Proposal for an ISSI Team Project - Call 2023

Evolution of turbulence in the expanding solar wind

PART A - Scientific Justification

Abstract. *The recent launches of Parker Solar Probe, Solar Orbiter, and BepiColombo offer unique opportunities for investigating the evolution and dynamics of the expanding solar wind. This Team will perform coordinated studies using multi-point in-situ and remote observations from these and other spacecraft, which will allow us to obtain the most accurate measurements of the radial evolution of solar wind turbulence energy budget and overcome the broad uncertainty of the more standard single-spacecraft statistical estimates. Data analysis, models and numerical simulations will be used to obtain such estimates and to subsequently address unresolved questions:* ***1) How do turbulence properties and plasma heating precisely evolve with the heliocentric distance? 2) How does the solar wind expansion affect these properties? 3) Can solar-wind models be improved using multi-spacecraft observations?*** *This well complemented Team will tackle such questions to maximise the science return of the available spacecraft configurations in the inner heliosphere.*

Scientific Rationale

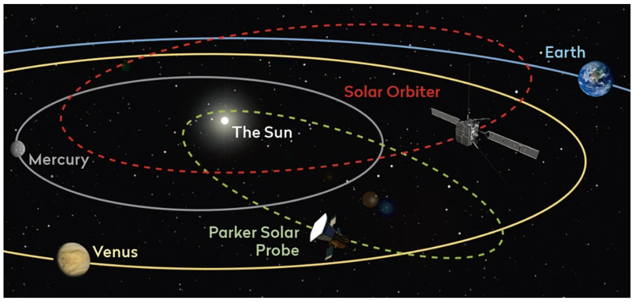

Figure 1. Example of SO and PSP orbits

Background, motivations and science questions. The magnetic structure of the Sun and of the solar corona drives the solar wind throughout the heliosphere. Turbulence, particle energization and energy transport are profoundly interconnected across a broad range of temporal and spatial scales, and constitute a uniquely accessible system for understanding the way stellar systems work. After more than half a century of in-situ measurements, our understanding of the heliospheric dynamics is still incomplete, motivating space agencies to support dedicated missions. Most of our present understanding of the solar wind stems from observations near the Earth, implying that the complex spatio-temporal dynamics of the heliosphere is heavily undersampled. The radial evolution of solar wind waves, turbulence and heating have been mostly studied using broad ensembles of single-spacecraft measurements taken at different times and heliocentric distances, and under different solar wind and solar conditions (Bruno & Carbone, 2013, Chen et al., 2020). However, due to the intrinsic variability and inhomogeneity of the solar wind and of its solar sources, this approach provides largely variable parameters, and cannot capture their fundamental radial evolution. The latter is crucial for **understanding how solar wind turbulence is affected by the expansion in the heliosphere.** All these factors are important ingredients of the heliospheric modelling, which should be constrained by realistic observational parameters that vary with specific plasma conditions and solar distance. One of

the major hindrances to the advances of our understanding of heliophysical plasmas stems from the historical difficulty in the connection between solar wind sources and points of measurement across vast distances, and also across very diverse physical scales. We are nowadays in a privileged position to finally address these problems, following the emergence of an increasing number of spacecraft that probe the solar wind at different distances from the Sun and from each other, allied to the development of several physical models that, together, can cover such separations. In practical terms, we now have a perfect opportunity to connect across regions and regimes, and to validate our models with multiple data points simultaneously (rather than just solar bound, or spacecraft bound, as done historically by the community). This can be done using coordinated multi-spacecraft observations of genuine radial evolution, unravelling all the many variability factors affecting statistical observations. Previous missions such as Venus Express, Messenger, and Stereo potentially enabled multi-point coordinated studies with missions at L1 (e.g., ACE, Wind). However, their payload was not tailored for detailed studies of the fluctuations, so that only minimal advances were obtained for the evolution of turbulence. Sporadic coordinated studies of Helios, ACE and Ulysses data (e.g., Schwartz & Marsch, 1983; D'Amicis et al., 2010) provided evaluation of some basic radial evolution parameters, which were however outdated with respect to today's understanding of space plasma turbulence.
The recent launch of Parker Solar Probe, Solar Orbiter (see Fig.1) and BepiColombo, together with the flotilla of spacecraft orbiting near Earth, provide today an unprecedented opportunity to probe the inner heliosphere. The abundance of underexploited past and upcoming possibilities of coordinated studies using multi-spacecraft measurements enables us to investigate the radial evolution of turbulence to a greater detail than ever before. **The goal of this Team is to obtain a more accurate measurement of the turbulence properties in the radial evolution of the expanding solar wind.** The significance of the proposed study is manyfold. The targeted results will: (i) provide more accurate estimates of the global energy budget for the expanding solar wind, which will be complemented by modelling; (ii) help assess how much of the energy of the large-scale solar wind structure is processed by the turbulence and converted into heating; (iii) estimate how much energy is left in the large-scale fluctuations and is available for particle energization; and last but not least (iv) make it possible to constrain and validate models of heliospheric expansion, and to understand the physical processes regulating the evolution of expanding turbulence and the subsequent plasma heating.

Project Methodology. The team will be focusing on the following four main tasks:

Task 1 - Selection of event studies. The recently launched Parker Solar Probe (PSP), Solar Orbiter (SO) and BepiColombo (BC) orbit the Sun covering a range of distances spanning from 0.04 to 1 au carrying state-of-the-art in-situ payload measuring fields and plasma moments. Together with other past or still operating missions (e.g.: Helios, Wind, ACE, Ulysses, STEREO-A, DSCOVR), as well as with the possible addition of ESA's Juice cruise phase measurements (launch in April 2023), they represent a phenomenal multipoint, multi-instrumental observatory for the dynamical evolution of solar wind turbulence. Extensive preliminary investigations identified several dozens of interesting spacecraft configurations, listed in Annex 1 (Velli et al., 2020; Hadid et al., 2021; Telloni 2022). Additional potential configurations with Juice are currently being examined. This Team will primarily focus on a carefully selected set of rare radial alignments between two or more spacecraft that potentially **sampled the *"same plasma"*** as it expands in

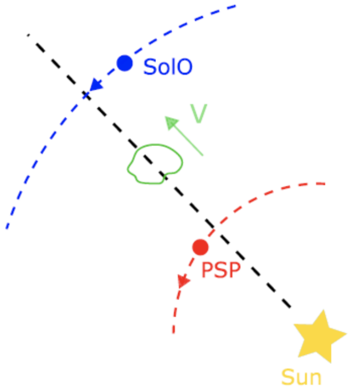

Figure 2. An example of radial alignment between PSP and SO: a "same plasma" event

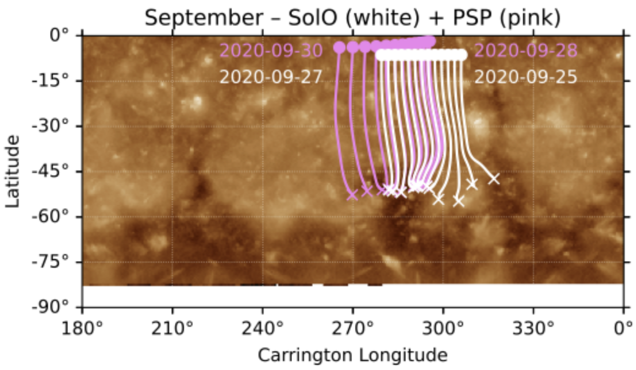

Figure 3. An example of configuration between PSP and SO: a "same source" event

the heliosphere (see Fig.2, Telloni et al. 2021). The selection will be based on the identification of the exact time intervals of the joint observation using the measured solar wind parameters and possible tracking structures. When possible, it will be confirmed that the plasma of the two points of measurements proceeds from the same solar source, using connectivity tools to map the in-situ plasma to their source regions as shown in Fig.3 (Rouillard et al., 2020). In addition, other spacecraft configurations will be selected, where the *"same plasma"* conditions will be relaxed, requiring instead that the plasma is **emitted from the *"same source"*** on the Sun, if the solar source can be considered sufficiently stationary (Perrone et al., 2022).

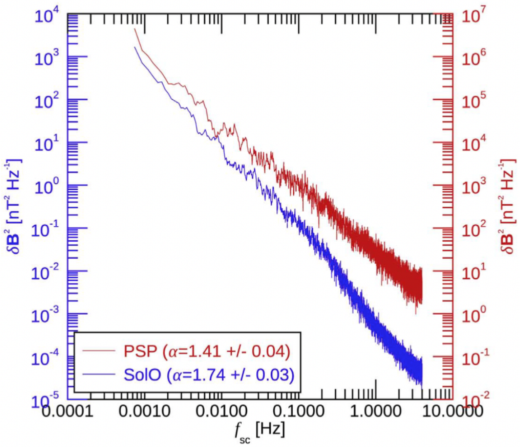

Figure 4. Evolution of magnetic spectra in the "same plasma" measured by PSP and SO

Task 2 - MHD and sub-ion scales turbulence characterization. The turbulent fluctuations and all relevant physical parameters of the selected events will be obtained by applying well established and novel statistical methods to measurements of magnetic field and plasma moments (velocity, density, temperature). These include: cross-helicity, magnetic helicity, residual energy, compressibility, fields spectra (see Fig.4) and higher-order scaling laws (Bruno & Carbone, 2013; Dudock De Wit et al., 2013), as well as energy cascade transfer estimates (Marino & Sorriso-Valvo, 2023). From these parameters, the fine details of the turbulence radial evolution and the associated heating and energy decay will be obtained for the respective solar wind and solar activity conditions and at different radial distances at the time of the measurements. Heating profiles will also be evaluated using turbulence models (Vasquez et al., 2007) and compared with a stochastic heating model (Chandran et al., 2013).

Task 3 - Study the local effects of expanding turbulence. The role of solar wind expansion in driving, constraining or modifying the turbulent fluctuations at the different scales is still not completely understood. Well established expanding-box numerical simulations of magnetohydrodynamic (MHD) turbulence (Verdini & Grappin 2015, 2016; Grappin et al. 2022) will be used to evaluate the effect of expansion and anisotropy on turbulence at MHD scales, to be compared with the observational results from Task 2. In addition, direct numerical simulations of reflection-driven turbulence (RDT) in magnetic-flux tubes extending from the coronal base to beyond the Alfvén critical point will be used to provide a complementary description of the effects of expansion and reflection on turbulence in the solar-wind acceleration region (Perez & Chandran 2013, Chandran & Perez 2019). In particular, the radial decay of energy, Alfvénicity, and cascade rate, and the radial trends of intermittency and anisotropy of fluctuations, will be studied and compared to observations. The cascade rate and other terms entering the energy budget equation are directly accessible in simulations and will be used to evaluate the accuracy of observational proxies and assumptions on geometry and incompressibility of fluctuations.

Task 4 - Constrain heliospheric models. In this task, the observational results from the selected conjunctions will be used to constrain and refine an ensemble of models that includes: the data-driven numerical model of the nascent and low heliospheric solar wind MULTI-VP (Pinto & Rouillard, 2017); an analytical model of Alfvén wave (AW) heating of the solar wind (Chandran, 2021); and a two-fluid kinetic-MHD model of the solar wind that accounts for temperature anisotropy, collisionless heat flux, and turbulent heating (Chandran et al. 2011). The modelling will enable a synergy with the magnetic connectivity estimations performed in Task 1 for establishing the "same plasma" and "same source" solar wind. Also, the modelling of the transport of waves and heat along them from the Sun to the interplanetary medium will be compared with the heating rate obtained from observations from Task 2. The modelling can also provide information on the properties of each specific wind propagation path to the expanding box. Runs of all models will be performed using a few selected events with the most consolidated and complete set of constraining parameters selected from Tasks 1 and 2, to produce the most accurate solar wind modelling so far. This data-driven feedback will also help refine the phenomenology of the models, since the underlying statistical input will be significantly improved when based on the multipoint configurations rather than on one point of measurement.

Project Work Plan. The Team plans two one-week meetings at ISSI-Bern, with the following flexible agenda:
1) winter 2023/2024 (date tbd): Selection and verification of events, including data availability and quality check, and identification and coordination of synergistic studies between observations and modelling.
2) **spring 2025 (date tbd)**: Presentation of preliminary science results, including observational feed to models and comparison between observations and numerical simulations. Final report on the science planned during the first meeting; draft of a paper collecting the main results.

Expected output

The expected scientific output of the proposal is the successful implementation of analyses of multi-spacecraft coordinated events. Outcomes from Tasks 1-4 will be published in scientific papers in relevant peer-reviewed journals (e.g.: A&A, APJ, Phys. Plasmas, Frontiers). The major outcome will be one paper summarising the new insights obtained from the novel synergistic approach, to be prepared after the second Team meeting.
We will also promote the project outcome at various international conferences (e.g., EGU, AGU) and dedicated workshops.

Financial support requested from ISSI.

We require per-diem and accommodation for 12 participants, for the two one-week meetings at ISSI-Bern; travel costs for the two team leaders; full support for two young researchers.

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