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Who Needs Turbulence?

A Review of Turbulence Effects in the Heliosphere and on the Fundamental Process of Reconnection

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Abstract The significant influences of turbulence in neutral fluid hydrodynamics are well accepted but the potential for analogous effects in space and astrophysical plasmas is less widely recognized. This situation sometimes gives rise to the question posed in the title; "Who need turbulence?" After a brief overview of turbulence effects in hydrodynamics, some likely effects of turbulence in solar and heliospheric plasma physics are reviewed here, with the goal of providing at least a partial answer to the posed question.

Keywords Magnetic reconnection · Turbulence · Solar wind · Corona

1 Introduction

Hydrodynamics has been studied for millenia, and turbulence in geophysical fluids has been studied at least since da Vinci. While principles of static equilibria and laminar flows date to Archimedes, Bernoulli and many others, observers of geophysical flows generally accept the idea that eddies and vortex structures can form on many scales and can be highly unsteady.[1] Anyone observing a tornado or a blustery August afternoon thunderstorm can attest to the near ubiquity of turbulent eddies. There are subtleties of course. Small viscosity is frequently not well approximated by zero viscosity—and therefore the ideal Euler equations may not capture the physics. This was realized perhaps the first time in the recent epoch in the design

[1] As seen in daVinci's illustrations. An example of which is reproduced on the cover of *Turbulence*, by U. Frisch (Cambridge U. Press, 1995).

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of systems of water pipes. We know now that computing the resistance (and therefore the power needed to pump the fluid) requires consideration of the Navier Stokes equations and the effects of viscosity even when the flow is laminar. But when the viscosity becomes very small, a smooth system can transition to an apparently chaotic or turbulent one. Pipe flow, channel flow and flow exterior to a cylinder all experience transitions to turbulence followed by a strongly turbulent regime (see e.g., Orszag and Kells 1980). This happens as the effects of viscosity are weakened, the Reynolds number becomes large, and the flow becomes highly nonlinear. To a great degree it is the importance of the nonlinear effects that make fluids and turbulence a challenging subject. Galileo is supposed to have said "The movements of heavenly bodies despite their great distances from the earth have presented fewer difficulties to me than the movements of water which is within my reach" (Plesset 1951).

In contrast the study of plasmas is relatively new, and there have been a number of factors that have discouraged investigations of complex behavior such as turbulence. For example, major components of plasma theory originate in the study of fusion devices, where the goal (or hope) is to produce stable, hot plasma configurations that are close to equilibrium (e.g., Bateman 1978). The study of waves and/or instabilities generally presupposes that the system of interest is already close to such a state. Furthermore, applied mathematics shows that plasmas might support a very rich variety of normal modes and equilibria, so there has been plenty of work employing those approaches. Finally, space and astrophysical plasmas are often threaded by large scale magnetic fields. This organizes the large scale appearance of the system, and gives the coarse grained impression that the associated dynamics must be smooth, laminar, and maybe even static.

There does indeed appear to be a substantial difference in the cultural attitudes towards the role or even the presence of turbulence in the fluid dynamics and plasma physics communities. Those who are acclimated to the fluid turbulence perspective do not have a difficult time seeing the analogous opportunities for turbulence effects in plasma behavior. These possibilities are especially evident in the context of magnetohydrodynamic (MHD) flow, which resembles hydrodynamics in many ways, and which is accepted as a low frequency, long-wavelength description of the plasma dynamics of the solar wind, magnetosphere, corona and interstellar medium (e.g., Parker 1979). Likewise strongly magnetized $E \times B$ drift plasmas bear a strong resemblance to hydrodynamics (Driscoll and Fine 1990), while also providing a leading order description of ionospheric plasmas. Diagnostics describing these solar and heliospheric plasmas suggest that they are in very complex configurations, and clearly not in equilibria. Instead the photosphere, as revealed for example by TRACE, appears to be a roiling tangle of magnetic activity at all scales (Schrijver and Title 2002; Schrijver et al. 2005). The solar wind is typically found with powerlaw fluctuations spanning three of four decades of scale (Jokipii 1973; Tu and Marsch 1995). The magnetosheath and plasma sheet are noisy, bursty and randomly structured (Borovsky et al. 1997). In hydrodynamics such characterizations would be viewed as nearly synonymous with turbulence, strong nonlinearity and cascade. A certain fraction of space physicists would find themselves in accord with the hydrodynamicists on this point. But a surprising portion of the space physics community perennially relegates turbulence to a fossil concept, or assumes that such states can be described as a superposition of waves. Equally implausible from a nonlinear dynamics perspective is the view that the entire turbulent medium is built of smooth structures that persist over many correlation lengths and correlation times of the observed fluctuations. Armed with these ideas and a repertoire of conveniently defined wave modes, static structures and linear instabilities, skeptics of turbulence in heliospheric physics sometimes are quick to dismiss turbulence investigations as unnecessary and esoteric. Thus arises the title question “who needs turbulence?” Here we will argue that there are many affirmative answers to this question. We begin with discussion of circumstances in which hydrodynamics problems would be almost universally assumed to be strongly turbulent, citing key physical features that distinguish turbulence from laminar flows. We will progress to discussion of indications of turbulence and it effects in solar and heliospheric plasmas. Finally we turn to specific discussion of turbulence effects on magnetic reconnection, which also takes on many guises.

2 Who Needs Turbulence in Hydrodynamics?

Probably the most familiar and important effect of turbulence in fluids is that it vastly enhances the rate of *transport phenomena*. A familiar example, given by Orszag (1977), is that the time for mixing a drink would be at least a day if the process relied only on molecular diffusion. Turbulent mixing occurs over times that are much shorter than mixing times based on laminar estimates using molecular diffusion coefficients. Similarly great enhancements due to turbulence are found in other types of transport.

One type of transport, *viscous diffusion*, is of special importance in turbulence because it controls the rate of energy dissipation. The rate of decay of energy in strong turbulence is not controlled by the material viscosity, but rather by the eddies themselves (de Kármán and Howarth 1938). This *turbulent viscosity*, estimated as $\nu_T = uL$, where L is the characteristic length and u the characteristic speed of the turbulence. At high Reynolds number, the effective viscosity is typically much greater than the viscosity obtained from kinetic theory.

In a flow system with boundaries, in the turbulent regime, the *resistance to the flow* is not well estimated by Euler equations or by Navier Stokes equations using laminar theory. For example, in pipe flow for $Re > 2300$ the resistance is not well approximated by laminar theory. And above about $Re > 4000$ the resistance is in a fully turbulent regime (Moody’s law).

Flow around obstacles also attains a turbulent regime. Flow around a cylinder famously becomes a *Karman vortex street* for moderate *Re*, and then *fully turbulent* and chaotic at much higher *Re*. For these cases the instantaneous flow looks nothing like the time averaged flow (see illustrations in *Album of Fluid Motion*) (van Dyke 1982).

A related issue is that of drag on a body moving through a fluid. At sufficiently high Reynolds numbers there are regimes of *turbulent drag*, which cannot be understood in terms of laminar flow. One expects that the drag force on a body is linear in velocity at low speeds. As the Reynolds number increases, the body experiences shape-dependent variations in the drag force, including a sudden decrease in drag with increasing Reynolds number known as the “drag crisis.” At still higher Reynolds number the drag eventually becomes proportional to speed-squared. For lifting bodies and wings, drag is related to *lift*, and also experiences complex variations due to changes in turbulence properties, including Reynolds number (Richter and Naudascher 1976). As one might expect, the observed drag-lift relationships at modest Reynolds numbers $\sim 10^6$ have very little resemblance to what is computed from laminar theories. It is worthwhile to recall what is considered one of the classical paradoxes of airfoil theory (Birkhoff 1960): although one might think a smooth flow around an airfoil is essentially ideal and well approximated by Euler equations, the lift is exactly zero if the viscosity vanishes. However, airplane wings generally work very well.

Turbulence changes macroscopic properties of fluids such as those described above. It is also responsible for many frequently observed *statistical properties* of fluids. Probably the most familiar of these are the second order statistics—structure functions and wavenumber spectra—that are associated with the classic turbulence theories of Kolmogorov, Obukhov and others (Kolmogorov 1941a; Obukhov 1941b; Monin and Yaglom 1971, 1975). The famous specific predictions for second order structure function, $D_2(r) = \epsilon^{2/3} r^{2/3}$, and for the omnidirectional wavenumber spectrum of the velocity, $E(k) = C_k \epsilon^{2/3} k^{5/3}$, may be considered the signature results of classical turbulence theory. Most importantly, it is not difficult to find at least approximate confirmation of these theories in many fluid systems and in simulations. In addition, theoretical developments such as the Refined Similarity Hypothesis of Kolmogorov (1962) provide a basis for understanding the behavior of higher order structure functions. Such scaling laws reflect the presence of coherent structures in turbulence and the intermittent distribution of strong gradients and associated nonuniformity of dissipation. Turbulence theory provides a basis for describing and understanding these features, *which are frequently observed in nature and in the laboratory*. There is ample and convincing evidence that turbulence is a phenomenon of widespread importance in the physics of fluids.

3 Turbulence in Solar Physics: Is it Needed in the Dynamo, the Chromosphere and the Corona?

In solar physics, turbulence is probably ubiquitous. Its presence and impact in the photosphere and in the convection zone are unquestioned. Furthermore the complexities of turbulence enter into the fundamental physics of the dynamo. There seems to be no doubt, for example, that the stochasticity of dynamo reversals is intimately related to the nonlinear dynamics and self-organization properties of the MHD dynamo, even if the details are still being elucidated. Turbulence and nonlinear dynamics in the corona, in both open field regions and closed loops, has been recognized as a factor in heating and possibly in the origin of the solar wind itself. Meanwhile very low frequency variations, probably originating with self-organization properties of the dynamo, appear to affect the corona and even the observed magnetic and density variability in the solar wind at 1 AU. Far from only being an issue of an inertial range Kolmogorov cascade, the nonlinear properties of the system influence the behavior across a very wide range of space and time scales. The landmark imaging of instruments such as TRACE, Lasco, and EIT have defined graphically the degree of structure and variability in the solar dynamical system.

3.1 Chromosphere and Corona

The chromosphere, transition region and corona remain mysterious regions of the solar atmosphere. Here the temperature rises above its minimum photospheric value, slowly at first in the chromosphere, and then suddenly, by about two and a half orders of magnitude, across the transition region into the corona. The photosphere itself is the site of evolving turbulence, as displayed by its prominent multi-scale convection cell pattern dominated by granulation and super-granulation. Ultimately, the chromospheric/coronal heating and solar wind heating and acceleration problems are those of the transfer, storage, and dissipation of the abundant energy present in motions in the photosphere. The key question is to identify how a small fraction of that energy is supplied and transformed into thermal energy above, sufficient to make-up for losses into radiation and conduction by the corona in confined active region loops, with temperatures in excess of 2×10^6 K, and to the kinetic energy flux into the solar wind, for the darker, open coronal holes.

Both emerging magnetic flux and the constant convective shaking and tangling of magnetic field lines already threading the corona contribute to these processes in what is an extremely structured, highly dynamic region of the solar atmosphere. The energy in photospheric motions is dominantly at large scales and low frequencies, associated with granulation and super-granulation, and with time-scales of minutes to hours and scales of hundreds to thousands of kilometers. Comparing these scales with the scales at which dissipation due to resistivity, viscosity, or kinetic processes such as wave-particle interactions are involved, i.e., several hundred meters and frequencies in the kilohertz range, implies that there must be dynamical mechanisms acting to transfer the energy across scales. Non-linear interactions, and a turbulent cascade are a natural candidate.

So how is turbulence connected to the chromospheric and coronal heating problem and the subsequent acceleration of the corona into the solar wind?

The answer depends on the region in question (chromosphere, corona, solar wind) and the topology of the magnetic field. The results depend on whether the field opens into the heliosphere or whether it returns to the photosphere. Let's begin by considering the lower atmospheric layers, the chromosphere and transition region. As the cadence and resolution of remote-sensing instrumentation has increased, so have the complexity of the structures and plasma motions detected in the chromosphere and lower corona. Spicules, X-ray jets and other plasma outflows, driven by the Sun's convective energy and ignited by highly dynamic magnetic effects such as reconnection, are born and decay over a significant range of temporal and spatial scales. The chromosphere is the region where plasma characteristics begin to change dramatically. The exponential decrease of density is accompanied by expansion of magnetic field lines so that the plasma goes from having much larger thermal pressures than magnetic pressure, except perhaps in the intense kilogauss flux-tubes forming the super-granulation pattern, to having pressure much smaller than the magnetic pressure in the corona. Much of the heating in the chromosphere can be accomplished by hydrodynamic buffeting due to turbulent convection with consequent shock formation, but these processes probably provide a negligible direct contribution to the corona above. Coupling to magnetic fields overcomes the trapping and evanescence of chromospheric acoustic and acoustic gravity waves, allowing the formation of magnetoacoustic shocks on magnetic flux concentrations (De Pontieu et al. 2007) and also the propagation of a significant amount of magnetohydrodynamic waves into the corona.

In addition to the power in waves, substantial energy may be stored in closed coronal magnetic fields by slower, DC currents induced by photospheric motions having periods comparable to supergranulation times. The tangling of coronal magnetic field lines caused by the turbulent shuffling of photospheric footpoints in regions of closed magnetic topology causes a secular increase in the stresses in coronal loops. Parker (1972) conjectured that the continuous footpoint displacement of coronal magnetic field lines must lead to the development of current-sheet discontinuities as the field continuously tries to relax to its equilibrium state, and that the dynamical interplay of energy accumulation via foot-point motion and the bursty dissipation in the forming current sheets would naturally result in a high temperature solar corona, heated by individual bursts of reconnection, or nanoflares. The latter, Parker posited, could be the extreme low-energy limit of all observed bursts of coronal energy releases. In fact the histograms of the number of flares as a function of total energy content, peak luminosity, or duration all display well-defined power laws, extending over several orders of magnitude, down to instrumental resolution. Whether the observed statistics of events can account for coronal heating is still a matter of controversy; yet the robust power-law distributions are an extremely interesting indirect indicator of the general solar activity processes.

What then does turbulence have to do with the nanoflare heating scenario? Parker himself strongly criticized the use of the word "turbulence," the formation of the current sheets being due in his opinion to the requirement for ultimate static balance of the Maxwell stresses. But the relaxation of the magnetic field toward a state containing current sheets must occur through local violations of the force-free condition, the induction of local flows, and the collapse of the currents into ever thinner layers—a nonlinear process generating ever smaller scales. From the spectral point of view, a power law distribution of energy as a function of scale is expected, even though the kinetic energy is much smaller than the magnetic energy. The last two statements are clear indications that the word turbulence provides a correct description of the dynamical process.

3.2 Closed Field Coronal Loops

The simplest realization of the above problem is to consider a coronal loop to be a finite volume of plasma, bounded by two conducting plates and threaded by a uniform magnetic field, and then consider boundary motions at the plates that shear the initial field. Many authors have developed coronal heating models with this preface based on the idea that an MHD turbulence cascade will result (see e.g., Van Ballegooijen 1986; Heyvaerts and Priest 1992; Mikić et al. 1989 for early numerical simulations). Other modelers (Georgoulis et al. 1998; Dmitruk and Gómez 1997) carried out very simplified simulations of this problem considering just a 2D cross section of a loop, using a purely magnetic random forcing function to replace the effects of field line shuffling. In this way, they were able to show that a magnetically dominated turbulent cascade occurs in loops, and in addition proved that as a result of the dissipation occurring in a distribution of current sheets, the overall dissipated power was distributed in discrete events whose total energy, duration, and peak intensity were indeed distributed according to power laws.

Numerical simulations of this process using the Reduced MHD representation (Dmitruk et al. 2003; Rappazzo et al. 2008) led to a more detailed understanding of the dynamics of field line tangling, an important new result being the derivation of scaling laws showing how the macroscopic heating rate depends on the dimension of closed loops and intensity of the magnetic field, and their connection to the resulting inertial range spectrum of magnetic fluctuations. The simulations showed how the MHD turbulence regime which develops may be thought of as a particular example of weak MHD turbulence, with magnetic energy dominating over the kinetic energy at the large scales, and different spectra for kinetic and magnetic energy. The magnetic spectra were found to be steeper than Kolmogorov, all the way to slopes of ~ 3, while the kinetic energy spectra were flatter. Such simulations at the same time yield a well defined coronal oscillation spectrum associated with the turbulence. The spectrum is not dominated by specific photospheric oscillation periods but rather has a powerlaw shape with superimposed overlapping resonances associated with the normal mode oscillations of the coronal loops. This dynamical scenario involves numerous random reconnection events embedded in the turbulence—we will return to a further discussion of the reconnection aspect of this problem in a later section.

Parker (1991) extended the nanoflare idea to the low lying bipoles in the overlying unipolar field of the coronal hole, arguing that most of the energy is injected in the near coronal hole, in the form of jets of gas, lashing flux bundles, and superheated plasma from a bipole interior suddenly freed by a reconnection and released into the ambient unipolar field. This vivid description strongly resonates with the recent observations from the Hinode spacecraft, whose high spatio-temporal optical telescope SOT has revealed a previously unrecognized second type of spicules (De Pontieu et al. 2009) that is a prime candidate for establishing a link between corona and chromosphere. These type II spicules have much shorter lifetimes (10–100 s), are more violent (upflows of order 50–150 km/s), and often fade rapidly from chromospheric lines, which suggests rapid heating associated with magnetic reconnection.

3.3 Open Field Corona

McKenzie et al. (1995) hypothesized the existence of such reconnection events, located in the upper chromosphere/transition region, which would launch high-frequency waves able to heat minor ions in coronal holes via the ion-cyclotron resonance either directly or within a few solar radii thanks to the rapid decrease of the ion-cyclotron frequency with height in the corona. SOHO/UVCS observations (Li et al. 1999; Kohl et al. 1998) of extremely large and anisotropic effective temperatures in the lower corona above coronal holes, correlated with the rapid acceleration of high speed streams (Telloni et al. 2006), and the anisotropic ion distribution functions in the fast wind seemed to support the ion-cyclotron theory of heating and acceleration. Recent reexamination of the density fluctuations at heights of about 5 Rs and above with interplanetary scintillation measurements (Chandran et al. 2010), however, seem to discount ion-cyclotron interactions in favor of dissipation by high perpendicular wavenumber kinetic Alfvén waves.

A completely different idea to supply the energy required not only to heat the open regions of the coronal hole, but also provide the momentum deposition required to accelerate the fast wind, is based on a model similar to that of the Parker problem. In this case however, the photosphere only shuffles one footpoint of field lines, the other extending to infinity. In this case, there is no significant energy storage in the corona, but a flux, essentially of Alfvén waves, propagates upwards from the photosphere. These waves, depending on their frequency, are more or less reflected by the stratification density gradient, a process which is fundamental to trigger nonlinear interactions, since incompressible MHD requires waves propagating in both direction along the field. In this view, the density fluctuations observed by scintillation would be forced, as a secondary effect, by the reflection generated turbulent cascade (Matthaeus et al. 1999; Verdini and Velli 2007; Cranmer et al. 2007). As a result of reflection, which dominates in the lower layers of the solar atmosphere, a cascade develops and significant dissipation occurs: such incompressible turbulence models of coronal heating appear to be successful in creating realistic high speed solar wind streams (Cranmer 2010; Verdini et al. 2010), though the picture of an Alfvénic turbulence driven solar wind remains controversial (Roberts 1989; Roberts 2010), specifically with respect to the nature of the Alfvénic turbulence observed in situ. The problem, discussed further below, is that the typical waves expected should have periods of tens of minutes, while the turbulence observed in situ has energy at lower periods, up to a few hours.

Alfvén waves propagating from the corona could also drive compressive interactions and steepen to form shocks, either directly or indirectly through decay instability or mode conversion (Malara and Velli 1996; Malara et al. 1997): a coronal heating and acceleration model based solely on this effect has been developed in one dimension (Suzuki and Inutsuka 2006) leading to a solar wind that contains extremely large fluctuations in radial velocity and density oscillations close to the sun.

A short review article cannot properly deal with the complexity and diverse features of the dynamic solar atmosphere. However, it does seem essentially certain that turbulence, and in fact at least several varieties of turbulence, occupy key roles in the dynamics and structure of the photosphere, the chromosphere and the corona. Remote sensing has revealed an immense amount of information that is still being intensively studied. For direct confirmation of turbulence properties, we anticipate the pioneering direct probes of the lower solar atmosphere that we hope will be accomplished by Solar Orbiter and Solar Probe in the next decade. We now turn to the outer solar atmosphere—the solar wind—for which we have a wealth of direct in situ evidence for the role of turbulence.

4 Who Needs Turbulence in the Solar Wind?

In the past decade or so, there has been a great increase in understanding the basic physics of heliospheric turbulence, and in understanding how turbulence enters in many ways into the complex, coupled solar-heliospheric dynamical system.

Solar wind studies have often led the way, due to the availability of large amounts of data to carry out the statistical studies that so often characterize turbulence studies. Indeed, the state of the system at 1 AU has been and remains a testing ground for turbulence theories. Correlation functions and associated spectral distributions of energy, cross helicity, magnetic helicity, and Alfvén ratio are familiar descriptions of the state of the turbulence, and these have leading order implications for plasma heating and for scattering and transport of energetic particles.

A number of properties of solar wind turbulence have been found to be in accord with theoretical expectations based on turbulence theory and accurate simulations of turbulence. Such studies have enriched our perspectives on the dynamics of the interplanetary medium, and at the same time have sometimes helped to clarify the scope of the theory.

4.1 Heating and Spectra

Perhaps the most significant of these connections is the one that has emerged between *turbulence cascade and heating*. The solar wind expansion is highly nonadiabatic in that the proton temperatures fall off much more slowly than would be expected for a freely expanding ideal gas (Richardson et al. 1995). One would expect the temperature $T(r)$ in a spherically symmetric adiabatic expansion to behave as $T \sim 1/r^{4/3}$. However, the best fit to Voyager temperature observations out to about 20 AU behaves as $T \sim 1/\sqrt{r}$. What is adding internal energy to the solar wind? Turbulence cascade provides a ready solution to this question, as was originally suggested by Coleman (1968). This scenario is appealing because there are substantial energy reservoirs at large scales that could power the heating of the wind, provided that the energy in the large scale MHD degrees of freedom can dissipate and produce internal energy. The turbulence cascade facilitates this dissipation by efficiently communicating energy across the length scales spanned by the powerlaw inertial range. In the solar wind this powerlaw range extends approximately four decades in scale at 1 AU. Without a turbulent cascade, we would be left with the problem of identifying some other process that could dissipate the required energy quickly enough to account for the observations. Quantitative estimates (Coleman 1968; Verma et al. 1995; Sorriso-Valvo et al. 2007; MacBride et al. 2008) suggest that turbulence is adding internal energy to the plasma at 1 AU at a rate of approximately 1000 J/kg/sec.

The heating issue is a major factor in controlling the very structure of the heliosphere; there is, however, a growing list of other empirical connections of turbulence to observed features of the solar wind. The strong observational connection between features of turbulence and the state of the solar wind readily motivates deeper inquiry into the nature of interplanetary turbulence. Prominent among these features is the typically encountered powerlaw *wavenumber spectrum* that strongly suggests the presence of turbulence even to nonspecialists. Roughly speaking, the one-dimensional magnetic fluctuation spectrum (Jokipii 1973; Matthaeus and Goldstein 1982; Tu and Marsch 1995) as well as the spectrum of total fluctuation energy (flow plus magnetic) are found to be approximately "Kolmogorov" in nature, having a spectral index in the neighborhood of $-5/3$ (Tessein et al. 2009; Chen et al. 2010). For many years (Coleman 1966) this robust observation has provided a baseline motivation for seeking an understanding of solar wind fluctuations in terms of turbulence theory.

The appearance of high cross helicity Alfvénic fluctuations, with well correlated (or anti-correlated) velocity and magnetic field fluctuations has been historically viewed as indicative of a *wave* description. Indeed, it is unquestionable that Alfvénic states are seen in relatively pure form in the inner heliosphere and are more frequently seen in high speed winds. However, the *evolution* of cross helicity strongly supports a picture of radial evolution due to turbulence. In fact, it has been shown that the Alfvénicity systematically decreases with increasing radial distance, both in low latitude wind (Roberts et al. 1987a, 1987b) and in high latitude wind (Bavassano et al. 1982a, 1982b; Breech et al. 2005) This cannot be explained using WKB wave propagation theory (Hollweg 1990) but models of shear-driven turbulence, both simulations and analytical, show that this type of MHD turbulence decreases Alfvénicity in very much the same way as seen in the solar wind (Roberts et al. 1992a, 1992b; Goldstein et al. 1999; Breech et al. 2005)

Closely related to the evolution of Alfvénicity is the evolution of the so-called Alfvén ratio, defined as the ratio of fluid kinetic energy and magnetic energy in fluctuations. Often this ratio is computed only for fluctuations in the inertial range, or in spectral bands. For Alfvén waves, even large amplitude Alfvén waves, this ratio is unity, a fact often invoked to argue for equipartition of magnetic and kinetic (flow) energy in the fluctuations (Kraichnan 1965). Once again one finds that WKB theory predicts only very small departures from unit Alfvén ratio in a weakly inhomogeneous medium (Hollweg 1997). In contrast, the observations point clearly to a non-unit Alfvén ratio, with magnetic energy $>$ kinetic energy in the inertial range. Furthermore, this ratio begins at values closer to unity in the inner Helios orbit, and drops by 1 AU to values near $1/2$ and more or less remains there, on average, to at least beyond 10 AU. The same kind of evolution to values of about $1/2$ in the inertial range is found in simulations of MHD turbulence (Matthaeus and Lamkin 1986). Along with the concurrent evolution of Alfvénicity, seen in simulations prepared with Alfvénic initial data and driven by shear (Roberts et al. 1992b), this provides another "smoking gun" for the presence of active turbulence evolution in the interplanetary medium.

Still another familiar property of interplanetary fluctuations that relates to turbulence is the evolution of the "breakpoint" that separates inertial range and energy containing range. Frequently the inertial powerlaw region has a one dimensional spectral index of around $5/3$, and the lower frequency "energy" region has a flatter shape. For many model spectra this breakpoint is associated with the fluctuation correlation scale or coherence scale (Jokipii 1973). The radial variation of the breakpoint is a matter of some delicacy, as its determination depends upon accurately measuring low frequency power, and this is intrinsically difficult. Furthermore prediction of movement of the breakpoint in wave theory depends on assumptions about the spectrum. It is noteworthy however that homogeneous turbulence (say, in wind tunnels) generally causes the correlation scale to increase something like $\sim \sqrt{\text{time}}$ (Monin and Yaglom 1971, 1975) while a free spherical expansion induces a transverse perpendicular expansion that grows linearly in time.

4.2 Anisotropy

Another prominent example of interplanetary turbulence effects is the emergence of dominant "quasi two dimensional" spectral features. For some time this phenomenon has been known from laboratory experiments (Robinson and Rusbridge 1971) and simulations, and it can be understood (Shebalin et al. 1983; Oughton et al. 1994) as due to suppression of spectral transfer parallel to the mean magnetic field, while perpendicular transfer proceeds unabated. This process leads to conditions in which the strongest gradients are those perpendicular to the mean magnetic field.

Magnetohydrodynamics develops anisotropy due to the influence of the wave-like couplings that average out nonlinear couplings, limiting their effects, for all nonlinear triads except those that are insensitive to propagation induced by that the large scale magnetic field. The couplings that are insensitive to propagation effects are in two classes. The first set of couplings is one in which all three interacting modes are insensitive to propagation. These are the truly quasi-two-dimensional couplings, involving in effect energy exchange among sets of three modes, zero wave frequency. The second type of nonlinear triad coupling that is insensitive to propagation effects is the case in which one mode is quasi-2D, while the other two modes propagate in opposite directions and with equal wave frequencies. In that case, the coupling is said to be "resonant." In both cases energy transfer proceeds mainly towards higher perpendicular wavenumber, intensifying gradients perpendicular to the mean magnetic field. This process is well documented in theoretical work (Shebalin et al. 1983; Oughton et al. 1994). However, there are numerous indications that the MHD scale fluctuations in the solar wind also behave in this way. Direct examination of correlation functions or spectra from single spacecraft datasets (Matthaeus et al. 1990; Bieber et al. 1996) show a strong component of quasi-2D fluctuations. Multispacecraft studies confirm this (Narita et al. 2006; Osman and Horbury 2007, 2009; Weygand et al. 2009).

Spacecraft studies also strongly support the idea that the MHD-scale cascade becomes dispersive and dissipative near ion gyroscales, and that the dissipation near proton scales is mainly of low frequency quasi-2D fluctuations (Leamon et al. 1998a, 1998b, 2000; Hamilton et al. 2008; Bale et al. 2005; Sahraoui et al. 2010). The dissipation is, however, not exclusively of this type (Leamon et al. 1998a; Bieber et al. 1996). It is also found that the degree and type of anisotropy vary with wind speed (Dasso et al. 2005), and that all solar wind types appear to be evolving towards greater 2D-type anisotropy (Ruiz et al. 2010). This latter conclusion has been questioned (MacBride et al. 2010).

While many detailed features of this picture continue to inspire debate, there is at this point an impressive compilation of results from various methods, spacecraft datasets and from different authors that support a consistent conclusion: Solar wind fluctuations show spectral and variance anisotropy and other evidence of cascade, of a nature very similar to what is expected in turbulence.

4.3 Higher Order Statistics

Much activity has concentrated on understanding the second order statistics—spectra and second order correlation functions, but there has also been a growing interest in higher order statistics in the solar wind. As in hydrodynamics, there is a wealth of dynamical information to be found in the statistics higher than second order.

At third order, the unsigned structure functions represent part of the fractal hierarchy that defined the intermittency structure of MHD turbulence. Motivated by the successes of the Kolmogorov Refined Similarity Hypothesis (KRSH) in hydrodynamics (Kolmogorov 1962; Obukhov 1962a; Monin and Yaglom 1971, 1975), MHD theorists have examined the sequence of powerlaw exponents $\xi(p)$ for fits to the increase with spatial separation of the structure functions of order p. The polynomial behavior of $\xi(p)$ is indicative of the multifractal structure of the turbulence. Similar multifractal behavior is seen in both simulations (Müller and Biskamp 2000) and in the solar wind (Horbury et al. 1995). The scaling behavior of these higher order moments is usually discussed in terms of favoring one or another of several families of theoretical descriptions (Kolmogorov 1941a; Obukhov 1941a; She and Lévêque 1994; Frisch 1995). A detailed discussion of these theories would steer us far afield at present. The important thing to realize is that solar wind fluctuations bear a striking resemblance to the statistical features of turbulence running much deeper than the most familiar spectral laws.

The *signed* third order moments in steady turbulence are not involved in multifractal hierarchies and for practical reasons are much more difficult to evaluate. However, as in hydrodynamics (Kolmogorov 1941b; Monin and Yaglom 1971, 1975), the third order signed structure functions provide in isotropic MHD (Politano and Pouquet 1998b) a direct key to evaluation of the cascade rate. This remarkable relationship applies in differential form to the anisotropic case (Politano and Pouquet 1998a; Podesta et al. 2007; Podesta 2008; Wan et al. 2009b). The cascade rate so obtained is expected to be a good approximation to the heating rate. However, the latter can also be evaluated at 1 AU by measuring the average temperature gradient, along with a few simple assumptions such as steady state (Vasquez et al. 2007b). It is a notable fact that these evaluations of the heating rate of the solar wind plasma at 1 AU are in substantial agreement, further supporting the hypothesis that turbulence is actively cascading and heating the interplanetary plasma.

4.4 Structures and Intermittency

There is a growing collection of phenomena observed in the solar wind that can be explained or accounted for in turbulence theory. In some cases dynamical properties identical or similar to the observations are captured by turbulence simulations. In other cases analytical theory provides the required connections (e.g. Hartlep et al. 2000; Breech et al. 2003).

One particularly interesting case is that of interplanetary discontinuities, usually magnetic discontinuities, which have been observed since the early days of space exploration (Burlaga and Ness 1969; Tsurutani and Smith 1979). Historically, the standard explanation for these directional discontinuities (DDs) is that they are members of a class of stationary convected structures (tangential discontinuities, TDs) or propagating structures (rotational discontinuities). In ideal MHD both of these are persistent solutions. This itself has been frequently viewed as an adequate explanation of their occurrence. Typically little has been said concerning their dynamical origin, except when they are traced back to the corona, or even the photosphere (Tu and Marsch 1993; Borovsky 2008). However, with the emergence of other evidence linking solar wind properties to expected properties of a turbulence, efforts have emerged to understand discontinuities in this perspective as well (Vasquez et al. 2007a; Greco et al. 2008, 2009).

It transpires that the hierarchy of interplanetary discontinuities, of varying intensity and size, are associated with statistical distributions and waiting times that are readily reproduced in the inertial range of MHD turbulence simulations (Greco et al. 2008, 2009). This growing body of evidence helps to understand that many of the "structures" found in the interplanetary medium may be the characteristic coherent structures produced by the cascade itself. In isolation, this evidence leaves open the question of what fraction of such structures are produced in the corona and convected outward, and what fraction emerge due to *in situ* dynamics. However, studies (Wan et al. 2009a) indicate that coherent structures such as current sheets, and their associated non-Gaussian statistics, emerge very rapidly in simulations that begin with random incoherent noise. This happens in less than a single nonlinear time scale. Estimates of solar wind time scales place the transit time to 1 AU as equivalent to several nonlinear times. It seems quite likely that some substantial fraction of the observed discontinuities have evolved in the solar wind itself.

A recent development regarding discontinuities relates to the suggestion made years ago by Burlaga and Ness (1968) that "D-sheets" (a type of discontinuity) are preferentially heated in the solar wind. In a statistical survey (Osman et al. 2011) based on the identification of discontinuities using the PVI-statistic (Greco et al. 2009), Osman et al. find that the ensemble of coherent nonGaussian structures observed in the solar wind shows enhanced proton and electron temperatures, as well as enhanced electron heat conduction. Therefore we are beginning to see an additional level of convergence between nonlinear theories of turbulence and properties of the solar wind: the heating that is implied by the existence of the cascade seems to be concentrated, at least to some degree, in the smaller scale coherent structures, whose presence is again expected on the basis of intermittency, a generic property of the Kolmogorov cascade in hydrodynamics and its MHD relatives.

In closing this section, we remark on the prospects of a unified description of turbulence and the issue of "universality." When a new approach enters a scientific field, there is a natural tendency for researchers to seek out the essential character of the theory, a simple and most general statement of its import. It is fair to say that in hydrodynamic turbulence, Kolmogorov's 1941 theory (K41) plays that role—for example, one frequently encounters the famous $-5/3$ spectral law. However, one must also take into account the developments related to Kolmogorov refined similarity (Kolmogorov 1962; Obukhov 1962b), because the intermittency and nonGaussian properties of turbulence are clearly of central importance. Similarly the "pre-Kolmogorov" contributions of von Karman and Howarth (1938) are expected to be even more general than the K41 theory. Given the history of its hydrodynamics antecedent, it is not surprising that effort has been expended in magnetohydrodynamics and in solar wind turbulence research to find the most general possible turbulence principles. We emphasize here the difference between searching for general principles of physics, and finding universal laws. While the former surely exist, there is no guarantee of "universality" of any single specific quantity, such as a spectral index. In this regard the reader is directed to the recent paper by Lee et al. (2010), which shows specific simulations that demonstrate how nonuniversal MHD turbulence can be.

In spite of the complexity of an MHD fluid or a plasma description, searches for "universal" laws in turbulence continue. Such efforts must be moderated by the prevalent observations of a dynamic and highly variable medium, driven ultimately by solar variability itself. Generally one finds broad (and frequently log-normal) distributions of turbulence properties such as energy densities and correlation scales, while powerlaw indices and anisotropies are also broadly distributed from parcel-to-parcel. The heliosphere contains not just one type of turbulence, but rather a family of turbulence types, reflecting the variability of the coupled components of the heliospheric system. Understanding and monitoring this variability is a problem of great fundamental and practical importance. Understanding the radial and latitudinal variation of turbulence throughout the solar cycle is an essential element in the study of both space weather (inner heliosphere) and the boundaries of the heliosphere (Breech et al. 2008). This major ongoing area of inquiry is essential for prediction in the geospace environment, for support of potential human exploration, for understanding galactic cosmic rays, and finally, as a prototype for many astrophysical problems.

5 Turbulence and Reconnection

The relationship between turbulence and reconnection has been studied for several decades, and in a variety of guises. For example, a key role for reconnection is implied for standard astrophysical problems such as the large scale dynamo, and for the previously described "Parker problem" in which dynamics in solar flux tubes is driven by slow mixing of field lines anchored in the photosphere. These two cases comprise widely separate regimes, flows driving the field in the dynamo, but being generated by the magnetic field relaxation dynamics in the "Parker problem". Both the dynamo and solar flux tube problems can be viewed as problems of an essentially turbulent nature.

In the dynamo problem, a familiar formulation might be that of a magnetofluid, driven mechanically at intermediate scales with a weak seed magnetic field. The driving is often random, and might be helical (e.g., Brandenburg 2001). The Reynolds number and magnetic Reynolds numbers are parameters, and typically both are large. However the ratio might be either large, order-unity or small, and the associated variation of magnetic Prandtl number is known to be a significant factor in dynamo physics (Ponty et al. 2005). The typical evolution is that the magnetic field is wound up and stretched, thus increasing magnetic energy. However, at relatively early times, the increased magnetic excitation is inevitably going to be mainly at the small scales. On the other hand, a successful judgment of "dynamo action" is often *defined* to be the eventual permanent maintenance of a *large scale* magnetic field. This matches our intuition regarding the conditions that must be met to dynamically maintain the observed planetary, stellar and galactic magnetic fields. Attaining the last condition—a large scale magnetic field—given the excitation of the small scale field, requires that *magnetic reconnection* act to change the connectivity and topology of the magnetic field from small scale islands or sheets into large scale structures. Consequently in most formulations of the turbulent dynamo problem, magnetic reconnection is required, and in some cases, it becomes the limiting factor.

As discussed before, turbulence and reconnection are inseparable also in the Parker problem. A magnetic field is viewed as emerging from and embedding in a heavy conducting plasma on two parallel surfaces separated by a substantial length. At one or both ends the field lines are dragged around by a convective motion in the plane(s), and the highly conducting but more rarefied plasma between the planes responds dynamically. This is usually modeled using magnetohydrodynamics or Reduced magnetohydrodynamics (RMHD) and represents a simple model for the evolution of closed flux tubes randomly stirred at the photosphere, and extending upwards into the solar corona. The original conception is that the dynamics seeks a succession of relaxed states as the flux tubes wrap up, forcing the development of strong current sheets, which then experience magnetic reconnection. Implementation of the model in simulations (Einaudi and Velli 1994; Velli et al. 1994; Einaudi et al. 1996; Dmitruk et al. 2003; Rappazzo et al. 2010a) has repeatedly shown that the wrap-up of the flux tubes leads to turbulence and anisotropic cascade, with enhanced stochastic heating in the current sheets that are copiously formed. The turbulence, which can be quite strong for certain parameters, proceeds in concert with ongoing random reconnection events.

The interplay between these two fundamental plasma processes—turbulence and reconnection—is central in numerous applications, several of which will be described briefly in the subsequent section. Here we focus on fundamental physics aspects of this relationship, in two subsections that have, in some sense, opposite premises.

5.1 Turbulence in Reconnection

Imagine your favorite reconnection problem. It could be two dimensional, focusing on a small region in which two large scale flux tubes are brought into contact with one another. It could be solar flux tubes driven by photospheric motions of the magnetic footpoints as discussed above. Or, perhaps, the solar wind field reconnecting with a CME moving through it, or interacting with the magnetospheric magnetic field. In the first attempt to draw a picture of this reconnection process, all the field lines would probably be smooth and well behaved. There would be a single reconnection region or layer. The process would be *laminar*. The conditions upstream, on the "inflow sides" far from the reconnection zone will probably be quiescent, possibly motivating use of so-called "inflow boundary conditions." Having set up the problem to one's liking, one can imagine going back and adding everywhere broadband fluctuations to the magnetic and velocity fields. The fluctuations change the inflow conditions, and the topography of the field lines near and in the reconnection zone. Furthermore, the Sweet-Parker analysis now must become statistical, since truly steady conditions may not exist. Furthermore, these fluctuations can in principle be of large amplitude. How has the reconnection process changed by the addition of this turbulence? There are at least three ways that have been well documented:

First, one can adopt a space-time decomposition into mean and fluctuating field, for example, using a Reynolds decomposition. In that case, when considering the behavior of the mean, or large scale fields, the effect of fluctuations can be grouped in a way that looks like modifications to the transport coefficients (e.g., Kim and Diamond 2001a), or that appears as local random driving of the electric field (Sakai et al. 1984). These effects can be analyzed approximately by methods analogous to quasilinear theory (Kim and Diamond 2001b). We see then that turbulent fluctuations at the fluid scales are responsible for what are sometimes called turbulent viscosity and turbulent resistivity. If the fluctuations in question are at kinetic scales, the nomenclature sometimes becomes "anomalous resistivity." Of course, fluid scale fluctuations are typically larger than kinetic scale fluctuations, and so one would also expect the 'turbulent" transport modifications to the transport to be greater than the "anomalous" contribution. However, either way, the turbulent fluctuations will be responsible for enhancements of transport, including the diffusive effects in the Sweet-Parker analysis that leads to an expected rate of reconnection.

A *second* documented effect of turbulence on reconnection is the effect of *multiple reconnection sites* within the diffusion region (Matthaeus and Lamkin 1985, 1986; Loureiro et al. 2009). Like most features of the reconnection process, this has been mostly studied in 2D, where it takes the form of *multiple magnetic X-points* in the reconnection zone. This implies that there are small secondary magnetic islands, or "plasmoids" present within the layer. The history of multiple magnetic islands goes back thirty years or more. Several authors, for example, discussed instabilities, such as secondary tearing instability, which can lead to emergence of small islands in current sheets (Biskamp 1986). The secondary islands also may be the direct effect of pre-existing turbulence, even at very low levels, which itself can be reinforced by the reconnection process (Matthaeus and Lamkin 1985, 1986; Lazarian and Vishniac 1999). From the perspective of the large scale reconnection process, what seems to be most important is that secondary islands and multiple X-points change the bookkeeping of the magnetic flux, effectively relaxing the flux constraint that limits the rate of reconnection in the Sweet-Parker argument. Therefore it is almost certain that the presence of multiple islands will elevate the rate of magnetic reconnection (Matthaeus and Lamkin 1985). An interesting issue that remains to be quantified is the level of turbulence that is required before secondary instability is swamped by the almost indistinguishable influence of the pre-existing fluctuations in and near the reconnection region. Recent studies have been able to quantify effects of secondary islands to some degree (Loureiro et al. 2009; Cassak et al. 2009) and it appears that the reconnection rate is indeed accelerated by their presence. It is possible that the rate scales as the square root of the number of X-points in the reconnection zone. This number is expected to increase with magnetic Reynolds number, as smaller structures become possible in the cascade. Consequently, it seems very likely at this point that the simplest single X-point theories underestimate the rates expected in a natural system that is characterized by very large magnetic Reynolds numbers. An interesting sidelight is that a linear instability can be found that generates secondary islands, provided that one assumes that the current sheets become very thin (Bhattacharjee et al. 2009). The only motivation we know for such thinning is turbulence itself, so it is unclear if the instability is realizable in situations in which preexisting finite amplitude fluctuations will break up the laminar current sheet (Matthaeus and Lamkin 1985).

A *third* effect of turbulence on the reconnection process is the modification of the upstream or inflow conditions. In this regard it is essential to recall that the standard reconnection theories of Sweet-Parker and Petschek (Parker 1957; Sweet 1958; Petschek 1964) assume that the conditions away from the current sheet on the strong field inflow sides are both uniform in space and steady in time. When turbulence is present, it is likely that neither condition is true. Some time dependent variations in the upstream plasma can be associated with fluctuations that enter the inflow region, and thus propagate and convect inwards to the reconnection zone, contributing to the multiple X-point phenomenon mentioned above (Matthaeus and Lamkin 1986). Other upstream modifications, those of low frequency and long wavelength, can modify the upstream total pressure "at infinity", thus dynamically modifying the boundary conditions, leading in effect to a driven reconnection problem. In some sense this effect has been known since very early studies (e.g., Sato and Hayashi 1979). Sensitivity to variations of external driving is also seen in kinetic simulations (Ishizawa et al. 2004).

The above modifications to upstream conditions are in some sense external, mainly governed by the medium well away from the reconnection zone. However, in the nonlinear regime, reconnection itself can enhance its own inflow. One way to look at this is that localization of current in a region of rapidly reversing magnetic field produces a quadrupolar distribution of torque at the corners of the reconnection zone (Matthaeus 1982). This torque quadrupole spins-up the magnetofluid, generates vorticity, and enhances both the inflow and outflow. The same effect was noticed more recently (Lapenta 2008), where it was argued that the nonlinear linkage of the reconnection outflow to its own inflow will enhance reconnection rates to fast, order one levels.

Each of these three classes of influences of turbulence on reconnection can arguably increase the rate of reconnection. Furthermore there has been in each case at least some demonstration of the nature and degree of the suggested increase in reconnection rate. All three effects were suggested based on 2D decaying sheet pinch calculations (Matthaeus and Lamkin 1985, 1986). More recent higher resolution simulations have shown very similar results, based on background turbulence (Lapenta 2008; Loureiro et al. 2009) or based on localized driving in the reconnection zone that emulates effects of high Reynolds number turbulence (Kowal et al. 2009). At this time, it is difficult to say with generality which type of turbulence has the greates influence on reconnection. However, it does seem clear that the simple assumptions in laminar steady problems lead to restrictions on dynamics and limitations on rates of reconnection that may be unrealistic in many natural and laboratory circumstances.

5.2 Reconnection in Turbulence

Another problem of central importance is to understand the role that reconnection plays in the turbulent cascade. The basic physics of the cascade process provides an intuitive picture of the necessity of this role. As seen for example in discussion of the dynamo problem and the Parker solar flux tube problem, discussed in a prior section, the same processes that give rise to turbulence effects imply the existence and possible central role of reconnection. Turbulence and reconnection go hand-in-hand. Whether driven mechanically or electromagnetically, an MHD system in the turbulent regime must exchange energy across scales, and between flow and magnetic field, all the while rearranging its topology to accomplish these transformations. This occurs also in undriven turbulent relaxation, as was explicitly demonstrated (Matthaeus and Montgomery 1980) in an early two dimensional numerical study of selective decay relaxation processes.

The picture in 2D is reasonably clear: The energy-containing structures in 2D MHD turbulence are magnetic islands. Turbulence buffets and distorts the islands and frequently aids in more forceful "collisions" between islands. Strong current sheets form between the islands, and reconnection occurs. This can occur at a variety of scales, as interacting islands can be present anywhere in the turbulence spectrum. Depending on the amount of velocity shear that is present, the overall level of turbulence, and the Reynolds number, both the islands and the reconnection process may become distorted relative to the standard textbook pictures.

Recognizing that reconnection is an ongoing and statistical aspect of a turbulent medium, and with modern computers having the resources to study these effects, Servidio et al. (2009, 2010) introduced recently a direct quantitative study of the reconnection that occurs in turbulence. The approach was to simulate 2D MHD turbulence in a parameter regime in which there are many magnetic islands. In various runs carried out there were hundreds to a few thousand islands. Employing spectral method codes with carefully controlled resolution to avoid numerical effects (Wan et al. 2010), the turbulence was permitted to evolve for at least a characteristic nonlinear time scale. At this point the cascade has established many active reconnection sites. In fact the number of reconnection sites is comparable to the number of magnetic islands. An analysis was carried out of the critical points (locations where magnetic field vanishes) and the Hessian matrix of second derivatives of the magnetic potential at the critical points. The electric field at an X-type neutral point is the rate of magnetic reconnection at that particular reconnection site. This study also established a scheme for delineating the diffusion-dominated region near an X-point, i.e., the reconnection region, even in highly distorted cases. Following this procedure it is possible to compute all the reconnection sites and their reconnection rate in an ensemble of self consistently interacting magnetic islands. The interesting conclusions of this study are: (1) there is a broad distribution of reconnection rates, most of them very weak, but a "tail" of strong events extending to reconnection rates of several tenths in Alfvén units; (2) the length L and thickness δ of the reconnection sites are distributed broadly, but L generally lies in a range of a decade or so near the correlation scale of the turbulence, while δ is broadly distributed between the Taylor microscale and the Kolmogorov dissipation scales of the turbulence; and (3) the fastest reconnection events are associated with the highly intermittent extreme events in the current distribution. Notably it is found that the strong events are consistent with a form of the Sweet Parker theory in which the rates are regulated by the local properties of the *fluctuations*, that is the rates are controlled by the turbulence, with random parameters.

Evidently reconnection is an inherent feature of turbulence, and there is now evidence, in the 2D model, that reconnection can be controlled by turbulence in the way described by Servidio et al. (2010). It should be very interesting to see how these results carry over to other models, such as Hall and reduced MHD, and of course to three dimensions. We await greater computing resources as well as further theoretical insights to attack these more realistic problems, but we suspect they will soon become tractable.

6 Relation of Turbulence to Other Fundamental Processes

Turbulence is likely to have an impact on other basic physical process in space and astrophysics, and can be important in other venues beyond the solar and interplanetary contexts discussed above. In this section we review a few other possibilities for turbulence applications, with no attempt whatsoever at either completeness or scholarly coverage of the background.

Magnetospheric dynamics. The magnetosphere in itself is a complex nonlinear system, and driven by interactions with the turbulent solar wind. Turbulence is also potentially major factor in magnetospheric dynamics and in solar wind-magnetospheric couplings. Recently, simulation tools used in these studies have apparently become powerful enough to study the fully nonlinear system as one that admits forms of turbulence. Turbulence-style data analysis studies are providing some guidance in understanding the nature of the several varieties of turbulence in the geospace system (Borovsky and Funsten 2003; Retinó et al. 2007; Weygand et al. 2009). This turbulence seems to be not very high Reynolds number, not approximately homogeneous, and not very well described by MHD. This promises to be a difficult and interesting problem in coming years.

Dynamo. In various formulations of the dynamo problem, its efficiency is related to coupling across scales and behavior of fluctuations and small scale reconnection activity. Both the regularity and the stochasticity of reversals must be related to properties of the turbulence and nonlinear dynamics, and this remains an active area of research. Ultimately these are the drivers of the magnetic atmosphere of the sun, which controls the properties of the heliosphere.

Magnetic self-organization. This term refers to the dynamical generation of long lived nonlinear structure in a turbulent plasma or MHD medium. It is well known in plasma confined devices such as Reversed Field Pinch or Spheromak experiments. It also has antecedents in pure electron plasmas and in two dimensional or rotating fluids, and in certain MHD systems with a large scale conserved quantity such as magnetic helicity. Analogous physics is present in the dynamo, and in magnetic flux tubes such as coronal loops and even potentially in open field regions of coronal holes. Not surprisingly the statistical dynamics of turbulence plays a key role in understanding the dynamical path to self-organized or relaxed states. Interestingly, there is recent evidence from simulations, and from laboratory experiments, that self-organization can lead to generation of very long time tails on correlation functions. Some solar observations seem to support this idea as well. This generation of very low frequency "noise" directly influences predictability. This is a "large scale" effect of turbulence, in contrast to the direct cascade smaller scale effects. This brings home the point that study of turbulence also involves large scale features.

CME dynamics. In the inner solar wind, a major problem is to understand the interaction of CMEs and shocks with both pre-existing fluctuations and with possible admixtures of self-generated turbulence. The turbulence interactions can be expected to have a major influence on the forces, such as drag, that are imposed on the CME. The back reaction on the ambient medium is also complex, and directly affects particle acceleration and transport. These are major factors in space weather prediction and need to be understood in the coming decade. The problem of the interaction of CMEs with background interplanetary medium is analogous to high Reynolds number turbulent flow past an obstacle, but more complex because of expected kinetic effects. Turbulent drag, self consistently generated fluctuations, particle acceleration, and leading edge shock formation are aspects of the problem that depend on turbulence. This is a very important class of problems for space weather.

Prediction and space weather. A variety of effects influence our ability to predict magnetic fields and particle distributions at an particular point in the heliosphere, such as decorrelation of fluctuations in time, field line random walk, turbulent drifts, trapping and stochastic orbits. Each of these depends in detail on turbulence properties. Consequently, prediction for space weather purposes will be limited as a matter of principle by these effects. It will be important to develop a quantitative understanding of these influences, beginning from theory, and supported by extensive observational studies.

Dissipation, heating and intermittency. Termination of the turbulent cascade through kinetic processes, commonly described as "dissipation," is a fundamental problem in space physics and in plasma astrophysics in general. Irreversible conversion of collective fluid or kinetic scale motions into internal energy, or "heating" is a closely related concept. Neither is well understood in plasmas such as the corona and solar wind, yet the operation of such mechanisms is responsible for the presence of the wind and the overall structure of the heliosphere. This is a major fundamental issue in which turbulence ranging from fluid to kinetic scales clearly plays a central role. Recent observational and theoretical evidence connect dissipation and small scale non-Gaussian inhomogeneities such as current sheets. Far from being only an academic problem, the intermittency of turbulence provides a dynamical connection between coherent structures (e.g., current sheets), patchiness of dissipation, and the entire inertial range of turbulence. Understanding this truly cross-scale relationship is a challenge for the next decade.

Shock structure. Shocks are widespread in space and astrophysics and represent important boundaries between plasmas and sources of energetic particles. There is a growing indication, from both theoretical and observational directions, that turbulence plays an important role in shock formation and dynamics, in addition to being an essential element in diffusive shock acceleration. Further research in shock-turbulence interactions including observational study is needed to fully understand this topic, which also has important implications for astrophysics, such as in SNR shocks that propagate in a turbulent medium as well.

Particle acceleration. The two most of prominent models of charged particle acceleration are diffusive shock acceleration and stochastic acceleration. Both depend in an essential way on the nature of the turbulent fluctuations, which are often viewed either as self-generated by the energetic particles or as random phase waves. Treating the fluctuations more realistically as turbulence allows for coherent structures—it then becomes possible to have trapping and other effects that further enhance acceleration. The more general interaction of turbulent dissipation electric fields with the self-consistent particle distributions in a plasma environment with few collisions and the resulting tails in particle distribution functions have only begun to be explored. The possibility that the ubiquitous $1/v^5$ spectrum is due to such types of effect is an important subject to be studied.

Particle scattering and transport. Scattering theory depends explicitly on turbulence properties, including the energy spectrum, the time variations, and in principle, the higher order statistics. The attainment of the diffusive limit can be directly influenced by certain details of the turbulence properties. Furthermore, coherent structures such as persistent flux tubes can cause trapping effects and delayed attainment of diffusion. Evidently particle transport cannot be understood without a fairly sophisticated knowledge of the turbulence.

Solar modulation of galactic cosmic rays. This classic problem in Heliospheric Physics is a "grand challenge" problem in understanding the effects of turbulence. It involves understanding large scale flows over great distances, and it involves knowing how the particle transport properties depend on the turbulence properties (i.e. the diffusion coefficients). Finally it involves understanding how the turbulence properties vary in space and time throughout the heliosphere. Every aspect of this problem depends upon understanding the turbulence.

7 Concluding Remarks

Turbulence enters into many crucial heliophysical dynamical processes, influencing cross scale couplings in an essential way. Therefore beyond its justification as basic physics (which may be a matter of aesthetic appeal), study of turbulence emerges as an essential component of solar and heliospheric research. We are led to offer a firm answer to space physicists who raise the question "*Who needs turbulence?*" We answer that the complex coupled nonlinear heliospheric system contains turbulence effects in many guises, some of which we have briefly reviewed here. To make progress, researchers in our field, along with researchers in related areas of plasma astrophysics, need to acknowledge the impact of these important physical processes. One occasionally hears jocular statements such as "we don't need any of this kay equals kay-prime plus kay nonsense," intended to brand turbulence as unessential esoterica. Perhaps soon such as approach will be widely recognized as counter-productive to the advancement of our physical understanding.

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