THEORETICAL RESEARCH ON SOLAR WIND TURBULENCE

A White Paper Submitted to the NRC Decadal Survey of Solar and Space Physics

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Fluctuations in the flow velocity, magnetic field, and electric field are ubiquitous in the solar wind.[13,36] These fluctuations are turbulent, in the sense that they are disordered and span a broad range of scales in both space and time. The study of solar wind turbulence has been motivated by a number of factors. Not only are these fluctuations a fundamental feature of the solar wind, but they may hold the key to understanding the SW's origin and thermodynamics, as described in section I below. Moreover, an understanding of solar wind turbulence will help astronomers to understand magnetized, astrophysical plasmas more generally, as described in section IV.

Research into solar wind turbulence and magnetohydrodynamic (MHD) turbulence has seen a number of seminal developments since the 1960s. For example, Iroshnikov and Kraichnan showed that Alfvén waves (AWs) interact nonlinearly with one another only when they propagate in opposite directions in the plasma rest frame.[19,23] Thus, AWs propagating away from the Sun do not interact with one another, but they do interact with AWs propagating towards the Sun. As shown by Barnes, at wavelengths exceeding the proton gyroradius and in collisionless plasmas, AWs are virtually undamped while fast and slow magnetosonic waves undergo significant damping.[3] As a result, solar wind turbulence likely consists primarily of non-compressive Alfvénic fluctuations. In addition, when counter-propagating AWs interact, energy cascades rapidly to larger $k_\perp$ but only weakly to larger $k_\parallel$, where $k_\perp$ and $k_\parallel$ are the wavevector components perpendicular and parallel to the background magnetic field $\mathbf{B}_0$.[11,12,29,33]

In the following sections, we describe several questions and research areas in which further research promises to be particularly fruitful during the period 2013-2023 covered by the National Research Council Decadal Survey of Solar and Space Physics. We conclude in section V with some policy recommendations for strengthening the nation's space physics theory program.

I Does Turbulence Play an Important Role in Generating the Solar Wind?

The origin of the solar wind is one of the central problems in the field of space physics. Early studies by Parker and others demonstrated that some type of non-thermal energy flux is required in order to explain the large solar wind speeds and large proton temperatures that are measured near Earth.[14,24,30] However, the form of this non-thermal energy flux and the way in which it interacts with thermal plasma are still not understood.

One possibility is that AWs power the solar wind by transporting energy from the solar surface to the solar atmosphere and then on into the solar wind, as illustrated schematically in Fig. 1. Alfén waves can be launched from the Sun in a number of ways, including the continual shaking of the the footpoints of open magnetic field lines by convective motions in the photosphere. Some of the outward propagating waves reflect due to the spatial variation in the Alfvén speed, and the interaction between outward-propagating waves and inward-propagating waves causes AW energy to cascade from large scales to small scales. At sufficiently small scales (comparable to the proton gyroradius), the AWs dissipate, heating the ambient plasma and accelerating the solar wind.

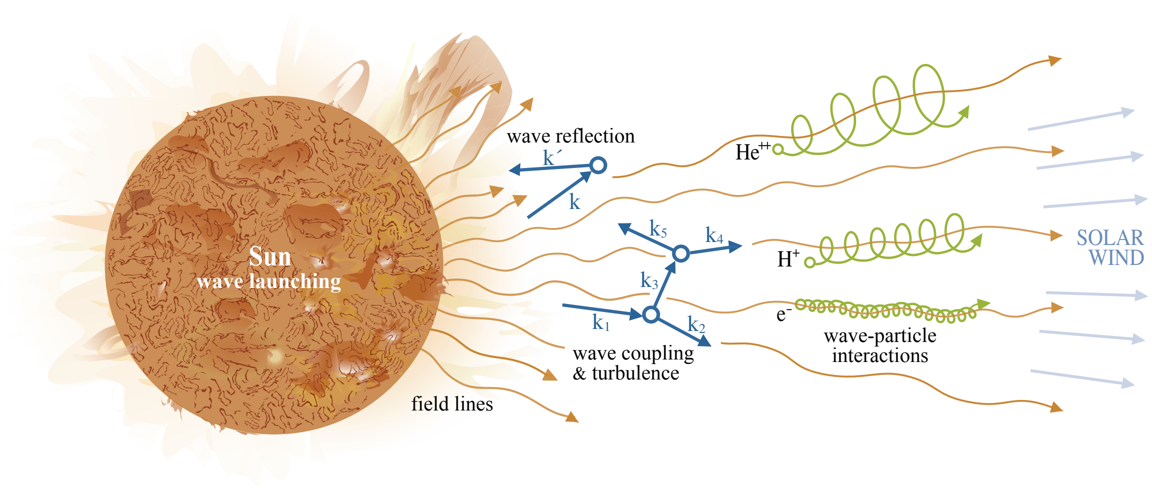

Figure 1: The possible role of waves and turbulence in generating the solar wind.

The above scenario has been the subject of numerous studies,[8,27,37,39] and is consistent with a wide range of observations, including *Hinode* observations of spicule motions,[9] ground-based observations of wave motions in the corona,[34,35] Faraday-rotation observations of magnetic fluctuations in the corona and inner solar wind,[16] and measurements of wind speeds, temperatures, and wave amplitudes near Earth.[8,39] On the other hand, there are at least two possible problems with this scenario:

1. It is not clear that AW turbulence can explain the perpendicular ion heating that is observed in coronal holes[1,10,22] and low-β fast-solar-wind streams.[15,26] The traditional explanation for perpendicular ion heating is via a cyclotron resonance between ions and high-frequency Alfvén/ion-cyclotron waves.[17] However, anisotropic turbulence theories and simulations show that AW energy remains at comparatively low frequencies as it cascades to small scales, so that a cyclotron resonance does not arise.[12,18,33]

2. Satellite observations show that the solar wind undergoes substantial heating and acceleration within a few solar radii of the Sun. It is not clear that the energy of the large-wavelength AWs launched by the Sun can cascade to small scales rapidly enough to explain this near-Sun heating.

A combination of theoretical and computational investigations will be needed to address these problems, including direct numerical simulations of AW turbulence in the inhomogeneous solar atmosphere as well as analytical and numerical investigations of stochastic heating and cyclotron heating by AW turbulence. These types of investigations are discussed further in the sections below. The importance of solving the above problems is underscored by the preparations underway for NASA's Solar Probe Plus (SPP) Mission. The primary science objective of this landmark mission will be to uncover the origin of the solar wind. Substantial progress in our understanding of the turbulence and its dissipation within the solar wind will be needed to interpret the measurements that SPP will provide and maximize the returns from SPP's historic visit to the Sun.

II Inertial Range Physics

Wave energy is injected into the solar wind (e.g., by the Sun) at a "stirring scale" or "outer scale" that greatly exceeds the length scales at which the fluctuations dissipate. The range of scales intermediate between the outer scale and the dissipation scale in a turbulent system is known as the inertial range. A widely adopted hypothesis in AW turbulence research is that fluctuations at inertial-range length scales are only weakly influenced by the details of the large-scale forcing or small-scale dissipation, and instead evolve primarily due to interactions among intertial-range structures. The result of such interactions is a cascade of AW energy from large scales to small scales. The inertial-range energy cascade is of critical importance in the solar wind because it controls the rate at which fluctuation energy is dissipated, and hence the rate at which turbulence heats the ambient plasma. The inertial range energy cascade also controls the anisotropy of the fluctuations in wavenumber space.

Over the last decade, a focus of turbulence research has been to determine the inertial range power spectrum of homogeneous, incompressible, MHD turbulence. Although a great deal of progress has been made on this problem, its relevance to the solar wind is limited, because the solar wind is neither homogeneous nor incompressible. A priority for the coming decade will be to extend our theoretical understanding of the inertial range by accounting for the following key effects.

Inhomogeneity and Wave Reflection. As mentioned in section I, some of the outward propagating AWs launched by the Sun are reflected by the gradient in the Alfvén speed, providing the mix of outward-propagating AWs and inward-propagating AWs that is needed to generate an AW energy cascade. As shown by Velli, Verdini, and others, AW turbulence driven by wave reflection differs fundamentally from AW turbulence driven by mechanical forcing, because wave reflections enhance the coherence between the inward and outward AW fields.[37,38] Direct numerical simulations of this type of turbulence will be critical for determining whether the AW energy cascade is fast enough to dissipate AW energy close to the Sun, before the AW energy escapes far into the solar wind.

Cross Helicity and "Imbalanced Turbulence." Cross helicity is the correlation between the velocity and magnetic field vectors in a turbulent flow. In the solar wind, it measures the excess of outward propagating AWs over inward propagating AWs. MHD or AW turbulence with nonzero cross helicity is also referred to as "imbalanced." Solar wind turbulence in the inner heliosphere is imbalanced, with an excess of outward-propagating waves. Most of the points of agreement within the community about the inertial range of MHD turbulence are restricted to "balanced" turbulence with zero cross helicity. There are now at least five mutually contradictory theories of imbalanced turbulence in the literature, and also several mutually inconsistent numerical studies of imbalanced turbulence.[4,5,25,31,32] A priority for turbulence research in the coming decade will be to delineate the different regimes of applicability (if any) of these different theories and simulations, and to determine the correct theoretical framework(s) for understanding turbulence in the solar wind.

Pressure Anisotropy. As the solar wind flows away from the Sun, its expansion acts to decrease the plasma temperature. However, because the solar wind is nearly collisionless, expansion has a different effect on thermal motions parallel and perpendicular to the magnetic field, which are measured by the parallel and perpendicular temperatures $T_{\|}$ and $T_{\perp}$. Between the outer corona and the Earth, expansion reduces $T_{\perp}$ to a greater degree than it reduces $T_{\|}$. As a result, much of the solar wind plasma near 1 AU satisfies $T_{\perp} < T_{\|}$. However, if $T_{\perp}/T_{\|}$ becomes too small, then the plasma becomes unstable to firehose instabilities. Measurements from the *Wind* spacecraft show that the values of $T_{\perp}/T_{\|}$ found in the solar wind are approximately bounded from below by the firehose-instability threshold.[2,21] Presumably, the excitation of (kinetic) firehose instabilities acts to limit temperature anisotropy, preventing the plasma from migrating far past the marginal stability point. Even when the plasma is stable, temperature anisotropy leads to fundamental changes in AWs and other wave modes in a plasma, which may in turn have important consequences for nonlinear interactions between waves, and hence for solar wind turbulence. To understand solar wind turbulence in detail, it will thus be necessary to move beyond traditional fluid descriptions to account for temperature anisotropy in both theoretical analyses and numerical simulations.

III Dissipation of Alfvén-Wave Turbulence

As AW energy cascades from large scales to small scales, it eventually reaches length scales comparable to the proton gyroradius, at which point the waves begin to dissipate. Because collisions are very weak in the solar wind and corona, the small-scale waves dissipate via collisionless processes rather than viscosity or resistivity. The collisionless dissipation of the AW cascade at small scales is not yet understood, but is critical for understanding the thermodynamics of the solar wind. For example, collisionless dissipation determines the fraction of the turbulent heating power that goes to each particle species, as well as the fractions that go to particle motions parallel to the magnetic field and particle motions perpendicular to the magnetic field. As mentioned in section I, one of the critical unsolved problems for the origin of the solar wind is whether the dissipation of low-frequency AW or kinetic Alfvén wave (KAW) turbulence can explain the perpendicular ion heating that is seen in the corona and low-β fast solar wind streams. Previous theoretical investigations suggest that low-frequency AW/KAW turbulence in the low-β corona may dissipate through “stochastic heating” of ions, in which low-frequency fluctuations in the electrostatic potential distort ion gyromotion and lead to perpendicular heating.[6,7,20,28,40] Further theoretical and numerical investigations are needed to test this suggestion, and to explore collisionless dissipation of AW turbulence more generally.

IV Broader Impact within Astrophysics

The study of heliospheric plasma physics can have a tremendous impact on a wide range of astrophysics problems. This is because the heliospheric environment is a critical laboratory in which physical processes can be studied in detail that are important in many astrophysical systems. In doing so, we believe that it will be critical to draw on the understanding of key physical processes observed and studied in detail in the solar corona and the broader heliospheric environment. Historically, this has been common: many ideas first developed in the solar context were later applied extensively to astrophysics problems. For example, the theory of the spindown of the sun by magnetic fields was later developed into models for jets from accretion disks around black holes and neutron stars.

Current studies of turbulence in the solar wind are impacting and/or have the potential to impact astrophysics modeling in a number of ways. We highlight two examples here:

1. There are many low collisionality astrophysical systems, including some accretion disks onto black holes, the intracluster medium of galaxy clusters, winds from other stars, outflows from accreting neutron stars and black holes, and highly energetic particles in the interstellar medium of galaxies. Pitch angle scattering by turbulent fluctuations self-generated from pressure anisotropies and velocity streaming (e.g., firehose, mirror) are believed to make the physics of these low collisionality systems more fluid-like, but this is not well understood in detail. Studying these fluctuations and their role in the dynamics of the solar wind will provide critical insight into the physics of a wide variety of low-collisionality astrophysical plasmas.
2. The turbulent heating of electrons, protons, and ions has been directly measured in the solar wind near Earth (and in the corona using spectroscopic diagnostics). These data are still not fully understood, but are very important for certain models of accretion onto black holes, where the same science question is the biggest uncertainty in our theoretical modeling. As the data and theory improve in the solar context, this will thus enable us to make more realistic models of black hole accretion. This is particularly important for the black hole at the center of our own Galaxy, which is the best case for a black hole in astrophysics.

V Recommendations

Theoretical investigations, including the types of studies described in this White Paper, will be essential if the community is to reap the full science return from existing and future missions. We thus strongly recommend increased support to NASA’s Heliophysics Theory Program, the NSF SHINE Program, and NASA’s Solar and Heliospheric Physics Supporting Research Program. In addition, just as the overall space science program is optimized when there is a balanced portfolio of experimental, observational, and theoretical studies, the theory program itself is optimized when there is a balance between numerical simulations and analytical theory. The support for computer simulations in space physics research has grown steadily over the past two decades, but support for analytical theory has declined to a level that is perilously low. We recommend that program officers within NASA and NSF help maintain a healthy mix of numerical and analytical research in the field by viewing the balance between analytical and numerical research as a programmatic factor when selecting proposals for funding.

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