White Paper for *Frontiers of Plasma Science Panel*

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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	P
• Interactions of plasmas and waves	S
• 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:	**Plasma Turbulence in Nature and Laboratory**
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General Importance: Understanding turbulence is at the cutting edge of basic plasma research. The importance of turbulence to fusion plasmas concerning confinement and anomalous transport has long been recognized. Although a rigorous understanding of plasma turbulence is yet to be fully realized significant insights into its nature have been gained through the study of low frequency and electrostatic turbulence in fusion plasmas. Turbulence, in its generalized form is more ubiquitous in the unbounded plasmas in the space and astrophysical environment where it determines the dynamical evolution and formation of structures. One of the major challenges in the analytic and numerical investigation of turbulence is its multi-scale nature both in terms of space scales and time scales. Nonlinear hydrodynamic (wave-wave) and kinetic (wave-particle) interactions can affect the spectral evolution through redistribution of energy in different scale sizes as well as affect electromagnetic wave and energy propagation by changing ray trajectory and group velocity. This, in turn, affects the global evolution of the plasma distribution and saturation. In space plasmas some of this is currently becoming apparent in the NASA/Van Allen Probe data from the radiation belts. Turbulence may explain the origin of exotic astrophysical phenomena, such as formation of giant magnetic structures observed in the molecular clouds that contain dusty plasmas and where stars are born. This begs the intriguing question: Does plasma turbulence influence the birth of a star? The knowledge gained from the understanding of the natural plasmas is likely to lead to innovative laboratory applications, but remains a largely unexplored and a challenging frontier area of plasma physics.

Approach: In general, turbulence can be weak or strong depending on the energy density. For lower energy densities a perturbative expansion approach leads to the weak turbulence framework in which some analytical progress can be made. On the other hand, strong turbulence research has been mainly limited to dimensional analysis and numerical studies in the hydrodynamic and magneto-hydrodynamic (MHD) limits primarily for heliospheric applications to understand the solar wind behavior. However these approaches do not highlight the microphysics of turbulence. Historically, when the observations were sparse and crude, the focus of solar wind turbulence was restricted to larger scale sizes for which the ideal MHD treatment is adequate. With the advent of modern high-resolution space probes, finer scale solar wind plasma structuring is becoming evident. In particular, spectral steepening is observed in between the inertial and the dissipation ranges as the scale sizes become comparable to the ion skin depth and smaller. The spectral power law behavior in this regime does not scale as the Kolmogorov -5/3 law, indicating that the physics is different at smaller scales than that at larger scales in the inertial range. An obvious question is what is the physics behind these departures from the ideal MHD picture? Could kinetic effects, ignored in the MHD formulation, be important?

There has also been decades of turbulence research in connection to fusion devices but they were mainly limited to low frequency drift and Alfven wave turbulence using a gyro-kinetic formalism. Recent studies in the inhomogeneous space plasma medium indicate that weak turbulence in the intermediate frequency range between the ion and electron gyro-frequencies can play a critical role in the magnetospheric and heliospheric plasma evolution and affect the "space-weather" especially under disturbed conditions when wave amplitudes are large. Kinetic plasma effects such as linear and nonlinear wave-particle resonances become important. For example, a baffling observation in the Earth's radiation belts is that the increase of energetic trapped electron flux during geomagnetic storms can quickly revert back to the normal ambient values for some storms but not for others. Why? This is yet an unsolved issue but there is a possibility that weak turbulence effects such as nonlinear wave-particle resonance may be responsible for it. This is not just an issue of academic interest but has practical implications since the orbital lifetime of satellites is indirectly proportional to the population of the trapped energetic electrons in the radiation belts. There are a number of such open questions, such as cause and effect and saturation of triggered emissions observed in the radiation belts as well as in tokamaks associated with fast particles in which the role of nonlinear meso-scale plasma dynamics and turbulence is central. These issues are not only intellectually challenging but practically compelling as well and are ideal focus areas for future plasma research.

With the advent of modern computers it is now becoming possible to simulate turbulence in realistic 3D electromagnetic environment including kinetic effects. Laboratory experiments can focus on limited but key elements of turbulence necessary for validation and anchoring of theoretical models. The validated models can then be applied to analyze and interpret the huge amount of space data that are routinely being gathered by national and international space missions. The synergy between laboratory and space turbulence study will allow deeper analysis of turbulence properties and vastly increase our understanding of the basic physics of turbulence.

Challenges and Benefits of Turbulence Research: Dedicated laboratory experiments to understand the key physics of generalized electromagnetic turbulence have been few and these experiments are constrained by the finite extents of laboratory devices. Quantization effects of a finite laboratory device can constrain the development of turbulence compared to its evolution in unbounded natural plasmas and this is not an easy problem to overcome. However it is possible to supplement the laboratory experiments

by using the near-Earth space as a natural laboratory for turbulence research. There are two aspects to using space as a laboratory; i) analyzing the natural *in-situ* data that are routinely gathered by satellites and ii) conducting an active experiment in the space plasma to induce turbulence and measure the consequent signatures. The advantage of the former method is that the data is readily available but the drawback is that the data is usually in the saturated state when the measurement is made and hence there is no information of the initial conditions from which the turbulence evolved. On the other hand, if turbulence can be seeded in space by some means, e.g., broadcasting waves from a space-based antenna, injecting high-speed beams in space, creating strong spatial gradients by introducing electron capturing agents in space, etc., then the initial conditions will be known and a more complete picture of the evolution and saturation mechanism of the turbulence can be quantitatively studied. Such experiments should be complemented with numerical particle-in-cell (PIC) simulations. Comparison of the experiments with 3D electromagnetic PIC simulations will lead to simple analytical physics models for turbulence from which relevant scaling laws can be gleaned.

Broad Open Questions in Turbulence Research:

Is plasma turbulence either strong or weak? Can the two types of turbulence coexist with spatial and temporal scale separation or overlap in meso-scales?

What is the criterion for seamless transition of hydrodynamic to kinetic nature of turbulence in terms of scale size of plasma fluctuations?

How can nonlinear and nonlocal aspects of plasma turbulence be addressed in the same analytical framework?

Can plasma turbulence be controlled, mitigated, or suppressed through active mitigation techniques?

Can plasma turbulence be artificially generated and harnessed towards a specific goal?