Current Sheets, Turbulence, Structures and Particle Acceleration in the Heliosphere

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Abstract

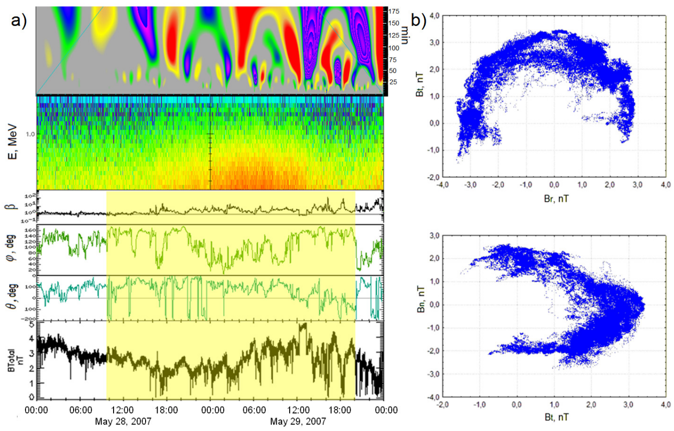
This project will address some of the most intriguing heliospheric processes, as magnetic reconnection in the Heliospheric Current Sheet (HCS), the simultaneous appearance of small-scale and intermittent structures, the ubiquitous presence of turbulence and the subsequent acceleration of energetic particles. One may ask if this is all an essential manifestation of turbulence. Inspired by recent theoretical results and observations, the Group will concentrate on the specific study of the remarkable co-existence in space plasmas of turbulence, reconnection, dynamical structures and current sheets, and energetic particles. The important aspect will be the study of these processes as function of the heliocentric distance and latitude.

We have assembled an international team of experts in the multiple, often individually addressed, physical processes associated with the proposed project, including expertise in observations, theory and modeling simulations, to synthesize our understanding of magnetic reconnection, turbulence, structures and particle acceleration. Besides being fundamental to virtually every aspect of space science and astrophysics, this synthesis will contribute practically to further Space Weather studies and the origin of high energy particle radiation. Finally, the format and the structure of ISSI meetings lead itself to successful and efficient international collaboration for a project such as this, that aims to synthesize typically disparate studies of fundamental physical processes.

1 Scientific rationale

Turbulence and coherent structures Both theory and observations show that turbulence is an underlying physical process that governs almost every aspect of solar wind physics in a very high degree, ranging from scattering of particles, basic dissipation processes to possible acceleration of the solar wind [1–4]. The dynamical and highly nonlinear interaction of fluctuations across extensive spatial and temporal scales, including the energy transfer cascade, are well-known. Far less understood is the nonlinear formation of coherent structures and their role in basic turbulence processes. These structures typically manifest as very bursty signals, localized in space – typical of high-energy and extreme phenomena. These singular and persistent structures can be classified in several ways [5], although the majority of them consists of strong inhomogeneities of the magnetic field [6, 7], namely current sheets. They can be generated both dynamically by turbulence, or they might be fossils of the primordial solar wind, or the corona. However, even in the latter case, they are subjects to instabilities and magnetic reconnection that, in a self-similar way, generates secondary current sheets and magnetic islands. This picture is consistent with a reconnection-generated turbulence, widely invoked in the literature as an ubiquitous phenomenon [8–13].

Current sheets and the Heliosphere The heliosphere is full of small and larger scale, short and long-lived current sheets that are very dynamical [14]. The largest and most stable current sheet is the heliospheric current sheet (HCS). Other quasi-stable current sheets are formed at edges of solar wind streams such as interplanetary coronal mass ejections or coronal hole flows. Our recent studies have revealed that intermittent turbulence associated with current sheets is an underestimated source of particle energization in space [3, 12, 13, 15–17].



This is a clear case of local particle acceleration observed at ~ 1 AU in the region filled with numerous magnetic islands. There were no other sources of particle acceleration besides magnetic islands separated by small-scale current sheets. (a) the local wavelet power spectrum of the IMF strength; energetic ion flux spectrogram; the plasma beta; the cone and clock IMF angles; the IMF strength. (b) Hodogram showing the IMF vector rotation in RTN coordinates. Figure adapted from [13].

Indeed electrons and ions can be accelerated stochastically by magnetic reconnection processes in solar wind regions filled with magnetic islands or flux ropes, which always have small-scale current sheets separating them. Magnetic islands themselves are produced by magnetic reconnection at larger current sheets. Particle energization occurs as a result of several potential mechanisms, including via the so-called anti-reconnection electric fields that forms from the merging of magnetic plasmoids, and when trapped particles experience multiple reflections from the strongly curved field lines at the ends of elongated contacting islands. Stochastic mirroring and acceleration of charged particles via either a first-order Fermi mechanism (in the case of compressible contraction) or a second-order Fermi mechanism (if the contraction is incompressible) result in an accelerated particle population. Seed particles trapped inside magnetic islands may be pre-accelerated via any classical mechanism, for example, if there is particle pre-acceleration at shocks or due to magnetic reconnection. This allows particles to reach MeV energies locally in the solar wind at any heliocentric distance.

Turbulence and reconnection, and PVI method Usually, reconnection and turbulence have been studied as separate topics, but more recently it has been suggested that these effects may coexist [18, 19]. Magnetic reconnection of thin current sheets can be described with both magnetohydrodynamics (MHD) and plasma-kinetic models [20]. At the same time, it has been proposed that the process of magnetic reconnection can be very efficient when turbulence develops "inside" thin current sheets [9, 21]. At very high Reynolds number, it is expected that these narrow current layers become strongly unstable, generating micro-plasmoids and secondary islands in a self-similar way [22, 23].
To trace the abrupt spatial changes of the magnetic field in observations, simulations and experiments, numerous methods can be found in literature. Among them, the Partial Variance of Increments (PVI) method [24] is intended to be a simple, easily implemented methodology for finding likely candidates to be identified as coherent structures, and to thereby facilitate the study of the statistics intermittency, and its related effects in observations. The PVI method is sensitive to directional changes, magnitude changes, and any form of sharp gradient in the vector magnetic field **B**. The PVI quantity is not biased toward a particular type of discontinuity (directional, tangential, and rotational discontinuities and shocks) or other structures. PVI is very effective in selecting active current sheets in simulations, while in solar wind observations, very strong PVI events can be used to identify likely exhaust jets [26] and possibly reconnection zone crossings [27]. Very recently, Greco et al. (2016), by implementing a new variation of the PVI technique, investigated the coexistence of reconnection and turbulence in space plasmas, inspecting the turbulent solar wind from large to small scales. The obtained results yield a picture of "reconnection-in-turbulence", where large-scale energy containing structures reconnect producing layers at scales on the order of the proton skin depth. The turbulence and reconnection further develop inside the outflows of the above current sheets, at scales smaller than the proton skin depth. Observations are consistent with a scenario where many current layers develop in turbulence and where the outflow of these reconnection events is characterized by complex sub-proton networks of secondary islands, in a self-similar way [9, 28].

Simulations support The Team will make use of advanced numerical modeling. In particular, in order to understand the nature of the turbulent current sheets and the associated kinetic effects such as thermalization of the plasma and particle acceleration, the proposal will employ MHD, Hall MHD and Vlasov-based simulations of the turbulent solar wind. Fluid like models, combined with the use of test-particles, will be compared with kinetic simulations such as Hybrid Vlasov-Maxwell and full PIC simulations of turbulence. Statistical properties will be directly compared with solar wind findings, supporting new theoretical models and the main goals of the project.

1.1 Goals of the project

The ultimate goal is to understand the physics of heliospheric current sheets, where particles might be energized and accelerated. This is a *hot topic* of space physics today and will be directly tackled by our ISSI proposal. The project will analyze sets of current sheets identified by classical methods [29] and sets of high-PVI structures obtained in the same period, estimating the fraction of current sheets in the total number of coherent structures observed at different heliocentric distances, using therefore a huge survey of data. One limitation of current solar wind studies is that they are largely focused at 1 AU and we have comparatively little knowledge of basic physical processes with increasing heliocentric distance or changing latitude. We will systematically explore the link between dynamical current sheets and turbulence at different distances from the Sun (and latitudes), comparing datasets from different spacecraft with theoretical predictions. One important aspect will be to investigate the relation between particle acceleration and current sheets-related intermittency. Our project will directly address the evolution of current sheets, their stability and the related question of changing magnetic reconnection efficiency with distance from the Sun. Simulations will be also performed, varying the plasma parameters, the configuration and the geometries.

The main objectives can be summarized as follows:

- To study the evolution of intermittent turbulence with heliocentric distance and latitude, up to 5.4 AU;
- To investigate the HCS and the embedded micro-current sheets within the heliosphere;
- To analyze changes in magnetic reconnection regimes and the main ingredients of turbulent reconnection (such as the plasma beta) in the solar wind;
- To study energetic particle transport, initial and secondary charged particle acceleration related to current sheets and turbulent neighborhood throughout the heliosphere, with the support of numerical models;
- To examine different methods of identifying current sheets, and other signatures like jets, electric field patterns, electron heat flux and higher order moments of the particle distribution functions.

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1.2 Timeliness of the project

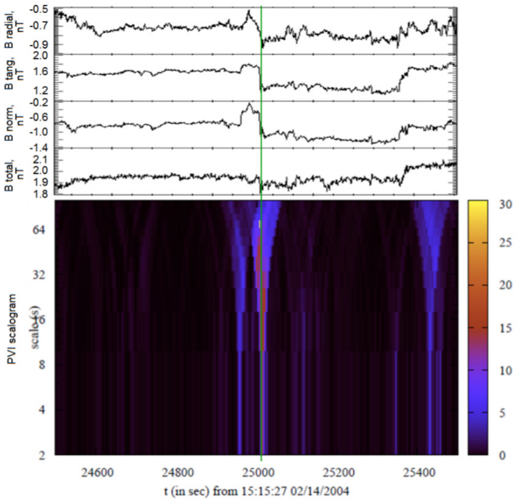
Turbulence, current sheets and magnetic reconnection emergence, and the subsequent particle acceleration mechanisms are today the most intriguing and spectacular phenomena in astrophysics. These topics are the motivating key-point of a number of spacecraft missions such as WIND, ACE, Cluster, MMS and so on. Current sheets, and their fragmentation effects related to turbulence, have not been studied in a self-consistent way, comparing also directly with observations. We expect a much broader impact of our project, potentially affecting not only research in the entire heliosphere, but also in solar physics, astrophysics, and laboratory plasmas.

Although dynamical current sheets are sometimes considered as objects closely related to turbulence, each process at/near them (for example, magnetic reconnection, magnetic island creation, particle acceleration etc.) is usually addressed separately. Inevitably, different researchers frequently arrive at different conclusions despite investigating essentially the same linked–coupled events. In this regards, the proposal is very timely because we have assembled a team that brings together a disparate set of perspectives and expertise to address the linkages that couple the multiple physical manifestations of dynamical current sheets and turbulence. Significant observational and theoretical progress has been made recently on specific aspects of the current sheet problem and it is now very timely to consider a synthesis . Not only will our study synthesize our current understanding but it will also clearly and systematically identify critical gaps in our knowledge. The Proposal involves scientists from Italy, Russia, United States and Greece. It comprises experts in observations, theory and modeling, it will therefore significantly advance our understanding of the dynamical evolution of turbulent processes, intermittent structures and associated particle acceleration throughout the solar wind. Many of us already have a record of joint projects and publications. The team meetings will further strengthen this cooperation.

2 Schedule of the project and Expected output

We will investigate in detail the properties of turbulent solar wind at different heliocentric distances and latitudes, analyzing multi-spacecraft data at various scales, from low frequency MHD to kinetic scales, comparing the results with existing and newly-developed models. In detail, we will address this challenge at different steps:

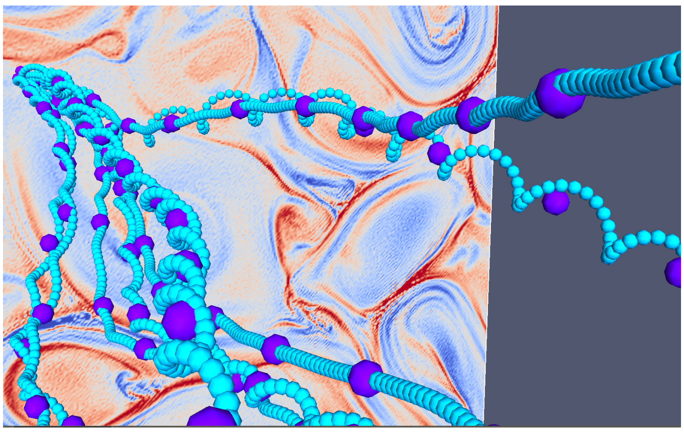
- Step 1
  Ulysses database preparation for selection of time intervals to allow comparison of PVI detected current sheets with those detected with classical methods. This will yield a first list of current sheets and PVI events. Ulysses spacecraft data analysis of turbulence properties at different heliocentric distances and heliographic latitudes. The possible correspondence of PVI events and parameters of current sheets will be explored.



A comparison of variations of the interplanetary magnetic field components (RTN coordinates, Ulysses measurements at 5.35 AU in the ecliptic plane) with a PVI scalogram. The vertical green line denotes a current sheet identified by the automatic current sheet detection method (Li, 2008). The current sheet position coincides with the strongest PVI event. At the same time, the PVI method reveals more intermittent structures, which altogether reflect a turbulent state of the solar wind.

- Step 2
  From a theoretical and observational analysis of properties of quasi-stable and reconnecting current sheets, we will estimate current sheet thickness and stability at different heliocentric distances and latitudes from Ulysses, ACE, Wind, Helios 1,2, STEREO A and B. This study will appear in our first paper.

- Step 3
  We will trace HCS-crossing associated energetic particle enhancements and magnetic islands using multi-spacecraft analysis, obtaining the morphology, properties, and character of atypical energetic particle events (AEPEs) and small-scale magnetic islands. An on-line illustrated catalog of traced structures will be developed. From theoretical studies of energetic particle enhancements determined by current sheet-associated intermittency, we will model the temporal/spatial evolution of intermittent structures and particle acceleration and apply to real solar wind observations.



Fast particles-dispersion process of particles in simulations of turbulent current sheets. The project will establish quantitatively the link between acceleration and reconnection phenomena.

- Step 4
  Comparison of theoretical and observational studies to address key properties of the solar wind plasma and energetic particles near current sheets at different heliocentric distances and latitudes. We expect to publish at least two papers from this material.

- Step 5
  Final report, summarizing the papers and databases.

Our deliverables will be:

- Scientific publications and reports, including conference proceedings and journal papers (at least 3);
- The project web-page with the description of tasks and deliverables;
- The list of current sheets and high-PVI events used in the analysis;
- The list of complex events of current sheet crossings characterized by increased turbulence levels and signatures of local particle acceleration.

We expect to hold two one-week meetings. The suggested date for the first meeting is in Fall 2017. The schedule for the second team meeting will be decided after the end of the first meeting.

3 Added value by ISSI for the implementation of the project

As discussed above, our goal is to synthesize studies of current sheets, turbulence and particle acceleration that are typically treated independently. The nature of the physical system clearly indicates that the three are manifestations of a single dissipative process. To enable such a synthesized perspective, we have assembled an internationally recognized team of experts in these different areas. The ISSI team structure is ideally suited to realize such a team. The format will promote in depth and extended face to face discussions which will strengthen international collaborations and enable inter-disciplinary research. An important project " success factor" will be the interactive interaction of theorist and observationalists , facilitating a "meaningful dialog".

4 Required facilities, Financial support

We require standard ISSI facilities: one meeting room with projector, Internet connection, a nearby printer, access to the library, and coffee/tea breaks.

We request the standard financial support package for international teams. This shall include the travel costs of the team leader, and hotel expenses and per diem for all team members for the two meetings. The hotel and per diem costs for a group of 3/4 young scientists per each meeting (to be identified once the proposal is selected) shall not exceed 20% of the financial means allotted to the team members.

5 List of Confirmed Team Members (more detailed descriptions can be found in the appended CV's and contact information)

Antonella Greco (ITALY)
Olga Khabarova (RUSSIA)
Roberto Bruno (ITALY)
Gang Li (USA)
Olga Malandraki (GREECE)
Helmi Malova (RUSSIA)
William H. Matthaeus (USA)
Oreste Pezzi (ITALY)
Sergio Servidio (ITALY)
Gary P. Zank (USA)