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White Paper

Plasma turbulence: Challenges and next transformative steps from the perspective of multi-spacecraft measurements

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Synopsis

We recommend to bring into reality the following within the next decade: 1. Measurements from multiple spacecraft covering a 3D volume and simultaneously spanning the MHD to kinetic scales (such as HelioSwarm). 2. Coordination of the new multi-scale mission(s) with existing multi-spacecraft missions such as MMS to maximize the power of cross-scale ion and electron measurements.

Exigency: The needs of a Technologically Advanced Civilization

Our society have become heavily reliant on electrical technologies, from power grids to GPS network to wireless communication. Any disruption of these systems will have severe global consequences. One major natural hazard that can cause such disruptions comes from solar wind disturbances that impact the near-Earth environment. Estimates are that a solar storm of the magnitude of the 1859 Carrington Solar Superstorm would cost the modern-day society over $2 trillions to remediate the damages [NRC, 2008]. In July 23, 2012, we had a near miss of a solar Superstorm that could have broken the record of largest such storms at Earth [Baker et al., 2013]. To enable pre-emptive measures against the hazard of solar storms, developing accurate space weather forecasts is urgent.

As much as understanding the underlying physics of atmospheric dynamics is critical to accurate terrestrial weather forecasting, a fundamental understanding of plasma physics is at the core of space weather forecasting. Of particular relevance is plasma turbulence in which distorted flows and magnetic fields transfer energy between scales, from larger injection scales down to smaller scales where dissipation and heating occur. Recent studies have shown the importance of turbulence in processes, such as magnetic reconnection, that are key agents of space weather. A primary challenge in understanding plasma turbulence and its global implications is its multi-scale nature, spanning from electron scales to scales larger than the magnetosphere. This white paper addresses the multi-scale challenge focusing on the contributions that multi-spacecraft measurements can make.

Multi-spacecraft measurements

In-situ probes forming multiple "n-hedrons (n >= 4)" and covering MHD to kinetic scales are key to meeting the multi-scale challenge of characterizing plasma turbulence. Current multi-spacecraft missions with 3D formations, the Magnetospheric Multiscale (MMS) [Burch et al., 2016] and Cluster [Escoubet et al., 2001], have made progress to address plasma turbulence. Yet the limitations of a fixed spacecraft formation size at a given time prohibit probing the multi-scale nature as well as the dynamical evolution of turbulence. The recently selected NASA Midsize Explorer mission HelioSwarm, consisting of nine spacecraft, represents a major breakthrough in multi-scale measurements of turbulence. For an in-depth description of the mission, see the White Paper submitted to the 2023 Heliophysics Decadal Survey "HelioSwarm: A Multipoint, Multiscale Mission to Characterize Turbulence" by K. G. Klein et al..

Major achievements and challenges from the Cluster and MMS missions

We briefly review the major achievements and challenges from the Cluster and MMS missions in the field of shock/foreshock/magnetosheath turbulence to provide a contrast with what can be achieved by a multi-scale mission. The major achievements of the Cluster mission on shock/foreshock/magnetosheath turbulence include: (1) Reconnecting current sheets were discovered in the turbulent magnetosheath [Retino et al., 2007]. (2) the dissipation due to reconnecting current sheets is estimated to be about two orders of magnitude higher than that due to wave damping [Sunskvist et al., 2007; Chasapis et al, 2015]. (3) The anisotropy of solar wind turbulence between the ion and electron gyroscales is measured by simultaneously probing a variety of directions (along pairs of the spacecraft) relative to the local magnetic field based on the four Cluster measurements and found to highly elongated along the magnetic field [C.H.K. Chen et al., 2010]. The full 3D anisotropy was also measured by the k-filtering method at proton scales [Roberts et al., 2017]. (3) the energy injection at the foreshock is determined to be at ion scales, and instabilities responsible for the waves are inferred [Narita et al., 2007].

The major achievements of the MMS mission on shock/foreshock/magnetosheath turbulence include: (1) Reconnecting current sheets were discovered in the turbulent shock transition region [e.g., Gingell et al., 2019], and electron-only reconnection in the downstream magnetosheath [Phan et al., 2018]. (2) In magnetosheath turbulence, structures with high intermittency are regions of significant electron heating with typical structures showing features consistent with magnetic reconnection [Chasapis et al., 2017], and evidence for electron Landau damping is discovered [CHK Chen et al., 2019]. (3) The energy partition between magnetic fields and plasma flows was examined for the magnetosheath, where the kinetic scale energy partition was found to deviate from that in the MHD scale and the electron flow energy dominates at the electron scale [Gershman et al., 2014]. (4) The wave modes in the magnetosheath above the ion scale were identified using the 4-spacecraft k-filtering technique [Gershman et al., 2014]. For MMS, one major challenge is that the multi-spacecraft technique cannot resolve the spatial scale of fast propagating structures even along the propagation direction due to the combined limitation of the small spacecraft separation and time resolution. This challenge is partially resolved by a configuration with four spacecraft separated by the d_i scale and forming a line. The co-linear configuration enables MMS to address one-dimensional evolution of turbulent structures moving past the four spacecraft (such as that shown in Figure 3 of Chen et al., 2020). Further advances will be made by missions designed to study the 3D multiscale nature of turbulence, one of the key science goals of HelioSwarm.

Both missions lack cross-scale capabilities that can only come from having more spacecraft with multi-scale separations at any given time. Having N spacecraft provides a maximum of N!/(4!(N-4)!) tetrahedra. The analysis capability quickly increases with an increasing number of measurement points. For example, having four spacecraft yields at most one tetrahedron, while 9 spacecraft could provide 126 tetrahedra.

One of the common challenges for studying self-generated turbulence is to obtain spatial scales reliably. Along the propagation direction, the spacecraft separation needs to be large enough to observe significant variations of the fields and smaller than the minimum wave length for both k-filtering (a technique enabling mapping from the frequency to wave vector space) [Pincon and Motschmann, 2000] and timing analysis. The scale size along directions other than the convection flow is mostly unknown. In addition, the existing multi-spacecraft analysis methods assume stationarity as the structure propagates through the spacecraft cluster. The multi-spacecraft analysis for spatial gradients requires approximations to tetrahedrons or higher order (n-hedron, $n > 4$) shapes of the spacecraft constellation. These challenges can only be overcome by multipoint, multiscale measurements.

Kinetic turbulence at the foreshock, shock, and magnetosheath

Here we use the shock/foreshock/magnetosheath turbulence as an example to briefly discuss the specifics of how multi-scale measurements achieved either by an N-spacecraft (N>4 in order to form multiple n-hedrons) mission, or by multiple missions, will transform the current state of knowledge. This choice highlights ion kinetic physics in creating turbulence that impacts planetary magnetospheres and ionospheres, and potentially leading to dayside escape of plasmas and hence evolution of planets.

Even when the Sun is quiet, and the interplanetary magnetic field (IMF) is steady, the machinery of ion-ion instabilities can brew mini-storms in front of magnetospheres, both intrinsic and induced [Chen et al., 2022]. Figure 1 illustrates one such ‘mini-storm’ example observed by the MMS mission at the foreshock. The left panel shows an envelope of the transverse wave components (By and Bz; IMF dominated by Bx) and solitary structures with strong negative Bz (~20 nT) comparable to the negative IMF Bz during a major geomagnetic storm (such as the 2015 solstice storm with a minimum Dst reaching -170 nT). Figure 2 presents corresponding simulations results that demonstrate how the foreshock waves and turbulence impact the magnetopause.

The solitary structures in Figure 1 represent further distorted magnetic fields and plasma flows produced by the nonlinear interaction between reflected ions and the incoming solar wind [Chen et al., 2020]. In this particular case, the growth of the waves and development of the solitary structures thrive on resonance with the solar wind ions, a fully kinetic process beyond any fluid descriptions.

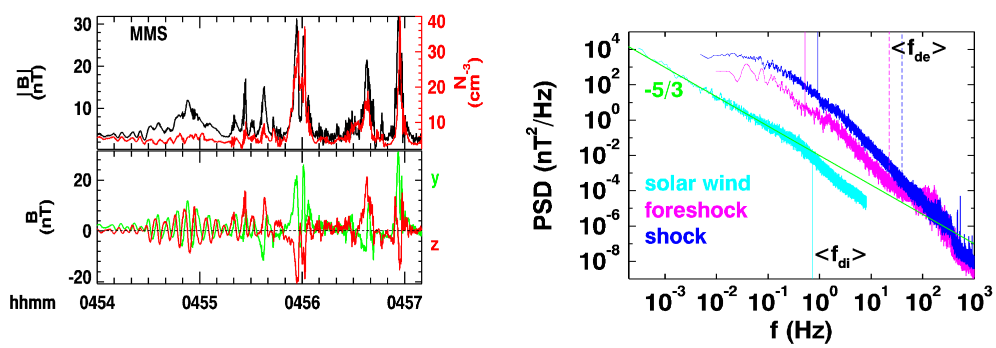

Figure 1: ***(Left)*** *Magnetic field (B) and plasma density (N) measurements from a foreshock crossing by the MMS mission showing an envelope of the transverse wave components (By and Bz) and solitary structures with strong negative Bz (~20 nT) [Chen et al., 2020].* ***(Right)*** *Magnetic field spectra from the foreshock and a bow shock observed by MMS. The strong foreshock magnetic turbulence is convected into the magnetosheath where kinetic scale current sheets have been found to reconnect [Retino et al., 2007; Stawarz et al., 2022]. The solar wind spectrum is shown as a comparison. The nine-spacecraft mission HelioSwarm will be able to determine the three-dimensional structure, size, and evolution of the foreshock/shock/magnetosheath turbulence for the first time.*

The kinetic turbulence discussed in Figure 1 along with its underlying connection with collisionless shocks and magnetic reconnection leads to complex interactions in the geospace environment, as revealed by global kinetic simulations in 2D [Karimabadi et al., 2014] and 3D [e.g., Chen et al., 2020; Ng et al., 2021]. The self-generated (in contrast with that convected from the upstream solar wind) turbulence takes the forms of nonlinear waves that penetrate into the inner magnetosphere [Takahashi et al., 2016, 2021], and steepened magnetic structures (such as those shown in Figure 1) resulting in plasma heating, particle acceleration, and reconnection [e.g., Schwartz, 1995; Chen et al., 2022 and references therein]. At the shock, the turbulence causes formation of high speed jets that penetrate the bow shock and bombard the magnetopause a few times per hour leading to dayside reconnection [Hietala et al., 2009, 2018; Ng et al., 2021], and has been shown to modulate the magnetopause reconnection rate [Zou et al., 2022].

The magnetic field spectrum from the foreshock (right panel of Figure 1, magenta curve; characterized by reflected ions and intense magnetic fluctuations with typical dB/B >> 1 such as that shown in the left panel of Figure 1) exhibits multiple magnetic spectral peaks at ion and electron scales, indicating multi-scale energy injections. The spectrum from an example shock containing ion-scale reconnecting current sheets (right panel of Figure 1, blue curve) presents a broad peak of enhanced magnetic energy in the vicinity of the ion inertial length (d_i) scale (marked by a vertical solid line and labeled as <f_{di}>). In the example, the dynamics of d_i-scale current sheets plays a critical role in dissipation. At the foreshock, shock transition, and downstream from quasi-parallel shocks in the magnetosheath, intense current sheets both reconnecting [e.g., Retino et al., 2007; Phan et al., 2018; Bessho et al., 2020, 2022; Ng et al., 2022] and non-reconnecting are abundant [Gingell et al., 2021]. Future multi-scale missions such as HelioSwarm will allow us to observe the generation, transport, and dissipation of these foreshock waves, as well as characterize the turbulence they generate in ways that single-scale missions are fundamentally incapable of achieving.

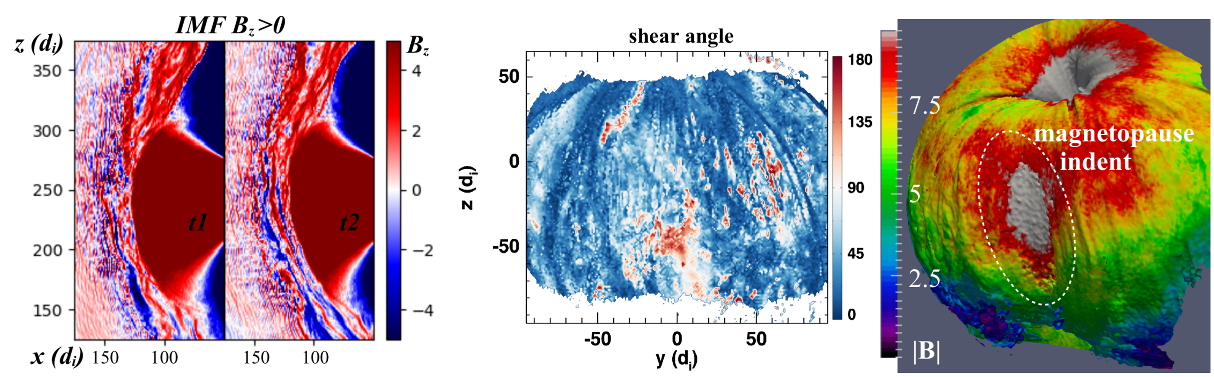

Figure 2: (Left) *Under constant IMF (Bz>0; Bx dominates) and solar wind conditions, turbulence stirred up at the quasi-parallel bow shock creates planet-sized regions of enhanced Bz with amplitudes comparable with stormtime IMF southward Bz (from a global hybrid simulation treating ions as particles and electrons as a fluid [Chen et al., 2021]).* ***(Middle)*** *The*

turbulence is further amplified in the magnetosheath, and the negative Bz when reaching the magnetopause, makes large magnetic shear angles conducive to magnetopause reconnection. ***(Right)*** *Planet-sized indentation at the magnetopause caused by the foreshock turbulence penetrating through the magnetosheath.*

Recommendations

We recommend to bring into reality the following within the next decade:

1. Measurements from multiple spacecraft covering a 3D volume and simultaneously spanning the MHD to kinetic scales (such as HelioSwarm). Such a mission will transform the landscape of multi-scale *in-situ* observations of turbulence. Furthermore, such a mission will spark powerful collaborations with new multi-scale laboratory experiments such as FLARES [Ji et al., 2018] as well as the new exascale 3D global kinetic simulations.
2. Coordination of the new multi-scale mission(s) with existing multi-spacecraft missions such as MMS to maximize the power of cross-scale ion and electron measurements. The 3D plasma measurements of the MMS mission are orders of magnitudes higher cadence than any existing missions. The remaining fuel of MMS can last for another 30 years, and its plasma spectrometers can be expected to operate nominally for another 10 years or longer. Coordinating any future multi-scale mission in terms of orbit implementation and launch so that the new mission can explore the same region with MMS will be highly advantageous.

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