Waves and Turbulence in Space and Astrophysical Plasmas

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1. Introduction and Current Status

Waves and turbulence are ubiquitous in space and astrophysical plasmas. Like fluid turbulence, plasma turbulence is one of the most important, unsolved problems of classical physics, and has significant implications for nearly every other topic discussed in this Workshop. The subject is treated extensively in many monographs and over a million papers, and it would be neither possible nor desirable to list all the important questions and strategies to tackle them in this brief narrative. Our focus is limited to identifying some key questions, broadly framed, that can be potentially transformative. While we will mention various astrophysical objects such as accretion disks, the interstellar medium and the intra-cluster medium, primarily one object in space---the solar corona and wind---will be treated in some depth.

Although we focus on the solar corona and wind, it should be kept in mind that most stars have hot coronae, with temperatures exceeding a million degrees. The Sun not only has a hot corona, but also a hot wind stretching to the interstellar medium. Among the most important questions pertaining to the origins of the solar corona and wind are: How are these nearly collisionless plasmas heated by waves and turbulence? What is the nature of MHD and collisionless turbulence in these plasmas that are permeated by magnetic fields? What are the dissipation mechanisms, and their roles in particle acceleration and heating? What are the effects of inhomogeneity and the role of coherent structures on waves and turbulence? Following discussions on these key scientific questions, we then describe a few major opportunities in laboratory experiments, fluid and kinetic high-performance computing, and *in situ* and remote-sensing observations. We conclude by summarizing the potential impacts of answering these key questions, and discussing connections to other topics.

2. Key Scientific Challenges

2.1 What is the nature of MHD and collisionless turbulence in magnetized space and astrophysical plasmas?

Plasma in the Universe is magnetized and turbulent. Observations indicate that plasma fluctuations span a huge range of scales, from hundreds of parsecs to hundreds of kilometers. Observations of the solar wind and the interstellar medium (ISM) reveal qualitatively similar scaling laws of magnetic, velocity, and density fluctuations, which extend down to the ion gyro scales. There is significant debate as to whether there is a "universal" turbulent cascade in such systems.

At large scales compared to plasma micro-scales, MHD provides a good description of plasma dynamics. The plasma beta in space and astrophysical plasmas is often close to or greater than unity, which distinguishes them from plasmas in laboratory (including fusion) plasmas. The sonic Mach number is of order of one, which distinguishes astrophysical turbulence from most terrestrial applications. Although such turbulence is compressible, incompressible one-fluid MHD is a useful point of departure. At small scales, which are close or below the ion gyro-radius (ρ_i) (or ion-sound scales in a plasma with $T_e > T_i$), plasma dynamics become much richer, as compressibility, two-fluid, and kinetic effects become important. Those scales are harder to address analytically, however, various two-fluid, gyro-kinetic and kinetic plasma modeling and simulations produce promising results. Observations of the solar wind turbulence provide guidance in these studies.

Incompressible MHD turbulence exhibits certain limiting regimes such as strong or weak and balanced or imbalanced. Different regimes may be present at different scales in the same system. For example, large-scale weak turbulence eventually becomes strong at small scales or globally balanced turbulence is locally imbalanced. It is important to understand under which conditions turbulence exhibits one of these regimes.

Weak MHD turbulence is dominated by Alfven waves weakly interacting with each other. Its practical applications are limited, as turbulence in nature is typically strong. However, weak MHD turbulence admits fuller analytical treatment and serves as a test bed for fundamental ideas in the theory of MHD turbulence, such as anisotropy and tendency to realize critical balance, locality and self-similar energy cascades, and so on and so forth. Strong MHD turbulence assumes balance between linear wave propagation and nonlinear interaction. It lacks rigorous analytical treatment. Good physical models and numerical simulations are therefore indispensable. A fundamental property of strong MHD turbulence is its inherent local anisotropy. Small-scale fluctuations are progressively more anisotropic at smaller scales as the balance between the linear and nonlinear interaction times is preserved independently of scale. This is the critical balance condition.

Both weak and strong turbulence can be either balanced or imbalanced. Imbalance means that energy fluxes associated with Alfven modes propagating in opposite directions along the guide magnetic field are unequal. Imbalanced turbulence has nonzero cross-helicity and it is not mirror-invariant. It is reasonable to believe that MHD turbulence occurring in nature and in the laboratory is typically imbalanced as it is generated by localized sources (e.g., solar wind, or antennae in controlled experiments). Due to the constraints imposed by conservation laws, imbalance cannot be destroyed by MHD dynamics if dissipation is negligible. Imbalance seems to be an inherent property of strong MHD turbulence. Recent numerical results indicate that strong MHD turbulence is locally imbalanced even if it is balanced overall. It spontaneously produces correlated regions of imbalanced fluctuations of both positive and negative signs.

The various regimes of MHD turbulence can be described in terms of the shear-Alfvén modes, which are incompressible. Compressible effects are associated with the fast and slow modes, and with the entropy mode. There are reasons to believe that these modes are either strongly damped or dynamically unessential in the turbulence cascades. A variety of plasma processes can be responsible for their damping at various scales.

A point of view is that the limiting regimes discussed above are "universal." An observational example is the spectrum of density fluctuations in the ISM is Kolmogorov (i.e., proportional to $k^{-5/3}$) over nine decades in wave number (k) space, which stimulated the Goldreich-Sridhar theory of anisotropic MHD turbulence. Another point of view argues against "universality", noting that the lack of universality occurs due to a number of reasons, such as the dependence of the turbulence on dimensionless physical parameters such as the plasma beta, the ratio of the magnitudes of the magnetic fluctuation to the background (or mean) magnetic field and/or the nature of the driving and initial conditions. So if MHD turbulence does not possess a single universal character, where do we go? It seems necessary to understand the cascaded ideal invariants in various parameters regimes, and that means understanding how turbulent relaxation processes operate in various parameters regimes. The spectra will be associated with fluxes of ideal invariants such as energy, while higher-order statistics are associated with characteristic coherent structures. Better understanding of fast (less than an eddy time) and slow relaxation processes will thus clarify not only spectral variability but also intermittency and its effects on topology of fields and flows as well as turbulent dissipation.

Interaction of turbulence with inhomogeneity represents a difficult problem, and methods for tackling it have been an active area of research, especially in fusion plasmas. Approaches include multiscale analysis leading to transport equations, and these need to be tested against observations or very large and multi-scale simulations for validation. This leads to extremely demanding computational problems. Fortunately, both computer simulations and theory are well positioned to make progress on these topics, which will immediately have impact on applications as diverse as coronal heating, solar wind radial evolution, space weather, cosmic ray propagation and galactic turbulence.

2.2. What are the dissipation mechanisms and their roles in particle acceleration and heating?

The inertial range of MHD turbulence in wave number space has a "break point" where the effects of dissipation typically leads to a steepening of the inertial range spectrum. In weakly collisional space and astrophysical plasmas, the beginning of the range of wave numbers where this occurs often has a two-fluid or kinetic origin (e.g., the ion skin depth or ion gyroradius (ρ_i)). While there is clear evidence of this dissipation regime in observations of plasma turbulence in the solar wind or the interstellar medium, there are, as yet, no definitive theories. Theoretical and computational models based on two-fluid (or Hall MHD) equations, gyro-kinetic equations as well as fully kinetic models have been put forward and compared with specific features of observations, with some successes. In several cases, it has been suggested that the dissipation range is itself multi-scale, contains new power-laws representing kinetic Alfvén and/or whistler turbulence, and that wave damping or particle heating occurs at high wave numbers within this range.

For example, the shear Alfvén-wave turbulence described under topic 1 becomes kinetic-Alfvén-wave turbulence when $k_\perp \rho_i \geq 1$. Then the ions decouple from the waves, and the damping is dominated by the electrons. As a result, the kinetic Alfvén waves do not undergo significant proton cyclotron damping in linear wave theory, but they do damp via Landau and transit-time damping. If kinetic Alfvén turbulence dissipates via Landau and transit-time damping, then the resulting turbulent heating should increase only the parallel component of the particle kinetic energy, thereby increasing the parallel temperature. On the other hand, in a number of systems such as the solar corona and solar wind, ions are observed to undergo perpendicular heating despite the fact that most of the fluctuation energy is believed to be in the form of low-frequency kinetic Alfvén wave fluctuations. Determining the causes of such perpendicular ion heating is one of the critical unsolved problems in the study of space and astrophysical turbulence.

It is likely that there is not just a single answer to questions about dissipation in turbulent astrophysical plasmas. In the so–called collisionless limit, there may be multiple mechanisms available, including those that operate in the parallel and perpendicular directions (of wave vector relative to the large scale magnetic field). Most mechanisms have been identified traditionally within the context of homogenous linear Vlasov theory or other reduced kinetic or two-fluid models. A major theoretical problem is to understand the realm of accuracy of this traditional approach. A complementary direction for theory is to look for inhomogeneous dissipation mechanisms, which may be associated with regions of strong magnetic or velocity shear, as well as regions of rapid variation of temperature or density. One promising candidate is dissipation in channels of strong magnetic shear, or electric current density. These are promising regions to look for strong inhomogeneous dissipation, even though magnetic reconnection may or may not be active in such regions. It is also reasonably well established (mainly but not exclusively from test particle simulations) that particles can be accelerated near current sheets and channels. The precise nature of this heating, especially its anisotropy, is currently being studied and discussed. Wave-particle interaction can also influence the suprathermal particle populations, and certain cases, such as cometary and interplanetary pickup ion assimilation, are veritable laboratories for quantitative exploration and testing of the associated theories.

There are many different plasma environments in which the dissipation of MHD turbulence gives rise to particle energization that is in some way "preferential" (i.e., dependent on charge and mass, or anisotropic in physical space or velocity space). This has been seen not only in space and astrophysical plasmas, but also in laboratory experiments, including several types of fusion plasmas. There has been much recent debate over the relative importance of various kinds of structure at the smallest dissipation scales of the type discussed under topic 4 below. In many environments, however, the number of suggested mechanisms and structures is bewilderingly large. For example, Figure 1 illustrates a subset of the many different kinetic dissipation processes that have been proposed to explain the strong preferential heating of heavy ions observed in the solar corona. Ion heating in many situations is likely to be just the final stage of a multi-step process of energy conversion between waves, turbulent motions, reconnection structures, and various kinds of distortions in the particle velocity distribution functions.

At present, there is no general understanding of how the smallest-scale turbulent fluctuations partition their energy between the different particle species. Simulation efforts are often focused, by necessity, on only one primary mechanism at a time. What is needed, however, is an objective assessment of the *relative* contributions from the large number of suggested dissipation processes. To do this, the scope of existing theory must be broadened to build true "sandbox models" that allow the most important processes to assert their dominance in the presence of many other competing processes. These broader models involve careful tradeoffs, in that they may not have the computational rigor of the more focused models, but they would be able to answer a wider range of questions than the focused models. Examples of such tradeoffs could include: (1) not modeling the full dynamics of the turbulent eddies, but instead treating the cascade as a diffusion process in wave number space, and/or (2) parameterizing the results of nonlinear particle simulations in terms of net rates of heating. These broader models are likely to require increased collaboration between groups, and increased community support for true *working* workshops (during which the specifics of these sandbox models are determined, and even the initial models are coded).

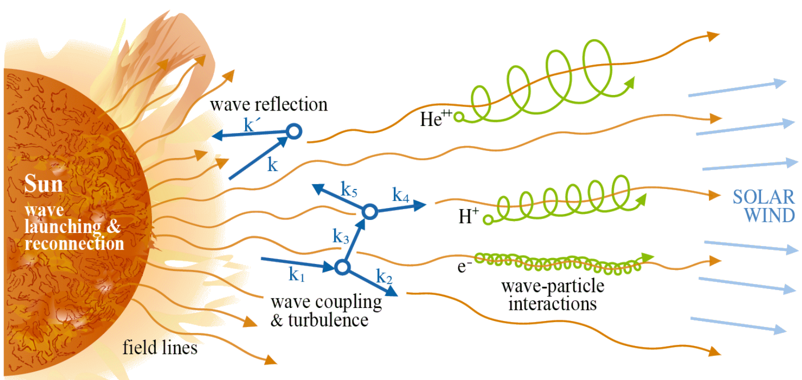

Figure 1: Cartoon illustrating various kinetic dissipation processes in the solar corona. (Image courtesy of B. Chandran, M. Lee, and K. Donahue of the University of New Hampshire.)

2.3. What are the effects of inhomogeneity and interactions of turbulence with mean fields? What are the roles of coherent structures?

Virtually all relevant or real instances of waves and turbulence involve inhomogeneity, which can drive turbulence (e.g., density and temperature gradients can drive drift-Alfvén turbulence, velocity gradients can drive magnetorotational turbulence). Inhomogeneity can reflect, modulate, and scatter waves (e.g., Alfvén waves in the solar wind) and can couple to velocity space structure (e.g., resonant Alfvén excitation by cosmic rays). Inhomogeneity in plasmas has the effect of coupling phenomena that are often separable in homogeneous plasmas. It can affect *all* of excitation (i.e., waves and instabilities), linear propagation and nonlinear transfer (i.e., scattering, reflection, and modulation), and dissipation (i.e., resonant absorption). Moreover, inhomogeneity can contribute to the relevant time scales in the problem, as for shear flow turbulence when in the rapid distortion limit.

Traditionally, MHD turbulence has been divided into distinct realms of turbulence, which deal with issues such as cascades and structure functions, and "mean field" treatments that deal with dynamos, transport and other mean-field processes. This separation is increasingly seen as artificial. For example, it is now understood that a small-scale dynamo can alter or quench a large-scale dynamo and change the turbulence dynamics as well. Similarly, a strong mean shear flow can excite the magnetorotational instability (MRI) but also leave a 'foot-print' on the dynamics of smaller scales, via rapid distortion. Mean-field coupling, such as field amplification (i.e., dynamo) and/or turbulent resistivity (i.e., spatial transport or microscopic momentum exchange) will necessarily impact turbulence and wave dynamics via enhanced dissipation, induced alignment, and nonlinear modification of cross-phases. Turbulence can either amplify or quench mean fields and flows, and so must be treated on an equal footing with them, in order to satisfy relevant conservation laws.

Energetic particles are a ubiquitous means for excitation of MHD and plasma Alfvénic turbulence. Of particular note and importance are cosmic rays, which can resonantly and nonresonantly excite the Alfvénic MHD turbulence which 'confines' them to the shock, which in turn is thought to accelerate them by the direct shock acceleration mechanism. Many other examples exist, as well. Energetic particles can excite waves by linear resonance, mediate nonlinear evolution via nonlinear wave-particle scattering (i.e., nonlinear Landau damping) and terminate excitation by nonlinear trapping. Strong wave-particle resonance, leading to phenomenon such as structure formation, re-emission of waves, and frequency chirping that are rich topical areas which merit further study and increased emphasis.

Understanding the coherent structures that are formed in plasma and MHD turbulence is a central theoretical, observational and experimental issue. Coherent structures are not only likely to be central in understanding dissipation, but their formation and dynamics provide information critical to understanding cascade and relaxation processes. Based on hydrodynamic antecedents one would expect that dissipation occurs mainly in coherent structures although not exclusively in the most intense of these small-scale entities. Indeed, statistical intermittency of turbulence is connected with coherent structure formation, and to a great degree the content of multi-fractal analysis and the study of higher-order statistics is an effort to characterize quantitatively the nature of these structures. There has recently been considerable interest in understanding the relationship between observed near-discontinuous structure in the solar wind and MHD turbulence properties. Indications are that these may not always be fossil classical MHD discontinuities but rather might also be produced by local turbulence cascade processes. Further study of this type may be able to relate the current sheets and other discontinuities to rapid local relaxation due to turbulence. In this way, it is possible that relaxation might be related to a real-space picture of intermittency that is connected with observations and properties readily computed in simulations. Similar ideas may be applicable to the corona and various observations that show strong evidence of structure probably perpendicular to the local magnetic field direction. Beside their relation to cascade, intermittency and dissipation, coherent structures might also be related to larger scale topological issues such as the appearance, survivability and structure of large-scale flux tubes. These in turn may be very important in guiding or channeling energetic particle populations, in a way that random phase transport theory cannot capture. An example of this may be the well-known phenomenon of dropouts in solar energetic particle observations.

3. Major Opportunities

3.1. Laboratory experiments

While laboratory experiments cannot typically match astrophysical parameters, either dimensional or dimensionless, they can contribute to our understanding of plasma physics phenomena of relevance to astrophysical plasmas. Plasma waves, instabilities, and turbulence have been studied in detail in the laboratory for decades, and many concepts that emerged from theses studies have been employed to explain space and astrophysical observations. For example, electromagnetic wave emission by plasmas due to mode conversion of Langmuir turbulence was first studied in the laboratory before being invoked to explain radio emission from pulsars. Similarly, properties of double layers, which are often formed due to electrostatic instabilities and turbulence, have a long history in laboratory experiments, and are a prominent candidate for auroral acceleration in the Earth's magnetosphere.

There are a number of opportunities pertaining to waves and turbulence in space and astrophysical plasmas that can be addressed by laboratory experiments, including fusion devices. These include the basic physics of nonlinear wave interactions and damping, important instabilities driven by anisotropy (e.g. mirror or fire-hose), and the properties of turbulent cascades driven at large scale either through driven flows or injected Alfven waves. There are two complementary possibilities: either "basic plasma devices" which have typically simple geometry, low temperatures (~10 eV) and high collisionality (except at low density), and very detailed probe dynamics, or fusion confinement devices which typically have more complicated geometry, high temperatures and low collisionality, but are more difficult to diagnose even with sophisticated techniques. Since no laboratory experiments will match space or astrophysical parameters, a reasonable strategy is to identify physical processes that are common to both types of plasmas, and use theory and simulation to bridge the parameter gap. At the present time, it appears possible to design a new basic plasma device that is weakly collisional (with system size comparable to the mean free path), holding plasmas of moderate density and plasma beta of the order unity with a magnetic field that is large enough to allow enough separation between the system size and the ion gyroradius.

Laboratory experiments can also play a key role in testing the large-scale simulation codes that are of increasing importance in astrophysical research. For example, the kinetic Alfvén turbulence models for the solar wind discussed above are based on simulation codes developed to predict the behavior of laboratory plasmas. In particular, the measured decay of Alfvén wave energy in controlled laboratory experiments has provided a good test of theoretical models of damping based on ion-cyclotron and electron Landau damping. Predictions from kinetic simulation codes are being compared extensively with turbulence measurements in fusion plasmas such as tokamaks. This comparison can validate the ability of the code to capture the physics of kinetic processes in collisionless plasmas, providing confidence in extending the simulation to plasmas of astrophysical interest such as the solar wind or accretion disks. Anisotropic ion heating and its isotopic dependence is currently under study in reversed-field pinches by means of sophisticated diagnostic techniques, and may have important qualitative implications for analogous mechanisms of heating in the solar corona, discussed below.

3.2. High-Performance Computing

Following Moore's law, which predicts the doubling of computing power every 18 months, doubling the Reynolds number and thus the grid resolution in three dimensions occurs every 6 years, so direct numerical simulations (DNS) of turbulence advance slowly in the range of Reynolds and Lundquist number. This, and the fact that turbulent behavior may be dominated by spatially localized intermittent structures, are the driving forces behind one of the main objectives of the community to develop a suite of methods that complement each other, incorporating realistic conditions that pertain to the many facets of plasma turbulence, from fluid to kinetic (both Lagrangian and Eulerian) models, exploring fundamental as well as more applied features in complex systems.

Enhancing the realism of fluid turbulence simulations to include, for example, a complex magnetic geometry, background inhomogeneity, or kinetic effects requires enhancements not only in the mathematical models, but also improvements in numerical algorithms and solvers. Major challenges confronting fluid codes are parallel as well as algorithmic scalability.

Kinetic turbulence simulations in plasma astrophysics have benefitted greatly in recent years from cross-fertilization between fusion and astrophysics. Traditional particle-in-cell (Lagrangian) as well as continuum (Eulerian) algorithms have enjoyed successes in describing important astrophysical phenomena. The challenge for kinetic turbulence simulations is to be able to describe and resolve multiscale physics, that is mesocale and microscale physics.

Petascale and exascale computing initiatives, now under way at DOE and NSF, will be more effective and accessible to plasma astrophysicists if such initiatives recognize the strongly interdisciplinary character of plasma astrophysics, separate from the more traditional disciplines of astrophysics and plasma physics, with separate allocations tailored to the unique needs of the discipline.

3.3 Opportunities in in-situ and remote-sensing observations

Much of our knowledge about turbulence in distant astrophysical environments comes from remote observations that provide rather loose constraints on the properties of the fluctuations. In astronomy, “turbulence” itself is often defined apart from its fluid dynamics roots, i.e., all that is often required is a collection of motions that are unresolved either spatially or temporally and have no clearly dominant frequency. In many cases, firm evidence for the existence of an actual turbulent cascade awaits direct *in situ* exploration. Substantial progress can be made, however, if the remote-sensing observations are combined with theoretical modeling and extrapolations from existing *in situ* measurements. Theorists need to be better informed about the kinds of measurements that exist (and what does not exist), and observers need to be more aware that their data may be useful in advancing understanding in fields other than their own. In many cases there is insufficient communication between sub-fields in astrophysics, space physics, and laboratory plasma physics, such that there tends to be “reinvention of the wheel” regarding analysis techniques and model code development.

In addition to well-publicized observations, there are also many existing plasma properties that have some kind of empirical constraints on their values, but have not been adequately "processed" or published in forms accessible to the theoretical community. More effort needs to be devoted to cross-cutting analysis of archival data that may shed new light on important physical processes. In what follows, we discuss in greater depth the solar wind, widely recognized as a rich laboratory for turbulence studies.

The solar wind is the paradigm for more general stellar winds driven by magnetic activity. The solar wind flow at solar minimum is subdivided into high and low speed streams, with speeds of around 750 km/s and 400 km/s respectively (to be compared with the escape speed from the sun, ~ 600 km/s). The Ulysses mission has shown that the fast wind is the basic outflow from the corona at solar minimum, while the much more irregular slow solar wind is confined to the equatorial regions, presumably arising from regions adjacent or inside the streamer belt. As the solar cycle progresses, the streamer belt expands in latitude so that, at activity maximum, the corona appears to be nearly uniformly distributed around the solar disk, while high-speed wind streams occur over a much smaller volume. The fast solar wind, with average speed around 750 km/s, originates from regions where the coronal electron temperature is lower. This inverse correlation between flow speed and coronal electron temperature where the freezing in of minor ion charge states occurs shows that the foundation of Parker's original theory of the solar wind, i.e., that high coronal electron temperatures and electron heat conduction drive the solar wind expansion, needs to be reconsidered. SOHO measurements of the very high temperatures of the coronal ions, together with the persistent positive correlation of in-situ wind speed and proton temperature, suggest that other forces, namely magnetic mirror and wave-particle interactions should also contribute strongly to the expansion of the outer corona.

SOHO observations have shown that the slow solar wind, which is confined to regions emanating from the magnetic activity belt and seems to expand in a bursty, intermittent fashion from the top of helmet streamers, seen to expand continuously, in X-rays. A third type of flow arises from larger eruptions of coronal magnetic structures, or coronal mass ejections (CMEs), which also lead to acceleration of high-energy particles. As the solar activity cycle progresses, the simple fast-slow structure gives way to a much more variable, but typically slower, solar wind at activity maximum, apparently originating not only from the much more sparse coronal hole regions and quiet sun, but also from coronal active regions.

Several fundamental plasma physical processes discussed above, i.e., waves and instabilities and turbulent cascades, as well as magnetic reconnection (another theme of this Workshop) – operating on a vast range of temporal and spatial scales are believed to play a role in coronal heating and solar wind acceleration. Basic unanswered questions, described below, concern the storage, transport, and release of the mechanical energy required for coronal heating, the specific mechanism(s) for the conversion of energy between the magnetic field and thermal particles, and the dynamics of photospheric and coronal magnetic fields in the source regions of the solar wind. All of these questions are strongly affected by issues, articulated above, pertaining to waves and turbulence.

(i) What causes coronal heating and wind acceleration? The solar corona loses energy in the form of radiation, heat conduction, waves, and the kinetic energy of the solar wind flow. This energy must come from mechanical energy residing in photospheric convection, the solar magnetic field acting both to channel and store this energy in the

outer atmospheric layers. However, the mechanisms by which the energy is transferred and dissipated to generate the hot corona, solar wind, and heliosphere throughout the Sun's activity cycle remain one of the fundamental unanswered questions in solar and heliospheric physics.

(ii) What causes the rapid acceleration of fast solar wind streams so close to the sun? SOHO/UVCS observations using the Doppler dimming technique and interplanetary scintillation measurements indicate that the high speed solar wind is rapidly accelerated near the Sun, reaching speeds of the order of 600 km/s within 10 R_s. Observations of comet C/1996Y1 confirm a most probable speed of about 720 km/s for the solar wind at 6.8 R_S. Such rapid acceleration appears to result from the extremely large and anisotropic effective temperatures in the lower corona, which have been measured by SOHO/UVCS in coronal holes, though not directly for protons, the main solar wind constituent. These temperatures are much higher perpendicular to the magnetic field. The fast solar wind measured in situ shows what may be a relic of this anisotropy, smaller than that inferred from coronal observations, but persisting in the distance range from 0.3 to 5 AU. Proton, alpha-particle, and minor ion distribution functions in the fast wind also present a non-thermal beam-like component whose speed is comparable to the local Alfvén speed. All these properties suggest that Alfvén or ion-cyclotron waves play a major role in coronal heating and solar wind acceleration in high-speed wind.

(iii) Where are the different composition, plasma and turbulence properties of fast and slow wind established? The fast solar wind flow is steady, with fluctuations in radial speed of order 50 km/s, and the charge-state distributions indicate a low freezing-in temperature. The slow solar wind is variable, with higher but variable freezing-in temperatures. The composition of the fast and slow wind also differs, Mg and Fe being overabundant with respect to O in the slow wind. Solar wind protons and ions are however typically hotter in high-speed streams than in the slow wind. The difference between the fast and the slow solar wind extends to the shape of the particle distribution functions. The fast wind exhibits proton perpendicular temperatures that are slightly higher than the parallel temperatures. Proton distribution functions in the fast wind also present a beam accelerated compared to the main distribution by a speed comparable to the Alfvén speed, a feature shared by the alpha particles. Turbulence is also different in fast and slow streams, with fast streams containing fluctuations in transverse velocity and magnetic fields that are more strongly correlated in what is known as Alfvénic turbulence, a well-developed spectrum of quasi-incompressible waves propagating away from the sun. In the slow wind no such preferred sense of propagation is observed, while larger density and magnetic field magnitude fluctuations are present, revealing a much more standard and evolved MHD turbulent state.

The three issues (i)-(iii) discussed above do not exhaust the questions or important physical effects associated with the solar corona or wind. Our discussion has focused on issues pertaining mainly to waves and turbulence. We have omitted, for instance, any discussion of "velocity filtration" models that invoke non-thermal wings in particle distribution functions to account for coronal heating in a steady solar wind, or how coronal magnetic field structure orders the slow solar wind, or how impulsive events like nanoflares, microflares, or CMEs, in which magnetic reconnection is widely believed to play an important role, contribute to the intermittency observed in the solar wind.

4. Impacts and Major Outcomes

The questions identified in Section 3 are among the most important in experimental and theoretical studies of nonlinear waves and turbulence. Answering these questions and adopting some of the proposed solution strategies will have broad and deep impact on plasma astrophysics. We will be able to understand the nature of anisotropic turbulence in magnetized plasmas in the Universe, how they develop on the large scales and how they dissipate, and predict how they heat and accelerate ions and electrons. We will be able to predict how turbulence evolves in inhomogeneous plasmas and interacts with background fields to which it is strongly coupled, invalidating the artificial separation between "mean fields" and turbulent fluctuations, and understand the conditions under which turbulence can amplify or quench mean fields and flows. We will understand the important role of coherent structures that spontaneously evolve out of turbulence, and how they affect cascades, relaxation, and dissipation processes in space and astrophysical plasmas.

5. Connections to Other Topics

As mentioned in the Introduction, the topic of waves and turbulence touches upon and has significant implications for nearly every other topic discussed in this Workshop. For example, reconnection in turbulent systems, despite some recent interesting results, is one of the least understood and important challenges in astrophysical plasma physics. Turbulent mechanisms for particle acceleration and heating are synergistic with shock and reconnection mechanisms. Turbulence has very important consequences for momentum transport, for the accretion process in stars, and for the conversion of magnetic energy to particle energy in jets and outflows. And without a better understanding of how turbulent fluctuations quench or amplify mean fields, which is at the heart of the dynamo problem, it is unlikely that we will understand how the Universe is magnetized.