagnetic radiation in astrophysical situations.

References

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