White Paper for *Frontiers of Plasma Science Panel*

Date of Submission:	***June 15, 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	S
• 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	X
Poster	
Either Oral or Poster	
Will not attend	

Title:	**Heat Transport Rates in Plasmas**
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- ***Describe the research frontier*** **and importance of the scientific challenge.**

Research Frontier: Develop a comprehensive understanding of rates of heat transport in the plasma state, with the inclusion of radiation, electrons, acoustic waves and instabilities, strong coupling, multiple species effects, and any other important factors.

In numerous plasma applications at all densities, heat is introduced somewhere in the plasma and then is transported through the plasma. When the plasma is weakly coupled, has gentle temperature gradients, has comparatively small energy in acoustic waves, and when the absorption length of thermal photons is very long, then the iconic theory of Spitzer and Harm describes the transport of heat, as is described in various textbooks.[1] But even so, that theory does not self-consistently describe the perturbations of the particle distributions at all velocities. There is scope for substantial research, both theoretical and experimental, to establish and confirm a comprehensive understanding of heat transport rates. Existing theories of heat transport have been very strongly driven by specific applications, with work generally ceasing when whatever can be done easily has been done. What is needed is the study of heat transport from a more fundamental perspective, aiming at a comprehensive basic understanding.

For heat transport by electrons, the challenges to understanding involve the fundamental nonlocality of the energy transport (variations in electron range with energy), the competition between distortions and restorations of a Maxwellian velocity distribution, and the production of electromagnetic fields that may impede the transport. In addition, standard models of diffusive transport involve a ratio of scales (as "Log

Λ") whose meaning becomes, at best, confused in dense plasmas. Figure 1 shows x-ray images from an experiment in which lasers drove a heat front through a Ge-doped foam.[2] This experiment is in a regime that might be described as a laser-driven heat front, but the details of the energy propagation are not well understood and would be unlikely to be modeled correctly in detail by existing codes.

For heat transport by radiation, the challenges to understanding involve nonlocality, as is the case with electrons, and also the complex array of absorption and emission processes that participate in the flow of heat.

For strongly-coupled plasmas, the ions become correlated. One must find that modes of ion motion (acoustic waves but perhaps other types of interaction as well) can in some circumstances carry important amounts of heat through the system, thereby decreasing the degree of coupling.

One can note that there are entire journals devoted to heat transfer in mechanical systems, and by comparison that the work to date in plasmas is quite limited.

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

At root, the understanding of all forms of heat transport is based upon interaction rates evaluated by statistical calculations. In the simplest cases these involve integrals over known distribution functions, describing the statistics of particle distributions. But in more interesting cases the distribution functions are not known and indeed are affected by the transport. Even so, the plasma is a system of very many bodies and statistical methods should have some leverage in coming to understand the behavior.

Real experimental progress will depend heavily on diagnostic progress. To address the connection of observed heat transport rates with calculated values, one will need measurements of the electron distribution function out to several times the thermal energy, measurements of the photon spectrum even when the emission is quite dim, and measurements of ion-ion correlations in dense plasmas.

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

Progress in understanding heat transport in plasmas will improve our predictive understanding of plasma behavior. This fundamental advance will impact a wide range of plasma research and applications. In particular, such knowledge will be important for the invention and design of industrial processing and energy systems that involve the flow of heat through plasma.

References (Maximum 1 page)

[1] R.P. Drake, High Energy Density Physics: Fundamentals, Inertial Fusion and Experimental Astrophysics. (Springer Verlag, 2006).

[2] K. B. Fournier, J. H. Satcher, M. J. May, J. F. Poco, C. M. Sorce, J. D. Colvin, S. B. Hansen, S. A. MacLaren, S. J. Moon, J. F. Davis, F. Girard, B. Villette, M. Primout, D. Babonneau, C. A. Coverdale, and D. E. Beutler, Absolute x-ray yields from laser-irradiated germanium-doped low-density aerogels, Physics Of Plasmas 16 (2009).

Figures (maximum 1 page)

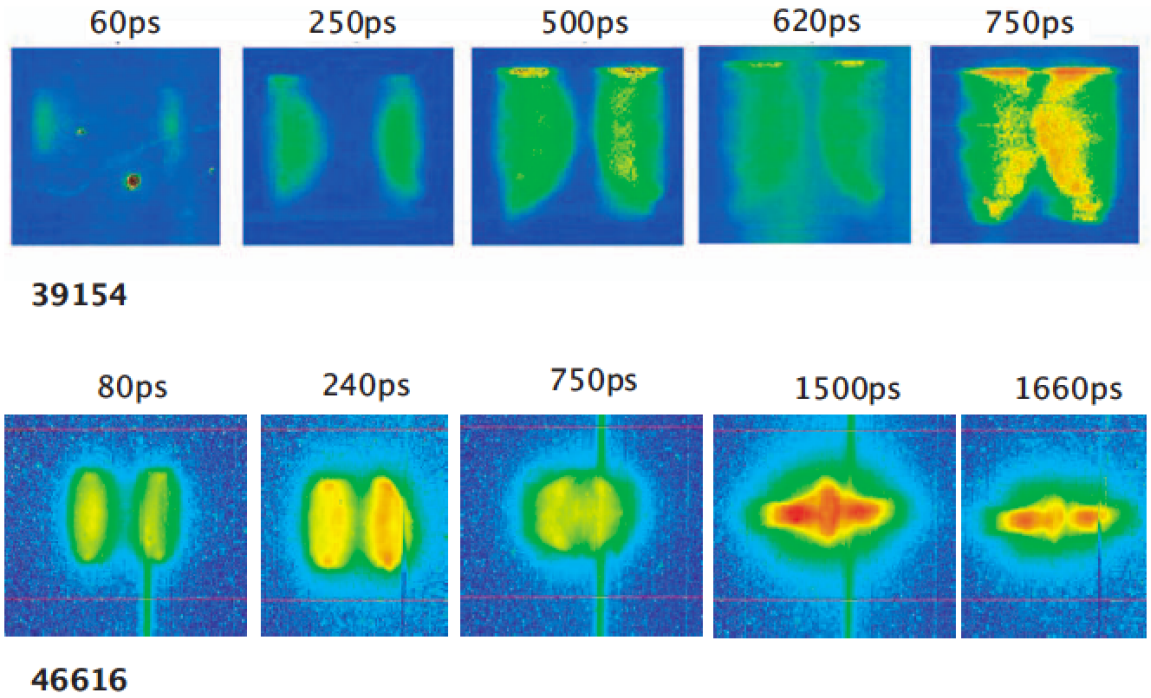

FIG. 11. (Color) XRFC images for shots 39154 and 46616. Both targets demonstrate the overlap of the heated x-ray regions from the open ends of the cylinders, but the target for 46616 shows the formation of a late-time jet of plasma on axis due to compression from cylinder-wall material that has stagnated on the axis.

Figure 1. The upper image shows x-rays emitted from a laser-driven heat front, created by irradiating a Ge-doped aerogel foam with several laser beams. From: Fournier et al., Phys. Plasmas 2009.