White Paper for *Frontiers of Plasma Science Panel*

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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	
• Turbulence and transport	P
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• Plasma self-organization	S
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Indicate type of presentation desired at Town Hall Meeting.

	"X"
Oral	X
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Title:	Heliospheric-relevant MHD Turbulence in Laboratory Plasma
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The universe is a magnetically-turbulent place. From the interior of stars, to interstellar winds, to planetary magnetospheres, magnetic field lines embedded in vast plasmas are extremely dynamic systems. Magnetohydrodynamic (MHD) turbulence has typically been studied through observations made by orbiting satellites or interplanetary spacecraft[1]—measurements made directly in these vast turbulent environments. On the other hand, laboratory studies of magnetic turbulence have centered around stability and confinement issues such as those encountered in fusion tokamak cores or edges. In fusion, turbulence is a detriment and research on it in that arena has focused on ways to mitigate and subdue it. However, in space, turbulence is unavoidable. Though studies of turbulent magnetic fields have been conducted in laboratory plasma[2,3], research into the kind of dynamical magnetic turbulence seen in space settings remains in a relativity nascent stage; thus, there is ample opportunity and motivation to study MHD turbulence in a more natural state both from the perspective of gaining a deeper understanding of turbulence itself, but also to produce a better picture of the heliosphere, the only plasma system that impacts us on a daily basis.

Satellite instruments have been measuring the turbulence associated with the solar wind and the magnetosphere for decades. However, despite extremely fruitful results, there remain many limitations to the study of heliospheric-relevant turbulence by satellites. These include the large expense both in time and money, as well as the ability to take only a few simultaneous spatial measurements (the state-of-the-art is four employed by satellite groups Cluster and the recently launched MMS). Turbulent plasma research has been augmented by computer simulation but there also remain challenges in reproducing the wide span of scales and physical mechanisms present in turbulent systems. Laboratory approaches to the study of heliospheric turbulence have lagged behind. This can be

attributed both to the lack of ability to make plasma with similar parameters as heliospherically-relavant plasmas, as well as on the focus on plasmas with rigid background fields. However, MHD turbulence research can be less dependent on absolute plasma parameters as other plasma astrophysical topics. As demonstrated by recent experiments on the Swarthmore Spheromak Experiment, techniques for generating dynamical magnetic turbulence coupled with high bandwidth, high dynamic range diagnostics can allow for laboratory-based, heliospherically-relevant turbulence to be studied and useful comparisons to be made[4,5,6].

Next generation satellite missions are also moving into a plasma regime where interpretations of the signal will become more difficult. Satellite measurements of turbulence generally rely on the Taylor Hypothesis, the ability to convert frequency spectra to wavenumber spectra based on the Doppler shift of the bulk flow. Upcoming missions to study the generation of the solar wind, in particular, will lose the ability to make such a simplification. While simulation and theorists have already begun the development of tools for analyzing this data[7], the situation also provides opportunity for laboratory based MHD turbulence experiments to make valuable input. Spacecraft exploring the early solar wind and the solar corona such as Solar Probe Plus[8] and Solar Orbiter[9] will be encountering plasma that is even more similar to what can be produced in the laboratory—higher absolute densities and magnetic field strength—compared to solar wind plasma or magnetospheric plasma at 1AU. Before these missions are even launched, laboratories dedicated to MHD turbulent study can be developing predictions for these observations. Also key to the laboratory approach is the ability to control parameters. Observational data is at the whim of the sun. If controllable plasma turbulence can be produced (for example, specifically high or low beta plasma), more detailed measurements can be made.

The Swarthmore Spheromak Experiment (SSX) at Swarthmore College has been at the forefront of MHD turbulence research in relation to heliospheric-relavant turbulence. In particular, the experiment has produced results which compare favorably to a variety of heliospheric plasmas using a variety of turbulence metrics including spectrum analysis[4,6], structure functions[4,5], and correlations, as well as newer metrics associated with information theory and entropy[10]. SSX has shown the ability to control some aspects of turbulence, particularly through the tunable injection of magnetic helicity[5]. The next iteration of this research comes with the development of a new laboratory at Bryn Mawr College, an all-women's school near Philadelphia, which will expand upon the design of SSX. In particular, the new laboratory will feature a slightly larger chamber to mitigate the effects of the boundary and longer pulses to increase the stationary period of the measured turbulence. The new experiment will also focus on other aspects of MHD turbulence including the interaction of turbulent magnetic fields with static magnetic fields (e.g. modeling of the collision and resulting turbulence of a coronal mass ejection with a dipole field around a planet or a satellite.)

Furthermore, since scale separation is an key element of turbulence, an even larger experiment can be developed with higher energy input in order to maintain a wide separation between the injection energy scale (the size of the chamber) and the dissipation energy scale (gyroradii or skin depths). On SSX, the scale separation is about two orders of magnitude with a chamber on the order of 15cm and energy input of about 10kJ. However, with an experiment with ten times the volume and 10-100 times the energy input, scale separations of four orders of magnitude would not be unreasonable.

A deeper understanding of MHD turbulence can have a myriad of benefits from basic turbulence theory to prediction of and protection from space weather. Many questions stemming from hydrodynamic turbulence research remain unanswered including questions about the nature of intermittency and the connection to the Navier-Stokes equation. Though studying turbulence using plasma rather than a conventional, neutral fluid adds complications, it can also add more opportunities for measurement and control of the turbulence for experiments. Understanding MHD turbulence can lead to better ideas of how coronal mass ejections are formed, and how they evolve, propagate and

interact with other magnetic structures. Specifically, laboratory experiments can observe how energetic particles are transported during these turbulent collisions which can inform the development of protection force fields around satellites or spacecraft, for example. Implications of MHD turbulence can span beyond the heliosphere, probing questions associated with the interstellar medium, colliding solar jets, black hole accretion disks and galactic dynamics. Finally, such MHD turbulence research can circle back to fusion research itself, and may open avenues for improvement of current confinement and turbulence reduction designs or spur the development of other approaches.

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