A Systems Approach to Turbulence in the Heliosphere

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Turbulence is pervasive throughout the heliosphere. Fusion in the center of the sun drives turbulent convection in the outer layer of the sun. Within this zone magnetic fields become twisted and amplified and emerge from the solar surface. These magnetic structures are believed to control processes that power the solar wind [Chandran et al., 2009, and references therein], accelerate high-energy particles, and affect the propagation of cosmic rays [Bieber et al., 1996] within the heliosphere. When the solar wind encounters planetary magnetospheres, turbulent boundary layers develop that control transport of mass, momentum, and energy, which determines how the magnetospheres are populated and controls their underlying dynamics [Chaston et al., 2008a; Yao et al., 2011]. The dynamics within planetary plasma sheets can at times be characterized as turbulent processes, which redistribute the plasma and dissipate energy leading to heating [Borovsky and Funsten, 2003]. Moreover, the dynamics of planetary plasma sheets couple to planetary ionospheres via Alfven waves, which cascade by means of turbulent processes to small scales where they efficiently accelerate electrons and heat ions leading to modifications in the ionosphere and outflows that couple back to the plasma sheet [Chaston et al., 2008b]. Because each of these turbulent processes has a major role in driving and controlling the space environment, they are fundamental to understanding and predicting space weather.

As plasmas interact nonlinearly in the electromagnetic environment of space, coherent structures are created. In the solar wind, field-aligned magnetic flux tubes of varying size have been observed [Bruno et al. 2001] leading to a picture of textured flux tubes [Borovsky, 2008] carried by the solar wind. Similarly, in planetary boundary layers, coherent vortex structures resulting from the nonlinear development of velocity shear instabilities are frequently observed [Hasegawa et al., 2004]. Fully developed turbulence involves the intermittent interaction of multiple coherent structures on various temporal or spatial scales in the presence of coarse-grained dissipation [Chang, 2009]. The typical turbulent spectrum of magnetic field or bulk velocity reveals a topology of the turbulent transfer of energy from a driving range corresponding to the largest scales that provides the energy content tapped by the energy cascade to a dissipation range corresponding to the smallest scales where energy is eventually dissipated and converted to thermal energy.

New interesting insights in the theory of turbulence derive from the point of view, which considers a turbulent flow as a complex system [Bruno and Carbone, 2013]. One of the key features of fully developed turbulence is the chaotic or unpredictable character of the time behavior. Although turbulent flows are extremely sensitive to small perturbations, it is often possible to identify statistical properties of the turbulence that are insensitive to small perturbations. Of particular importance are identification of scaling relations, cross-scale transfer of information, and causality.

While the long-range nature of correlations presents significant challenges to analytical and numerical approaches to turbulence, it also provides the possibility of simplification by virtue of invariance properties under scaling transformations. Self-similarity is the emergence of a replicating hierarchy of statistical quasi-equilibriums in the inertial range of turbulence that exhibits a similar dependence with scale and is revealed as a linear variation of a scale exponent described by a monofractal index. In real systems, fluctuations are often distributed unevenly across scales leading to bursty phenomena known as intermittency. Intermittency can play an important role in the dynamical response of coupled systems such as the dynamics that couple the solar wind and magnetosphere. Intermittency manifests itself with different scaling properties on

different scales, which from a practical perspective can help to identify the underlying processes driving the dynamics on those various scales and controlling the intermittent behavior.

One key property of turbulence is that coherent structures interact across scales, leading to cross-scale energy transfer. Whether coherent structures are interacting is a key question in the heliosphere. For example, Borovsky [2008] has argued that the coherent flux bundles seen in the solar wind are "fossil structures," seeded at the top of the "magnetic carpet," which are most likely not interacting even though they exhibit a power law spectrum. An alternative view of the solar wind is that Alfven waves are launched by the sun transferring energy outward. The waves become turbulent, which causes wave energy to cascade from long wavelength to short wavelength, which eventually dissipate, heating the corona and solar wind [Chandran et al., 2009]. Development of tools to probe the transfer of energy across scales is a key need in order to identify and characterize turbulence. Directional transfer of information can be identified by comparing the fluctuation spectra on different scales using discriminating statistics such as conditional mutual information and other generalized statistical measures.

Identification of factors that causally control turbulence (as characterized by its statistical properties) should also be a key objective of turbulence research. For example, turbulence in the magnetopause boundary layer could be controlled by solar wind pressure fluctuations or velocity shear instabilities. The turbulence in boundary layers can control transport across the boundary layer and, consequently, the state of a magnetosphere itself. It is therefore, also important to understand how turbulence causes transition in system dynamics. It would be particularly useful to develop discriminating statistics that can be used to identify factors that causally control turbulence and to systematically identify coupling functions that describe how the turbulence properties are controlled and how those properties control transitions in the dynamics of those systems.

To make progress, discriminating statistical tools should be developed and utitlized to characterize turbulence, understand energy transfer, and describe information flow in turbulent systems. Such tools include power spectral density, probability density functions and their higher order moments, structure function analysis, and rank ordered multifractal analysis (ROMA), which are useful for identifying scaling relations. Energy transfer across scales can be examined using higher order analysis of probability distribution functions that can characterize flow using mutual information and cumulants (or multispectra). Causal relationships can be examined using entropy-based tools based on conditional probabilities such as transfer entropy and conditional redundancy.

Some key questions that can be addressed by a systems approach to turbulence in the heliosphere and more broadly in plasma science are: In which regions are fluctuations better characterized by wave dispersion versus intermittent interactions of coherent structures?; How is the dynamics of coupled regions controlled by the distribution of fluctuations on different scales?; How is energy transferred across scales and at what scales is energy dissipated?; How does the turbulence vary with changing solar conditions?; What causally controls turbulence in different?; Can coupling functions be identified that describe the factors that control turbulence and the relationship of turbulence in different regions?

Relevant Publications

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