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High-resolution Modeling of the Solar Wind Turbulence: from Global to Micro-scales

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The solar wind is a prominently turbulent plasma medium with the full range of scales extending over eight orders of magnitude. The turbulent fluctuations transfer from structure at global heliospheric scales (1 AU and larger), cascading to ever smaller scales, and they finally begin dissipating at scales of ~100 km and smaller. This is illustrated in Figure 1 which shows a solar wind turbulence spectrum derived from multiple spacecraft. A fundamental question about whether, and to what extent, turbulent fluctuations can be generated in the solar wind in addition to those propagating outward from the corona remains unresolved. Furthermore, evolution through the interplanetary medium of turbulent fluctuations generated in the corona has never been investigated in a realistic global context. Shedding light on these compelling questions of Heliophysics in the coming decades is particularly timely given the wealth of data returned by the Parker Solar Probe, Solar Orbiter and other upcoming solar and heliospheric missions. The necessity to resolve the enormous range of scales over which the solar wind turbulence operates has put it essentially out of touch for global magnetohydrodynamic (MHD)-based heliosphere models which currently, at the highest resolution, typically resolve scales of >150,000 km at best (Merkin et al. 2018; Mostafavi et al. 2020, right panel of Figure 2), thus barely entering the inertial range (i.e., $\sim10^2 - \sim10^5$ km). An improvement in resolution is needed to study the solar wind turbulence in the solar wind well into the inertial range (even the dissipation range) while at the same time resolving the global heliospheric structure dominated by stream interaction regions. For this purpose, global inner heliosphere models with sufficient resolution are required and both MHD and non-MHD (e.g., two-fluid, hybrid and even kinetic) will certainly become feasible before 2050, with varying limitations.

The supercomputing power available to scientists throughout the world is continuing to increase. Ultra-high-resolution global data-driven models available in the future will run on these new architectures and will lead to breakthroughs in the physics of the inner heliosphere, as simulations of the solar wind structure and turbulence have never been performed at this scale. This is feasible given the growth of the expected computational power by 2050.

The primary models for studying both the corona and the inner heliosphere have been MHD models which have shown significant progress in recent years. However, optimal numerics for the corona and the super-fast solar wind are very different. Through the advancements in computer processing, future models will be able to start from the chromosphere and extend all the way through the heliosphere, capturing both the evolution of the coronal turbulence and its possible generation in the solar wind for the first time.

The NASA Parker Solar Probe (PSP) spacecraft was launched in 2018 and it is making outstanding observations of the young solar wind. PSP measures small scale phenomena and raises many compelling questions about the fundamental physics of solar wind turbulence and, including fully nonlinear processes. For example, it observed some rapid folds in the magnetic field, called switchbacks, on timescales ranging from seconds to hours (Bale et al. 2019). Although switchbacks or magnetic field reversals were observed by

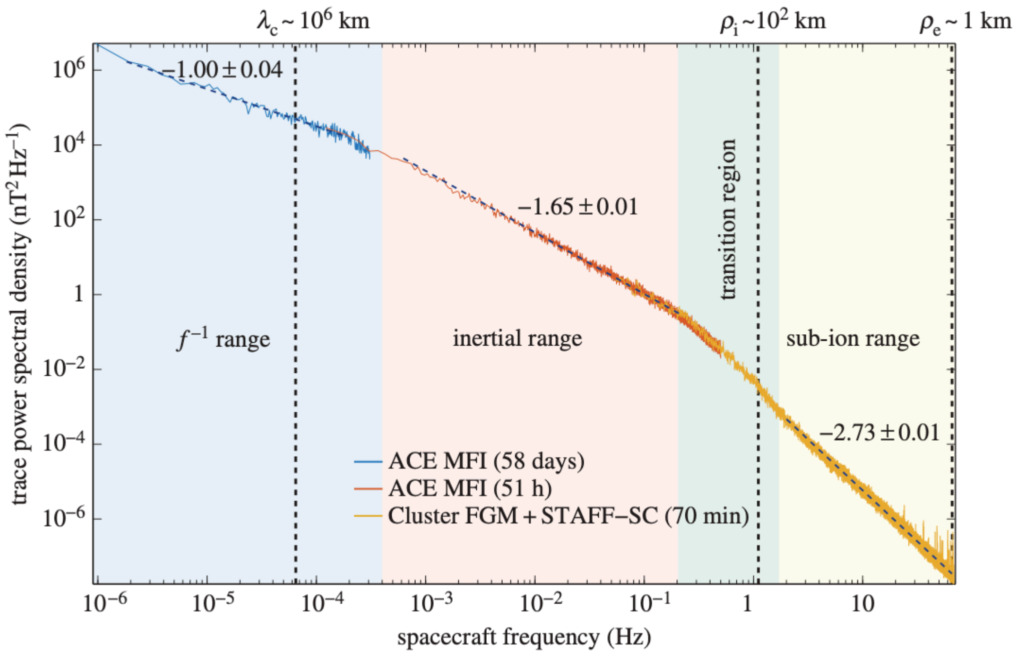

***Figure 1**. The power spectral density of magnetic field fluctuations of solar wind at 1 AU. Future simulations will extend a global inner heliosphere model well deep into the inertial range and possibly even enter the dissipation range of the solar wind turbulence. This will bridge the gap between state-of-the-art turbulence simulations and global inner heliosphere simulations. This figure is adapted from Kiyani et al. 2015.*

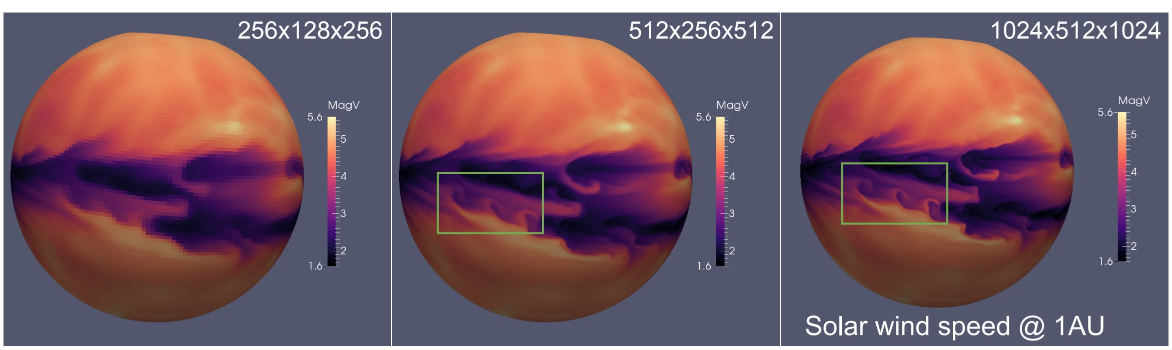

***Figure 2.** The Grid Agnostic MHD for Extended Research Applications (GAMERA) simulations of the inner heliosphere at progressively higher resolution demonstrate the development of mesoscale structure in the solar wind as the resolution increases. The simulation on the right is the highest ever resolution global MHD simulation of the inner heliosphere performed to date (Merkin et al. 2018; Mostafavi et al. 2020), resolving structures down to 150,000 km. Although it shows complex non-linear evolution of the imposed coronal structure, in situ generation of MHD instabilities is still out of reach. In the next decades, ultra-high-resolution global simulations of the solar wind will enable coverage of a large portion of the inertial range.*

other spacecraft at different heliospheric distances, the sources of them are still unknown and whether such structures are remnants of coronal processes related to wind formation and acceleration remains a mystery (see e.g., Ruffolo et al, 2020; Fisk & Kasper 2020).

Moreover, PSP observations of the perihelion orbits showed that the turbulence levels of the solar wind are increased by more than one order of magnitude compared to the turbulence observations at 1 AU (Chen et al. 2020). In the same perihelion regions, the turbulence cascade rates are elevated by a factor of around 100 (Bandyopadhyay et al, 2020) compared to 1 AU. The need for models capable of resolving multi-scale physics is therefore dictated by the recent PSP observations and is thus a timely investigation. Such models would help us understand the physics of observed turbulence by PSP, Solar orbiter, and future solar missions including IMAP, PUNCH, SUNRISE, and proposed multispacecraft missions such as HelioSwarm.

Summary and questions:

A partial list of unanswered questions to be addressed with next generation models may include:

- What are the origins of solar wind turbulence and waves, including both MHD and kinetic-scale waves?
- What is the role of Kelvin-Helmholtz (KH) instability in generating solar wind turbulence? Can the KH waves remain unstable in the inner heliosphere?
- What physical mechanisms can generate switchbacks, and how do these structures evolve in the solar wind?
- What is the relation between the turbulence and large-amplitude fluctuations such as switchbacks?
- Do interplanetary shocks contribute to turbulence in the inner heliospheric medium?

In order to address these questions, we will need to develop the following desired models by 2050:

- Ultra-high-resolution global MHD and non-MHD models, resolution reaching into the dissipation range to capture multi-scale physics of the solar wind.
- Models starting from chromosphere all the way through the heliosphere.

References:

Bale, S. D., Badman, S. T., Bonnell, J. W., et al.2019, Nature, 576, 237

Chen, C. H. K., Bale, S. D., Bonnell, J. W., et al.2020, The Astrophysical Journal Supplement Series, 246, 53

Merkin, V. G., Sorathia, K. S., Lyon J., Zhang B., Wiltberger M. J., (2018), High-resolution simulations of the heliospheric structure, ASTRONUM 2018 conference, Panama Beach, Florida, June 2018.

P. Mostafavi, S. Merkin, et al., to be submitted (2020)

Ruffolo, D. Matthaeus, W. H. Chhiber, et al., Shear Driven Transition to Isotropically Turbulent Solar Wind Outside the Alfven Critical Zone, ASstrophys. J. 2020 (in press).

Bandyopadhyay, R., Goldstein, M. L., et al. 2020, The Astrophysical Journal Supplement Series

Fisk, L. A. & Kasper, J. C. 2020, TheAstrophysical Journal, 894, L4

Kiyani, K. H., Osman, K. T., & Chapman, S. C. (2015). Series A, Mathematical, physical, and engineering sciences, 373(2041).