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Editorial: Solar wind turbulence: its origins, evolution, and impacts

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Editorial on the Research Topic
Solar wind turbulence: its origins, evolution, and impacts

Turbulence, as a fundamental phenomenon in solar winds, is believed to play a crucial role in heating and accelerating the solar winds and in transporting energetic particles. Therefore, it is also the base reality of space weather modeling. Despite decades of intense research, many questions about solar wind turbulence remain unanswered due to its nonlinear complexity and huge scale separation. With the significant advances in computational power and the deployment of numerous human-made spacecrafts throughout the heliosphere—one of them even reaching as close as 0.05 astronomical unit (au) away from the Sun, the ultimate origin—we are now in an unprecedented era for studying solar wind turbulence. This Research Topic gathers seven papers that cover recent advancements in a broad range of Research Topic related to solar wind turbulence. These include fundamental theories of wave-wave interactions (Sharma et al.), Parker Solar Probe (PSP) observations on turbulence evolution (Telloni; Wu et al.), numerical simulations of turbulence generated by magnetic reconnection (Nakanotani et al.), the introduction of a new three-dimensional (3D) pseudo-spectral magnetohydrodynamic (MHD) simulation code (Shi et al.), observation of heavy-ion composition in the solar wind (Carpenter et al.), and multi-point observations of coronal-mass-ejection flux ropes (Lai et al.). The following paragraphs provide a summary of the results from these papers.

How solar wind turbulence develops is still an unknown in classic physics. It is believed that waves contribute to turbulence, especially through nonlinear wave-wave interactions, which transfer energy across different scales, thereby helping to develop turbulence. In a plasma turbulence system, as we approach small-length scales down to ion kinetic scales, various kinetic wave modes and coherent structures may co-exist and undergo complex interactions. Sharma et al. explored how kinetic Alfvén waves (KAW) and dispersive Alfvén waves interact with other low-frequency modes and magnetic islands generated by reconnection, using semi-analytic calculations and numerical simulations. Their results reproduced power spectral slopes consistent with satellite observations at both the MHD scales and sub-ion scales, suggesting that solar wind turbulence involves the various nonlinear processes as mentioned above.

Nakanotani et al. also studied the interaction between turbulence and magnetic reconnection by conducting 2D and 3D MHD simulations coupled with test particles. The simulations were initialized with multiple current sheets, where reconnection is triggered by the growth of tearing mode instability. As magnetic islands interact, the system evolves into a highly turbulent state. The test particle simulation results show that particle acceleration due to turbulence is significantly more efficient compared to previous kinetic simulations, and it is more efficient in the 2D case than in the 3D case.

The two papers above highlight the importance of numerical simulations in turbulence studies. Shi et al. introduced a new 3D Fourier-transform-based pseudo-spectral Hall-MHD code LAPS. The code is parallelized using Message-Passing-Interface (MPI) and has strong scalability, which is key for massive numerical simulations. Notably, it is equipped with the expanding-box-model (EBM) so that spherical expansion of solar wind can be incorporated. Therefore, LAPS is a powerful tool in numerically investigating solar wind turbulence. It is open-source and published on GitHub.

As the Parker Solar Probe reaches unprecedented proximity to the Sun, we now have the *in-situ* measurements of the early-stage evolution of solar wind and the turbulence therein. Telloni utilized a unique feature of PSP's orbit, i.e., during certain intervals before and after perihelion, PSP moves almost purely in a radial direction in the Sun's co-rotating reference frame. This allows for long-duration measurements of the same solar wind stream, enabling the investigation of turbulence properties over a wide range of time scales. Telloni analyzed PSP's magnetic field data during such an interval in its seventh orbit, revealing a clear transition in the inertial range spectrum from a $-3/2$ slope to a $-5/3$ slope as we move to smaller scales, with a break frequency of approximately 5×10^{-1} Hz. In the steeper spectrum range, Alfvénicity decreases while the strength of intermittency increases. Wu et al. also used PSP observations to investigate solar wind turbulence. They identified two streams that both exhibited a high correlation between magnetic field and velocity but with different levels of normalized residual energy. They defined fluctuations with near-zero residual energy as Alfvénic fluctuations (AF) and those with large negative residual energy as magnetic-velocity alignment structures (MVAS). Wu et al. calculated the coherence between the two Elsässer variables for both streams and found significantly higher coherence in the MVAS than in the AF, suggesting that different nonlinear processes occur in the two types of streams.

Finally, we have two articles that, while not directly focused on solar wind turbulence, examine processes that are closely related to or strongly impact it. Carpenter et al., using Advanced Composition Explorer (ACE) and Solar Orbiter data, investigated the heavy-ion composition in the solar wind during the ascending phases of solar cycles 23 and 25. Properties of the heavy ions reflect the dynamic processes involved in the formation of solar wind streams deep in the solar corona and are strongly linked to the characteristics of turbulence. Carpenter et al. found that the O7+/O6+ ratio and iron fractionation in fast streams were higher during the ascending phase of solar cycle 25 compared to solar cycle 23. This suggests increased reconnection between the magnetic fields of equatorial coronal holes and helmet streamers or active regions.

Interplanetary coronal mass ejections (ICMEs), which are high-speed clusters of plasma carrying enhanced magnetic fields, strongly disrupt pre-existing turbulence in the solar wind and may inject a significant amount of energy into the turbulence. Lai et al. conducted conjunction observations of multiple ICME flux ropes using data from ACE, STEREO, Juno, and Solar Orbiter. They calculated the major radii, i.e., the radii along the toroidal axis, of the observed ICME flux ropes. Their results revealed a wide range of major radii and showed that these radii do not depend on the width of the flux ropes' cross-sections. These findings are expected to contribute to improving space weather prediction models.

Despite recent progress in the study of solar wind turbulence, a number of unresolved Research Topic remain, such as the mechanisms of energy-transfer between turbulence fluctuations and particles, the development of turbulence in the very early stages of solar wind, and the distinct Alfvénicity in solar wind streams from different sources. With ongoing advancements in computational power and the launch of more space missions, many of these questions are expected to be answered in the near future.

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