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Mini-conference on plasma turbulence in the corona, heliosphere and interstellar medium[a)]

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This paper provides a summary of some major physics issues discussed in the Mini-conference on plasma turbulence in the corona, heliosphere and interstellar medium. This is one of two Mini-conferences sponsored by the Topical Group on Plasma Astrophysics held as part of the American Physical Society Division of Plasma Physics Fall 2001 Meeting, 30 October–2 November 2001 © *2002 American Institute of Physics.* [DOI: 10.1063/1.1463067]

I. INTRODUCTION

A mini-conference on plasma turbulence in the corona, heliosphere and the interstellar medium was held in four morning sessions at the DPP meeting. It consisted of 14 solicited talks of equal length on Tuesday, Wednesday, and Thursday, and a session of contributed talks on Friday morning. Like the mini-conference on reconnection, this program was sponsored by the Topical Group on Plasma Astrophysics. The turbulence mini-conference was designed to bring together speakers and an audience spanning a number of fields of research in which low frequency magnetohydrodynamic (MHD) plasma turbulence plays an important role. The goal was to encourage discussion about physics issues of common concern in these fields, and to heighten cross-disciplinary awareness of theoretical and observational results that may provide constraints and guidance for understanding turbulence in its various applications. Here a brief summary is presented.

II. THEORY OF TURBULENCE

The first theme of the conference, represented by the first several presentations on Tuesday, emphasized the basic physics of MHD turbulence, and in particular, homogeneous MHD turbulence. Such models, often represented in numerical simulations by periodic boundary conditions and spectral methods, are perhaps the closest relatives of hydrodynamic turbulence theory[1] in the MHD context. Montgomery led off the presentations by describing numerical results for the periodic dynamo problem,[2] examining whether a large scale, energetically significant magnetic field can grow and be sustained by purely mechanical random stirring (the so-called turbulent dynamo problem). Using moderate resolution but rather long duration incompressible MHD simulations, Montgomery showed that the most effective dynamo action occurred when the guide field (dc magnetic field) is zero but the stirring is helical. This is consistent with earlier results[3] that have shown that this effect is due to an inverse cascade of magnetic helicity, which is indirectly driven by the injection of helical velocity field excitation at the forcing wave number. However, Montgomery showed the new result that an externally supported dc field suppresses the magnetic helicity inverse cascade, and therefore prevents dynamo action. Citing problems with periodic boundary conditions, including incompleteness for the dc field problem, Montgomery called for a new generation of nonlinear MHD computation that would employ more realistic boundaries.

Pouquet[4] presented a review of theoretical approaches to MHD turbulence, emphasizing closures and weak turbulence theory. Following a review of the various approaches to turbulence, her focus was to differentiate between conditions for strong and weak turbulence, and to show how the weak turbulence regime, which includes resonance conditions[5] for interacting wave packets, can be exploited to make progress in closures. At a fundamental level many of the closure theories are similar: the time evolution of triple correlations involve fourth order correlations, and so on. The next step is to decompose the fourth order terms into the quasinormal factorization, and a residual cumulant. The closure consists of modeling that cumulant. This is often done by taking the fourth order cumulant to be proportional to the triple correlation and to an eddy relaxation rate. If the relaxation rate is a constant, one gets the random coupling model; if it is a nonlinear time, the spectrum becomes ‘‘$-5/3$’’ or ‘‘Kolmogorov.’’ If the rate is the sum of the nonlinear and an Alfvén wave rate (frequency), one can get the ‘‘Kraichnan’’ spectrum or something intermediate.[6] Following a discussion of the conditions for breakdown of the weak turbulence approximation, Pouquet summarized her presentation by raising the questions of when isotropy on average should be recovered, and whether there is a continuous transition from a highly anisotropic spectrum to an isotropic spectrum.

Another perspective on MHD turbulence theory, presented by Zhou,[7] is to emphasize energy transfer across scales, and to cast the discussion in somewhat general terms, including analogy with hydrodynamics. In particular the large scale magnetic field in MHD can be seen as introducing a time scale of external origin. From the point of view of spectral transfer, Zhou looked at the interplay between ‘‘sweeping,’’ which induces nonlocal effects, and local straining due to nonlinear couplings. In effect, Alfvén wave

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[b)] Mini-conference organizers.

propagation acts as a form of sweeping. Wave or sweeping effects also influence spectral shapes and induce anisotropy. Many features of MHD turbulence seen in numerical simulation can be understood as a consequence of the balance between sweeping and straining. By introducing the time scales associated with sweeping and straining in an appropriate way, Zhou argued that more complete physics can be built into spectrum theory, closures and even large eddy simulation (LES) models for MHD turbulence.

III. SOLAR PHYSICS

Moving into the realm of applications, the mini-conference program explored the observed effects of turbulence in a variety of space and astrophysical contexts. First, several presentations related to solar physics were given.

Due to a late cancellation, the planned first talk on solar convection was replaced by a talk on coronal heating models presented by Matthaeus.[8] Heating in closed loops has been studied for some time and is thought to be powered, in one form or another, by fluctuations that induce nonlinear MHD interactions, described as turbulence, within the confines of the loop. Open field line regions, which characterize coronal holes and which dominate at solar minimum, present the problem that fluctuations can propagate away rapidly at the Alfvén speed (∼1000 km/s). This leaves little time for nonlinear interactions and has prompted most earlier models to mainly consider high frequency waves and direct cyclotron damping as the heating source. The model discussed here adopts an alternative perspective—that low frequency (100–10 000 s) fluctuations are supplied at the coronal base. These interact with the inhomogeneous coronal background density and magnetic field and are partially reflected. The resulting counterpropagating fluctuations can produce a nonlinear cascade to higher transverse wave number, where energy can efficiently dissipate. Numerical (reduced) MHD simulations indicate that this process can initiate and sustain a strong cascade that might provide an alternative heating mechanism for the open field line corona. While this mechanism can explain a heating function that is nearly exponential in radius, it remains to see if it can explain other observed features of the million degree corona, such as anisotropic proton temperatures.[9]

The scheduled solar physics program resumed with a talk best summed up by its title, “Are nonthermal motions seen in solar UV lines observational evidence for coronal heating by MHD turbulence?” Given by Chae,[10,11] this talk addressed the difficult and important task of extracting information from the new generation of solar instruments that can be compared in a meaningful way with plasma turbulence theory.

Chae discussed techniques employed to detect nonthermal motions using the Solar Ultraviolet Measurements of Emitted Radiation (SUMER) instrument on the Solar and Heliospheric Observatory (SOHO) spacecraft. Specifically, his analysis of the data shows excess Doppler broadening of a spectral line over instrumental noise and thermal broadening. This gives the most probable speed of the line of sight velocity component, which may be due to waves, turbulence or unresolved multidirectional motions of some other kind. Typically, SUMER data[12] provides a sweep over a small linear region (∼725 Km) focusing on spectral data near 17 spectral lines whose temperature sensitivity ranges from 14 000 K to 1.4 million K. These data are accumulated at a time cadence of 20 s or longer. Chae showed that some very remarkable features are seen in these observations. There is evidence for ∼20 km/s nonthermal fluctuations at small scales (<1000 km scale) and these appear to be (i) larger near network regions, (ii) essentially isotropic at all temperatures (different spectral lines), and (iii) mostly contained in periods <20 s. Chae suggests these signals may be associated with superposition of explosive flows, such as reconnection flows. He also concludes that the observations are not consistent with a simple upward flux of Alfvén waves originating in the photosphere. In addition, by estimating energy containing scales, associating them with the observed random motions, and comparing the resulting heating estimates with radiative losses, he concludes that the nonthermal motions are consistent with a Kolmogoroff-type cascade that can account for heating the corona. He also notes that this turbulence may be driven by ubiquitous magnetic reconnection. Further questions arise concerning extensions of these methods to measure possible turbulence at other scales, and to measure correlation scales more accurately.

Additional discussion of UV spectroscopy and how its data can be related to turbulence theory and plasma physics was provided by Cranmer.[13] The focus here again is on modern solar instruments exemplified by SUMER and the Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO. Cranmer explained that, looking off the solar limb, one can simultaneously measure the velocity distribution along the line of sight (from spectral line shape), as well as the velocity distribution in the sunward direction (from scattered line intensities). Along with these, visible light polarization measurements provide electron density. The SUMER data constrain the proton temperature to be less than 1 million K at the coronal base. However UVCS indicates that at 2–3 Rs, the protons exceed several million K, with anisotropic temperatures having Tperp>Tparallel. The minor ions are even hotter, with similar temperature anisotropy. At similar distances, UVCS data imply that the solar wind is already being accelerated—the minor ions such as O5+ having substantially faster outflow than the protons. Cranmer reviewed the standard picture in which high Tperp is interpreted as a signature of cyclotron damping, with the requisite hundred Hz to KHz waves originating in “microflare” reconnection in the network.[9] A detailed look at this picture reveals that heavy ions cyclotron absorb power before protons can experience any effects, and this minor ion heating is so strong that high frequency waves must somehow be replenished, e.g., by cascade, in order to supply adequate power to the protons to accelerate the wind in this way. The presentation reviewed several alternatives that might avoid these difficulties—turbulent cascade, kinetic Alfvén waves, etc. However, as yet no model appears capable of explaining all the known observational features. To make progress, Cranmer reminds us, what is needed[14] is an interplay between physics of the fluctuation spectrum and the microphysical kinetic processes—and this is still an open question.

IV. HELIOSPHERIC PHYSICS

Next, the focus of the mini-conference moved outward from the sun into the heliosphere, where plasma turbulence has found many applications, ranging from upstream wave theory, solar wind heating, cosmic rays scattering and as a component of shock acceleration, to name a few. Turbulence in the solar wind is so well studied observationally that it is often considered as a ''naturally occurring laboratory'' for MHD turbulence studies. In this data-rich environment, turbulence theory can be put into direct confrontation with experimental constraints, a feature all too rare but of great importance in plasma physics, and especially in plasma astrophysics.

This part of the program started with Zank's discussion[15] of theoretical and observational aspects of nearly incompressible (NI) MHD turbulence. The incompressible MHD equations are used frequently to describe interplanetary and astrophysical plasmas, and remarkably, under many circumstances, features of the nonlinear evolution of these systems are often well described by such an incompressible model. Nearly a decade ago, the question of why a compressible plasma should admit primarily incompressible behavior began to be addressed. The eventual outcome of these studies was described as ''nearly incompressible MHD'' (NI MHD), which not only explains the nature of this limit, but also makes a number of predictions,[16] of which many appear to be confirmed in applications as diverse as cosmic ray transport models and coronal heating. The mathematical structure of the approach to incompressibility, described by Zank, is such that for any plasma beta (ratio of thermal pressure to magnetic pressure), an ordering may be found in which the dominant part of the solution of the full MHD equations is a solution of the incompressible equations. Regimes are found in which the leading order density perturbations are passive nonpropagating ''pseudosound'' fluctuations. On equal footing propagating magnetoacoustic waves are permitted in the solution, and under some circumstances these remain properly ordered and the system can remain ''nearly incompressible'' over dynamically interesting length and time scales. Plasma beta also enters in an interesting way. At high beta the NI approach to incompressibility is fully three dimensional. However for order unity or small beta, NI behavior requires a collapse of dimensionality, so that the core incompressible solution is asymptotically two dimensional. Zank went on to discuss how observed density spectra and anisotropies in the solar wind fluctuations are consistent with the NI picture, although this picture has been mainly derived in terms of a spatially homogeneous model problem. The influence of inhomogeneity on the NI limit[17] is also a topic of current interest.

Effects of spatial inhomogeneity must become prominent at large scales. An estimate of when this occurs can be simply made, for a spherically expanding wind at constant speed U for which the principal effect of inhomogeneity is expansion, with characteristic time R/U at heliocentric distance R. If the energetically dominant turbulent structures or eddies are at a scale λ and the energy per unit mass of the turbulence is v^2 then the eddy turnover time v/λ is the time for nonlinear couplings to act. Therefore expansion (inhomogeneity) dominates for scale sizes larger than $\lambda > vR/U$. At 1 au $v\lambda \sim 20$ km/s, $U \sim 400$ km/s, so structures larger than about 1/50 a.u. will be expansion dominated. Interestingly, this is about the measured correlation scale.

Homogeneous turbulence theory, the mainstay of most theoretical turbulence work, becomes of limited usefulness in addressing the dynamics of the mesoscale structures in the solar wind. The mini-conference presentation given by Goldstein[18] showed how large scale numerical MHD simulation with realistic large scale solar wind geometry can be used to address the turbulent dynamics at these intermediate scales, which are of great importance in the heliosphere. Goldstein argued that the two essential elements that must be included in an expanding model of the solar wind are (1) to include heliospheric features such as fast and slow flows, a tilted heliospheric current sheet and a global magnetic field, and (2) that the inflow of waves and structures into the simulation volume be handled properly. An example from such simulations is the study of the interaction of high speed wind of polar origin with the slower flows near the equatorial plane. These simulations show a flow deflection pattern that agrees well with observations, and provides greater detail regarding the nature of the ''vortex street'' that is formed. Another problem examined by Goldstein and collaborators using simulation of the expanding solar wind is that of the formation of the observed energy and density spectra. These are puzzling for a variety of reasons, including the fact that the solar wind is neither isotropic nor incompressible. One result described by Goldstein is the verification that turbulence is suppressed when the nonlinear time exceeds the expansion time. The simulations can also be used to understand how cross helicity (dominance of one sense of propagation of Alfvén wave) evolves in the presence of shear and expansion. Recent results obtained in Goldstein's simulation studies have also shed light on how several idealized symmetries of fluctuations (''slab,'' ''2D,'' ''structures'') evolve in the presence of shear and expansion. Evidently, mesoscale inhomogeneous effects are essential for understanding how spectral symmetries evolve. This type of numerical approach shows great promise in understanding dynamics, symmetries, and potentially even particle propagation in the solar wind.

Moving from scales larger than the turbulence correlation length to those smaller, Leamon's[19] presentation focused upon questions regarding how the cascade through inertial range wave numbers interacts with the smaller dissipation range of scales. Here is where the interface between MHD turbulence and kinetic physics must occur. After a review of cascade and turbulent heating theories, Leamon focused on the higher wave number region, observed in the spacecraft frame at 1 a.u. typically near 1/10 to 1 Hz. Here the otherwise typically ''Kolmogoroff'' powerlaw spectrum steepens, from an inertial range $f^{-5/3}$ spectrum, to f^{-3} or f^{-4}. The change in self-similar behavior signals appearance of at least one new physical scale—presumably associated with kinetic effects including resonance, dissipation, mode conversion, dispersion, etc. The studies described by Leamon seek to understand the physical nature of the steepening, and this is addressed through a variety of observational tests.[20,21] Considerable insight is gained by looking at a number of observed intervals of steepening and examining the statistics to see which physical parameter correlates best with the break point between the distinct power law regions. Looking at the ion gyrofrequency Ωci, the parallel resonant wave number, K_{res}, and the ion inertial scale ρ_{ii}, study of 33 Wind spacecraft intervals, Leamon shows evidence that seems to rule out a simple parallel resonance condition. Leamon also reviewed other studies based upon assumption of a cascade, suggesting that there are both gyroresonant and nongyroresonant contributions to the dissipation. This conclusion is based upon examination of statistics of the distinctive signatures in magnetic helicity in the dissipation range. Leamon also pointed out that several lines of study, including observational results, point to the fact that solar wind fluctuations admit a significant population in wave vectors that are highly oblique to the local mean magnetic field. One estimate is that up to 90% of the turbulence energy resides in wave vectors at 60 degrees or more to the mean field. Of the possibilities examined, the best fit to the steepening occurs by assuming the small scale structure consists of current sheets with thickness ρ_{ii}, oriented at about 70 degrees to the mean magnetic fields. This picture is also supported by recent unpublished work by Horbury and Forman.

Coles' talk on radio scintillation studies[22] pointed out that, although *in situ* observations have provided a wealth of information about solar wind turbulence, remote sensing using radio scintillations provides many types of complementary information. Remote sensing also provides more extensive possibilities, since regions of the heliosphere and corona can be explored that are otherwise inaccessible. Heliospheric and solar observations may also be compared with astrophysical observations of similar phenomena. This solar wind and interstellar turbulence can be studied and compared using similar techniques. Coles provided an overview of results from scintillation studies that provide observational constraints on astrophysical plasma turbulence, including the interstellar medium, the solar wind, and the ionosphere. Feasible observations include spectra of velocity, Faraday rotation spectra and scattering by density fluctuations. Coles finds for the density typical characteristics, including power law spectra, two-dimensional features with axial direction magnetic field aligned, and characteristic velocity distributions. Axial ratios up to 15 or 20 are observed within 5 solar radii, and this decreases systematically with increasing distance to ratios of about 5 at 20 solar radii. Combining these measurements, recent work has enabled Coles and collaborators to study possible evidence for MHD waves in the corona. There is evidence, in the form of optimized cross correlation studies, that density microstructure ($\sim\rho_{ii}$) near the sun is caused in part by oblique Alfvén waves. Actually two models give equally good fits: oblique Alfvén waves with polar plumes, and a 50%–50% mixture of Alfvén and slow-mode waves. The observed waves have velocities on the order of the local Alfvén speed, and propagate mainly perpendicular to the mean magnetic field. These observations provide valuable insights into the physics of small scale ($\sim\rho_{ii}$) and relatively high frequency ($\sim$1 s) fluctuations in the corona. For example, Coles notes, such waves are efficiently Landau damped, and so these results suggest that an efficient cascade may exist.

V. ASTROPHYSICS

In the final set of talks the mini-symposium moved out of the heliosphere and into the realm of astrophysics. Random motions and magnetic fields appear to play important roles throughout the universe, and this plasma or MHD turbulence remains an important element in various aspects of astrophysics. In the minisymposium, talks addressed the role of turbulence in the galactic dynamo, scattering and transport of high energy particles, dissipation in the interstellar medium, and in star formation regions in molecular clouds.

The first of these talks was by Blackman[23] about the longstanding and still challenging problem of astrophysical dynamo theory. Magnetic fields permeate most observed astrophysical entities and act as an intermediary between gravity and radiation. Since galaxies and other objects of interest have large magnetic Reynolds numbers and develop turbulence, Blackman noted that one needs to consider MHD turbulence and its relation to dynamo theory in order to understand many astrophysical systems. The current perspective on galactic dynamo theory, described by Blackman, is to separate the magnetic fields into a small scale part extending from the input scale to the dissipative scale, and a large scale part which corresponds to ordered field larger that the input scale. For the large scale fields, inverse cascade, mean field and dynamo theory are relevant. The standard problem is seen as starting from a weak magnetic field seed and then driving the velocity field at an input scale, either with helical or nonhelical stirring. Key issues for the saturated fully nonlinear dynamo are whether there exists a very large scale ordered field, whether global equipartition of velocity and magnetic field energy is achieved, and whether there is spectral equipartition at the the small scales. With regard to the latter issue, it seems favored in the case of large magnetic Prandtl number. In some recent simulations,[24] the characteristic scale of magnetic energy remains small, and magnetic energy may exceed kinetic energy at small (viscous) scales. While this point remains controversial, according to Blackman, it does point to the possibility that restrictions on galactic dynamos may not be yet fully understood, as the spectral distribution of magnetic energy at saturation may be quite important in constructing workable models. Large scale dynamo action driven by the alpha effect and inverse magnetic helicity cascade (which appear to be closely related in general) also remains an active topic.[25] Here the classic picture is that kinetic helicity injection is followed by buildup of large scale magnetic energy due to inverse cascade of magnetic helicity.[3,26] This seems to capture the basic physics of large scale dynamo action. Going further, Blackman described some remaining important questions about the time scale for large scale equipartition and saturation, and also possible quenching mechanisms that may prematurely halt the inverse cascade process. In addition application of these ideas to real large scale dynamos such as the galaxy brings in questions concerning boundary terms, effects of gravity, and other complications.[25,26]

Another important application of turbulence theory in astrophysics is in the realm of charged particle scattering, transport and acceleration.

Suprathermal charged particles respond to the mean magnetic field through gyromotion and drifts. In addition, the turbulent component of the magnetic field provides scattering mechanisms that regulate transport in directions both parallel to, and perpendicular to, the mean field. In the quasistatic case generally one neglects motion of the thermal plasma (for high energy particles) and in this limit the quasilinear theory (QLT) calculation of diffusion in velocity space and real space is the standard formalism. Even in standard QLT there are interesting issues related to the structure of turbulence. Chandran[27] gave a presentation at the mini-conference on issues related to the use of highly anisotropic quasi-two dimensional magnetic field spectra and the influence of this assumption on scattering rates of cosmic rays. It is clear that certain problems relating to cosmic ray observations, even within the heliosphere[28] can be adequately explained by appeal to highly anisotropic turbulence spectra. However, because static 2D spectra give rise to little or no pitch angle scattering, certain anomalous results can emerge as well. In the heliospheric context, both theoretical and observational support exists for at least some weak component of turbulence that is not in quasi-2D modes. These can be parametrized as a two component model, having 2D (perpendicular wave vectors) plus 1D (''slab'' parallel wave vectors) ingredients. The 1D component provides for relatively potent pitch angle scattering, especially when dynamical effects[28] are included. In addition, the resulting field model lacks an ignorable coordinate, thus avoiding certain pathologies in particle transport.[29] The impact of turbulence on particle scattering is broader still when turbulent electric field effects are fully included, and this is a topic of current activity.

Spangler[30] provided an overview of turbulence and dissipation processes that might operate in various phases of the interstellar medium (ISM). He noted that the diffuse ionized gas phase (DIG), with densities of 0.1–0.5 cm^3 and temperatures ~8000 K is the best diagnosed remote astrophysical plasma.[31] One rather unique feature of the DIG, Spangler notes, is that observations provide a relatively reliable estimate of the absolute level of the magnetic power spectrum. As such it is possible to discuss cascade and dissipation issues in quantitative terms. Known mechanisms for dissipation and heating in interstellar turbulence include linear and nonlinear Landau damping, ion neutral collisions, decay instability, wave steepening, and kinetic Alfvén wave damping. Spangler examined the relative effectiveness of these processes for various choices of parameters, and concluded that turbulence in the ISM most likely lacks fast mode waves because they dissipate very fast. On the other hand, while a number of processes can produce the required volumetric heating rate of 10^{-25} $\mathrm{ergs/s/cm}^3$, the most robust mechanism appears to be ion neutral collisional damping. Interestingly, this operates at a ''mesoscale'' of order Alfvén speed/ion-neutral collision frequency, and not at the kinetic microscales. Spangler concluded by noting that most of the dissipative mechanisms considered this far for the DIG have been ''wave'' dissipation. An alternative, suggested to be worthy of greater attention, is that quasi two dimensional turbulence,[32] with dissipation occurring in intense current sheets, warrants further study in the ISM.

The final invited presentation was given by Low,[33] on the topic of highly compressible MHD turbulence in dense molecular cloud regions of the ISM. These are of fundamental importance[34] because they are the star forming regions and for a number of years it has been realized that the strength and scale of magnetic fields and turbulence in these regions can influence the process of gravitational collapse. Low points out that in this way MHD turbulence in molecular clouds might have a central role in regulating the population of stars in the galaxy. An interesting feature of molecular cloud turbulence is that it is highly supersonic, with Mach number $M \sim 10-50$ even on relatively small scales. Magnetic field strengths are more controversial but generally $V_{\mathrm{rms}}/V_{\mathrm{A}} \sim \frac{1}{2}$ to 2 is taken to be reasonable, with V_{rms} the turbulent velocity and V_{A} the Alfvén speed. The key question in star formation is given the free fall time (10^6 yr) and lifetime of the galaxy (10^{10} yr), why does star formation continue today? To slow this down, magnetic fields provide some static support against collapse, but turbulent velocities can also be effective. This has motivated Low and colleagues to intense numerical study of the properties of highly compressible MHD turbulence. Quite remarkably, Low found that[35] this form of supersonic turbulence has decay properties quite similar to incompressible hydrodynamics. Total energy tends to decay as a power law in time, t^{-a} with $a \sim 1$, and the decay rates of energy per unit mass scale as $kV_{\mathrm{rms}}{}^3$, where k is an energy containing scale or correlation scale. This is very similar to turbulence phenomenologies that work well in the solar wind.

While this result may be both surprising and comforting to the turbulence theorist, Low points out that it causes a problem in star formation. This is because the decay time of the turbulence would then be on the order of, or less than, the free fall time in molecular clouds. In order for turbulence to provide support and slow star formation, the ''initial'' turbulence would be inadequate—a resupply or forcing mechanism must be found. More complete (and more challenging) simulations incorporating self-gravity are used to explore this issue. Low finds that even when there is global support, collapse can occur locally, probably in a fractal sense. Further numerical studies of this type also reveal the distribution of shocks as well as the possibility that supernovae driven turbulence can increase magnetic energy even without helicity.

VI. SUMMARY

The mini-conference on astrophysical plasma turbulence explored a number of common themes, in applications having a variety of plasma conditions, and supported by a variety of observational techniques. It is clear that there are fundamental results, theoretical perspectives and methods that cut across all the fields we sampled. Classical Karman–Taylor–Batchelor turbulence theory, developed for hydrodynamics, is a useful framework, even in MHD.[36] However, distinctively MHD and plasma characteristics come into play, sometimes very strongly, as in the Alfvénic nature of the solar wind, the magnetic structure of the corona, the nature of turbulent dynamo processes, magnetic reconnection, and kinetic dissipation processes. There is also a commonality of methods, in that the entire community relies progressively more on accurate nonlinear simulations of MHD and other relevant nonlinear plasma models. Numerics are employed to uncover basic physical principles as well as to explore time and space scales and structures associated with turbulence in its various parameter regimes. It is clear that our subject inherits a close relationship to computational physics, and that practitioners of space and astrophysical turbulence must maintain quality control over the robustness and accuracy of the computational tools that we employ. Similarly, the new generations of observational methods require careful analysis and scrutiny regarding the implications of their data from a turbulence perspective, and we have seen in this mini-symposium a number of excellent examples of how this can be done.

While substantial ground was covered in our presentations, not all areas were covered that one might have liked to include. There were no presentations on solar convection, although thermally driven convective turbulence is of fundamental importance in turbulence theory and in astrophysics. There were also no presentations on nonlinear dynamics and turbulence in the terrestrial magnetosphere and ionosphere. However this is also an important and developing area, inspired in part by very interesting observational and theoretical studies that have been made of turbulence in the terrestrial ionosphere and magnetosphere (e.g., Refs. 37 and 38). Turbulence is also invoked at cosmological scales.[39]

Underlying many of the results that have been presented is the idea that turbulence can have profound effects on observed physical processes, sometimes in unanticipated ways. We end on a speculative comment in this vein—recent evidence[40] suggests that cloud cover, a known major influence on terrestrial climate, may be directly influenced by the flux of galactic cosmic rays incident on Earth. However, cosmic ray flux depends upon solar cycle in ways that are mediated by solar wind MHD–scale plasma turbulence. Thus cosmic ray modulation, and the plasma turbulence in space[41] upon which it depends, may ultimately be tied to terrestrial climate in an important way. The turbulence on Earth and the turbulence in space would be coupled to one another.

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