Dissipation and heating in solar wind turbulence: from the macro to the micro and back again

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The past decade has seen a flurry of research activity focused on discerning the physics of kinetic scale turbulence in high-speed astrophysical plasma flows. By ‘kinetic’ we mean spatial scales on the order of or, in particular, smaller than the ion inertial length or the ion gyro-radius—the spatial scales at which the ion and electron bulk velocities decouple and considerable change can be seen in the ion distribution functions. The motivation behind most of these studies is to find the ultimate fate of the energy cascade of plasma turbulence, and thereby the channels by which the energy in the system is dissipated. This brief Introduction motivates the case for a themed issue on this topic and introduces the topic of turbulent dissipation and heating in the solar wind. The theme issue covers the full breadth of studies: from theory and models, massive simulations of these models and observational studies from the highly rich and vast amount of data collected from scores of heliospheric space missions since the dawn of the space age. A synopsis of the theme issue is provided, where a brief description of all the contributions is discussed and how they fit together to provide an over-arching picture on the highly topical subject of dissipation and heating in turbulent collisionless plasmas in general and in the solar wind in particular.
1. Motivation

The physics of interplanetary space plasmas represents an archetypal non-equilibrium collective phenomenon; interdisciplinary in scope, it brings together several branches of physics from plasma physics and statistical mechanics to signal processing and high-performance computing. Plasmas exhibit diverse physical phenomena which range from macroscopic scales on the size of planetary and galactic systems where the plasma is behaving as a turbulent fluid with random intermittent magnetic field fluctuations, the so-called ‘magneto-hydrodynamics’ (MHD); to micro-scale kinetic physics and complex individual charged particle dynamics in electromagnetic fields. Among the scientific observations of astrophysical plasma that are available to us, the solar wind provides an excellent laboratory for the study of fully developed plasma turbulence. The solar wind and the near-Earth environment are also the only in situ observationally accessible highly turbulent plasmas [1–3] with magnetic Reynolds numbers of the order of $10^5$ [4] at 1 AU. In situ spacecraft observations from both field and particle instruments, show highly developed turbulence at 1 AU. This is evidenced by a very broadband power spectral density that illustrates the amount of energy at each scale and is one of the manifestations of the ‘turbulence energy cascade’ [5]. In this well-known paradigm, energy from large-scale fluctuations cascades through smaller and smaller scales until being dissipated into heat at very small scales. In neutral fluids, such as fast flowing water in a river or pipe, this dissipation is provided by microscopic collisions manifested macroscopically as the viscosity or stickiness of the fluid.

As in the case of many interplanetary and astrophysical plasmas, the near-earth solar wind is extremely sparse with very low densities (around 10 particles per cubic centimetre); this implies that collisions between particles are rare, and hence the plasma is considered collisionless. Indeed, the mean-free path (average distance between collisions) of the charged particles in the solar wind is of the order of 1 AU. Thus, the classic viscous channel is ruled out as a viable mechanism for dissipation. Owing to the extremely high conductivity of the solar wind, the resistivity is also negligible; and thus joule-heating is also ruled out as a mechanism for dissipation and heating. In the absence of these more classical macroscopic fluid channels, most of the relevant interactions in this collisionless plasma are in the form of necessarily kinetic field–particle interactions between the charged particles and the electromagnetic fields and currents that they create by their collective motion. In addition to this, kinetic scale changes to the magnetic field topology in the form of magnetic reconnection can serve to both convert the field energy into particle energy, as well as being a possible channel of dissipation and irreversible heating. An outstanding problem—and the central theme of this special issue—is how, in the absence of collisional viscosity in the solar wind, the broad range of large-scale MHD turbulence terminates at smaller scales. Understanding the nature of the dissipation processes will inform open questions such as how the solar corona is heated and how its heliospheric extension, the solar wind, is accelerated and heated.

The physics of solar wind turbulence is played out over a vast range of dynamical spatial and temporal scales from the period of one (synodic) solar rotation of 27 days and spatial correlations of mega kilometres to the smallest scales of electron gyration periods of a few hundredths of a second and gyro-radii of a kilometre or less. To this end, we organize the issue to some degree to match the scales of the various topics that will be discussed in each article. This is reflected in this introduction that presents this multiscale ordering of the subject from macroscopic to microscopic physics, and how this then feeds back to some extent into the macroscopic structure of the near-heliosphere. However, before we move to the synopsis of the theme issue, we briefly outline the underlying phenomenology of the turbulent cascade of energy in space plasma flows—a phenomenology that is constantly referred to throughout the issue. We also provide some clarification on terminology and nomenclature, which can on occasion obfuscate the discussion to those discerning researchers outside the topic.
Figure 1. Typical trace power spectral density of the magnetic field fluctuations of a $\beta_i \sim \mathcal{O}(1)$ plasma in the ecliptic solar wind at 1 AU. Dashed lines indicate ordinary least-squares fits, with the corresponding spectral exponents and their fit errors indicated. This spectrum represents an aggregate of intervals with each smaller interval being contained within the subsequent larger interval—hence the higher frequencies of this spectrum are not representative of the interval describing the lower frequencies. At the largest scales is a 58 day interval [2007/01/01 00.00–2007/02/28 00.00 UT] from the MFI instrument on board the ACE spacecraft, illustrating the large-scale forcing range (the so-called $f^{-1}$ range). The inertial range is computed from a shorter 51 h interval [2007/01/29 21.00–2007/02/01 00.00 UT] also from the same instrument. Both these datasets are at 1 Hz cadence, so they just begin to touch the beginning of the sub-ion range. The kinetic scale spectrum in the sub-ion scale range is given by magnetometer data from the FGM and STAFF–SC instruments on the Cluster multi-spacecraft mission, from spacecraft 4, while it was in the ambient solar wind [2007/01/30 00.10-01.10 UT] and operating in burst mode with a cadence of 450 Hz—the two signals from both of these instruments have been merged as in [6]. The vertical dashed lines indicate the three length scales mentioned above: $\lambda_c$ the correlation length, $\rho_i$ the ion gyro-radius and $\rho_e$ the electron gyro-radius. (Online version in colour.)

(a) Brief phenomenology of the energy cascade

We ask the reader to turn their attention to figure 1, which shows a canonical power spectral density at 1 AU in the solar wind. We have chosen the power spectral density as it is not only the focus of many, if not most, studies of turbulence, but also serves as a simple map to illustrate the scales of interest in the phenomena. It is also reflective—being the Fourier transform pair—of the two-point field correlation, another obsession of generations of turbulence researchers. Owing to the extremely high speed of the solar wind, faster than most temporal dynamics in the system, we can invoke the ‘Taylor frozen-in flow’ hypothesis to relate temporal scales to spatial scales (see [7] for caveats to this). Thus, although the abscissa shows a temporal scale of spacecraft frequency, for most of this spectrum (in the inertial range and above) it can be viewed as a proxy for spatial scales—some of which are marked at the top of the figure. In particular, we have highlighted four distinct regions of interest demarcated by three important length scales:

- The $f^{-1}$ range. At these very small frequencies—corresponding to temporal scales over many days—what we are actually measuring is the temporal variability of the source of the solar wind: the Sun and its solar atmosphere. Near the top of this range, we have the first of our important length scales: the correlation length $\lambda_c$. Below this scale (higher...
frequencies), fluctuations have lost memory of their solar origins and are a product of the \textit{in situ} dynamics as the solar wind travels towards the Earth. Above this length scale, the fluctuations retain memory of their solar origins and this is what comprises most of the so-called $f^{-1}$ range. A discussion of the origins of this $f^{-1}$ range can be found in [8], in this issue. The correlation length can be seen as the biggest size of the energy containing ‘eddies’ or structures in a turbulent flow and is normally defined through the two-point field correlation tensor mentioned above. Multispacecraft measurements of this scale at 1 AU in the ecliptic solar wind [4] have yielded a figure of $\lambda_c \simeq O(10^6)$ km which, with an average speed of 500 km s$^{-1}$, corresponds to a spacecraft frequency of about $6 \times 10^{-5}$ Hz.

— The inertial range. This is the range where the classic fluid (MHD) energy cascade from large to small spatial scales occurs. The power spectral density of magnetic field fluctuations at MHD scales is widely shown to be of power-law form with the now famous and ubiquitous Kolmogorov power-law spectra with exponent value of $\sim -5/3$. Although, the value of this exponent is still debated among some researchers, much of the phenomenology here is borrowed from neutral fluid hydrodynamics with additional physics such as anisotropy. The dynamics within this range is considered to evolve independently from the details of its initial conditions at larger scales, only constrained by the rate of energy driving the system, and is also ‘unaware’ of its fate at smaller scales—it is thus purported to be of universal form with the energy cascade progressing in a statistically scale-invariant manner. This range is bounded at the lower end by the correlation length $\lambda_c$ and at the higher end by an ion spatial scale: the ion inertial length $d_i$ for $\beta_i \leq 1$, or the ion-gyro scale $\rho_i$ for $\beta_i \geq 1$.

— The transition region and the sub-ion range. also known historically as the ‘dissipation range’ or in some quarters of the community as the ‘dispersion’ range [9]. This is bounded at the lower end by the ion gyro-scale $\rho_i$ and at the higher end by the electron gyro-scale $\rho_e$. If we ignore for the moment the dynamics parallel to the mean guide magnetic field (see [10] in this issue), this is essentially where the kinetic physics begins and is the main topic of this theme issue. One of the earliest presentations of the spectra of this range was shown by Denskat \textit{et al.} [11] using Helios spacecraft observations—albeit, not as detailed as figure 1 due to the scarcity of measurements. This study was followed by many others over the last two decades based on better cadence measurements from the ACE, WIND and Cluster spacecraft missions; the last one of which provides the most detailed measurement of waveforms to date (see [7] in this issue). These studies all showed the now well-documented fact that at scales around the typical length of an orbit radius of protons/ions gyrating around a magnetic field (proton/ion gyro-scale), the power-law spectra in the inertial range, mentioned above, break abruptly and at smaller scales another steeper power-law [12–17] is found spanning about two decades in scales (figure 1). At these scales the fluid picture given by MHD breaks down, and it is necessary to take into account kinetic effects of the individual charged particles. The value of the exponent of this second power-law is also variable and changes depending on plasma conditions such as magnetic energy, anisotropy of the magnetic field fluctuations with respect to the mean magnetic field and bulk plasma velocity, etc. [18–20]. The physics of these scales, in this sub-ion range, is still unknown and is hotly debated. Current studies anticipate a cross-over from the turbulence energy cascade, mentioned above, to dissipative and/or dispersive processes via wave-particle resonances, and reconnecting magnetic fields; with the associate transfer of energy from the electromagnetic fields to the plasma particles.

There is much that has been left out in this very brief description of the phenomenology, e.g. the very important aspect of anisotropy [10]. However, this and other topics will be discussed in detail in the theme issue and these contributions will be briefly discussed in the synopsis below.
2. Synopsis of the issue

This special issue is topical in the sense that the authors were encouraged to be relatively unhindered to express their views on the subject and what they think the future outlook on the field should be. In this respect, although the separate articles and reviews have been selected to represent a wide breadth of the field of solar wind dissipation and heating, they in no way represent a consistent set of views. This was done intentionally to reflect the different views of the subject within the community. The authors selected are among the leaders in the field (solar wind turbulence and related fields such as coronal heating and kinetic instabilities), many with several years of world-class research on the topic; some of whom are widely acknowledged as developing the subject to where it is today with key discoveries and theories. All of the contributions have been chosen to satisfy one or more of three criteria: the first being the author/s international leadership and expertise in the particular facet proposed in the subject title; the second being the quality and lucidity of the pedagogic prose in their scientific publications and lastly their ability to deliver an article which will be topical and contain new insights from their opinions on the subject and where future research outlook should be concentrated. The authors have also been deliberately chosen to represent a good mix between observationalists, theorists and those engaged in state-of-the-art computer simulations and experiments. The titles represent a mix of topical reviews that give a pedagogic background to key facets within the subject, and targeted articles that present new insights and results as well as opinions of the authors involved.

The theme issue starts with a review article describing some of the quintessential properties of turbulence and their role in generating the structure that one sees in plasma turbulence. Matthaeus et al. [8] describe how the nonlinearities in the dynamical equations of plasma turbulence can self-consistently explain the phenomenon of intermittency and non-Gaussian fluctuations, and the formation of various coherent structures such as current sheets, filaments and cellularization. Their explanations rely on the elegant formalism of dynamical relaxation, and on analogies with simpler models which retain the physics of interest. Importantly, they show with examples from simulation and observations, as well as phenomenological discussion, how large gradients at the boundaries of these structures can impact on dissipation, heating and transport of charged particles.

The next article of Cranmer et al. [21] reviews the current understanding of how the solar corona is heated and the solar wind accelerated with a focus on the role of MHD turbulence in obtaining better insights into how these outstanding problems can be solved. They debate the relative strengths of candidate mechanisms; in particular, between the dissipation of turbulent fluctuations emitted from the Sun, and those lower down in the solar atmosphere which, through the mixing effect of turbulent convection in the convection zone above the solar tachocline, causes the mixing and resultant reconnection of magnetic fields lines in the lower corona.

A staple of turbulence studies in the solar wind are attempts to ascertain the energy transfer rate of the turbulence cascade. The logic of this approach is simple: in the absence of dissipation in the inertial range, any energy that is cascaded through it will eventually be dissipated at the smaller scales—the exact process of the dissipation need not be known. The research article of Coburn et al. [22] reviews the main tool in calculating these energy cascade rates, third-moment theory and proceed to compare these with thermal proton heating using a very large ensemble of 1 h field and particle data intervals from 12 years of ACE spacecraft observations. One of the most interesting results of this study are that the measured energy cascade rates show highly intermittent values and statistics. This was briefly touched upon in the earlier review [8] as one of the sources of temporal intermittency in solar wind observations; borrowed from an idea for atmospheric turbulence first proposed by Oboukhov [23].

The recognition that MHD plasmas are strongly affected by the magnetic fields that thread through them is now a well-established fact of plasma physics. Any study which does not realistically take this essential anisotropic feature of plasmas into account has a significant shortcoming. Oughton et al. [10] review our current understanding of anisotropy in solar wind plasma turbulence, both in the inertial range and, crucially, at the kinetic scales of the sub-ion
range. Both spectral and component anisotropy are reviewed. The results show that although component anisotropy seems to be relatively well supported by observations in both the inertial and sub-ion ranges, with a broad agreement within the community, the jury is still out on the resolution of this in the case of sub-ion range spectral anisotropy.

Traditionally, simulations have provided an important and occasionally indispensable tool for the study of plasma turbulence. Although they lag behind spacecraft observations in the sense of not possessing enough spatial resolution to obtain the several decades of an inertial range as seen in figure 1, they provide unparalleled detail in nearly everything else, e.g. full determination of spatio/temporal dynamics, exquisitely detailed visualization of the structures and patterns within the flow (see front cover of this issue and [24]), etc.—much of which heavily limits definitive conclusions from single, and even multispacecraft, observations. Advancements in massively parallel high-performance computing have allowed one to augment the in situ observations from spacecraft missions with what are effectively computational experimental laboratories in the form of simulations of the various models of plasma turbulence. Until a decade ago, a full three-dimensional picture of plasma turbulence was confined to fluid codes such as incompressible/compressible MHD, Hall-MHD and Electron MHD codes; but now, we are at a stage where five-dimensional (2 or 3 space + 3 or 2 velocity) and even full six-dimensional (3 space + 3 velocity) kinetic simulations [25–28] are being conducted. Although we have already encountered such simulations earlier in the issue [8], the review by Gary [29] provides an overview of these fully kinetic simulations and how they relate to short-wavelength plasma turbulence.

Plasmas contain far richer physics than their incompressible fluid counterpart. Alongside the usual acoustic waves supported by neutral gases, plasmas support a veritable zoo of plasma wave modes and instabilities. The more physics that one includes, and the more complex the models, the more of these waves and instabilities with their associate damping and growth rates occur [30,31]. The review by Gary [29] also provides a short pedagogic review of both the fluid and kinetic instabilities that can occur in collisionless plasmas due to temperature anisotropies, and discusses how these instabilities can directly drive narrowband fluctuations in short-wavelength solar wind turbulence, thereby transferring energy from the particles to the fields. The energy in the fields can then cascade to smaller scales via the turbulent cascade and/or wave dispersion mechanisms. To complicate matters further, recent research [28,32] has shown that the large gradients attributed to coherent structures [8] can in turn drive the plasma to a state of temperature anisotropy and thus feedback into this process. This serves to not only show the connection between research on temperature anisotropy-driven instabilities and plasma turbulence, but also the complicated nature of the different channels available which are not necessarily sources of dissipation but of driving the turbulence, albeit at smaller scales than the normal correlation length drivers.

In addition to the instabilities discussed above, physics at the kinetic scales introduces more complicated dispersive wave modes. The role that these wave modes, and their fluid-scale counterparts, play in turbulence is still a subject of heated debates, with many within the community arguing that nonlinear interaction between these waves is responsible for the turbulence cascade observed in space and astrophysical plasmas. The topical review of Howes [33] advocates this approach (as does the previous review [29]) and discusses how much of what we observe in solar wind turbulence from both spacecraft observations and computer simulations can be explained by a detailed look at the dynamics of the nonlinear interactions of these wavemodes. Significant attention is paid to the role of Alfvén wave and kinetic Alfvén wave interactions in mediating the cascade and for the creation of current sheets. Collisionless damping in the form of ion and electron Landau damping is attributed to transferring energy from the fields to the particles, with significant changes to the ion/electron distribution functions. These changes are then smoothed out in velocity space by an entropy cascade which ultimately thermalizes this energy via weak collisions. It is also important to state that within the community advocating the wave-mediated turbulence cascade, there are also split opinions on what wavemodes are primarily responsible for mediating the cascade beyond the inertial range and into sub-ion scales,
with resultant splits over the exact damping and dissipation mechanisms for these wavemodes. This sub-topic itself has been, and continues to be, an active area of research within the space and astrophysical turbulence community.

Spacecraft field and particle instruments at cadences approaching and including ion-scales have been available for nearly two decades now with the WIND and ACE spacecraft, and some seminal work on kinetic scale turbulence was done using these instruments at the turn of this century [12,34–36]. However, the past decade has seen the greatest acceleration of sub-ion scale turbulence studies using spacecraft observations; with much impact and cross-pollination to other areas of space physics. This has largely been driven by the unprecedented high cadence magnetic and electric field measurements from the Cluster multispacecraft mission [37]. Goldstein et al. [7] review the historical development and the current state of the art in these observational studies. Moreover, they also discuss the future outlook of observational studies in the light of the recently launched Deep Space Climate Observatory (DSCOVR) and Magnetospheric Multispacecraft (MMS) missions, and the future Solar Orbiter and Solar Probe missions.

Until recently sub-ion scale particle instruments have been sorely lacking. Without high-resolution measurements of particle moments and distribution functions, our knowledge of kinetic scale physics is at best incomplete and at worse sorely inadequate to precisely test between competing theories and conjectures of the physics of sub-ion scale plasma turbulence. The Russian-led BMSW instrument (Bright Monitor of Solar Wind) on the SPECTR-R spacecraft mission launched in mid-2011 changed this. With a plasma cadence of 33 Hz, it can provide detailed time series of density fluctuations. The research article of Riazantseva et al. [38] details a statistical study focusing on the intermittent properties of ion flux fluctuations in solar wind turbulence. Similar to earlier studies of spectra from magnetic field measurements of the sub-ion range using the ACE, WIND and Cluster missions they find a variation in the parameters that they calculate to characterize the level of intermittency in these ion flux signals, as well as highly non-Gaussian fluctuation probability density functions.

The research article of Roytershteyn et al. [39] draws on some of the topics introduced in the earlier reviews that discussed the generation of coherent structures [8] and the role of temperature anisotropy-driven instabilities in small-scale plasma turbulence [29]. Through the use of massive three-dimensional fully kinetic PIC simulations, they show the self-consistent evolution of current sheets into pressure balanced magnetic holes at ion and electron spatial scales, aligned with the background guide field. Interestingly, all the structures they discuss at both ion and electron scales are associated with temperature anisotropy instabilities close to the marginal stability threshold of the mirror instability, consistent with other findings reported in [28,32].

The other candidate process for the dissipation of magnetic energy in collisionless plasmas is magnetic reconnection. Classically, this process occurs when the resistivity allows magnetic field lines to diffuse through the plasma in a so-called diffusion region where the magnetic topology is rapidly changed [40]. The resultant ‘snapping’ and ‘reconnecting’ of the magnetic field allows the transfer of energy from the fields to the particles. The determination and measurement of the reconnection rate is at the heart of both models and observations—the key problem being the reconciliation of predictions with observations. As well as being very turbulent, collisionless space plasmas are also extremely conductive indicated by very large Lundquist numbers of the order of approximately $10^{20}$. This implies a very low or negligible resistivity and thus a very slow rate of magnetic reconnection as described by classical resistive-MHD. However, many observations have now unanimously determined that the rate of magnetic reconnection is orders of magnitude larger than that predicted by such classical theories. The development of more fundamental theories of reconnection will inevitably need to include physics of scales smaller than the MHD (fluid) descriptions, i.e. at kinetic scales where wave–particle interactions become important. From both laboratory and observational studies, it has been proposed that fast reconnection spontaneously occurs when the current layer approaches the ion gyro-radius or ion inertial length [40–43]. As mentioned above, the interplanetary medium is highly turbulent with an enormous separation between dissipation and large-scale fluid structures. In the case of a solar flare, singular reconnection sites can be considered; however, in the majority of cases one has
to deal with multiple reconnection sites at many scales. The interplay between these scales and
the scale at which the reconnection occurs suggests cross-scale coupling with the possibility of
turbulent reconnection [44–46]. The final article in this theme issue is a topical review by Lazarian
et al. [47] that discusses the topic of turbulent reconnection. In particular, through their models
they show how turbulence can significantly modify reconnection, providing a mechanism for fast
reconnection, and in addition violate the notion of flux freezing in collisionless plasmas.

3. Outlook

It would be no exaggeration to state that turbulence, and its associated physical processes such
as transport, reconnection, etc., are the most fundamental processes at the heart of nonlinear
plasma dynamics. And yet these processes are the least understood. They are likely to be the
key ingredients in any description of particle acceleration and heating in astrophysics; which are
needed in order to answer the outstanding questions of coronal heating, solar wind acceleration
and the acceleration of highly energetic interstellar cosmic rays in the heliosphere.

This is an exciting time for the study of kinetic scale plasma turbulence; ripe for
discovery and for solving the problem of kinetic dissipation in turbulent astrophysical plasmas.
Recent availability of high-cadence measurements from in situ space missions, coupled with
advancements in simulating realistic kinetic scale plasma conditions, has led to a resurgence in
the study of turbulence, dissipation and heating. This has manifested in an explosion of quality
science in high impact journals, as well as fertile cross-pollination in other fields of space and
laboratory plasma research. The topic of this issue has been identified by international space
agencies as scientific questions, which should be addressed with future spacecraft missions. To
this end, the next 5 years will see data from the MMS and DSCOVR missions, as well as the
launch of Solar Orbiter and Solar Probe Plus. These will push the limit on the observations we
can undertake. At the same time, advancements are being made in simulating full kinetic scale
plasmas in three dimensions. Thus, this issue is very timely, allowing key observational and
numerical results to be consolidated, and giving leaders in the field an opportunity to frame the
main scientific questions and outlook for future research.

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