Interaction between magnetic reconnection and turbulence: From the Sun to the Earth

Proposal for an ISSI International Team

Application type:
ISSI-BJ

Research domain:
Space Plasma Physics (magnetic reconnection, turbulence); Solar Physics; Magnetospheric Physics

Abstract:

Magnetic reconnection is an important process in space plasmas, which converts magnetic energy to particle acceleration and heating through topological changes in magnetic fields. It is therefore believed to be responsible for explosive phenomena in space, especially solar flares and geomagnetic storms/substorms. Turbulence shaped by linear/nonlinear waves and coherent structures on magnetohydrodynamic (MHD) and kinetic scales (frequencies) is a fundamental component of space plasma. It is natural to consider the interaction between these two important aspects of space plasma. Recent studies have shown that magnetic reconnection can produce waves and coherent structures to form turbulence. On the other hand, turbulence can provide and enhance dissipation to allow and accelerate magnetic reconnection. In addition, in plasmas that are already turbulent, magnetic reconnection can play a major role in the dissipation of turbulent energy. Recently, new observations have opened up new windows into turbulence and reconnection occurring in different heliospheric plasma contexts, from the Earth's environment (THEMIS, ARTEMIS, MMS) to the solar wind and inner heliosphere (Parker Solar Probe, Solar Orbiter, Bepi Colombo). Thus, it is timely to establish an ISSI-BJ team with a balanced mix of theoretical, simulation, and observational expertise to study the interaction between magnetic reconnection and turbulence. The team will focus on four important space plasma regimes, the solar corona, the solar wind, Earth's magnetosheath, and Earth's magnetosphere. The team aims to answer the following questions: What waves and coherent structures are produced by magnetic reconnection to form turbulence? (2) What are the effects of turbulence on the process of magnetic reconnection? (3) What is the role of magnetic reconnection in dissipation of turbulent energy in turbulent plasmas? To answer these questions, the team will perform MHD, Hall MHD, hybrid, particle-in-cell simulations, which will be guided by and compared with in-situ and optical observations from the Sun to the Earth.

Scientific rationale:

Magnetic reconnection is ubiquitous in space plasmas, and turbulence is intrinsic in space plasmas, therefore, it is important to investigate not only magnetic reconnection and turbulence themselves but also the interaction between them. We put this investigation in the context of Sun-Earth space, therefore, we will mainly focus on three space plasma environments, the solar corona, the solar wind, and the Earth's magnetosphere.

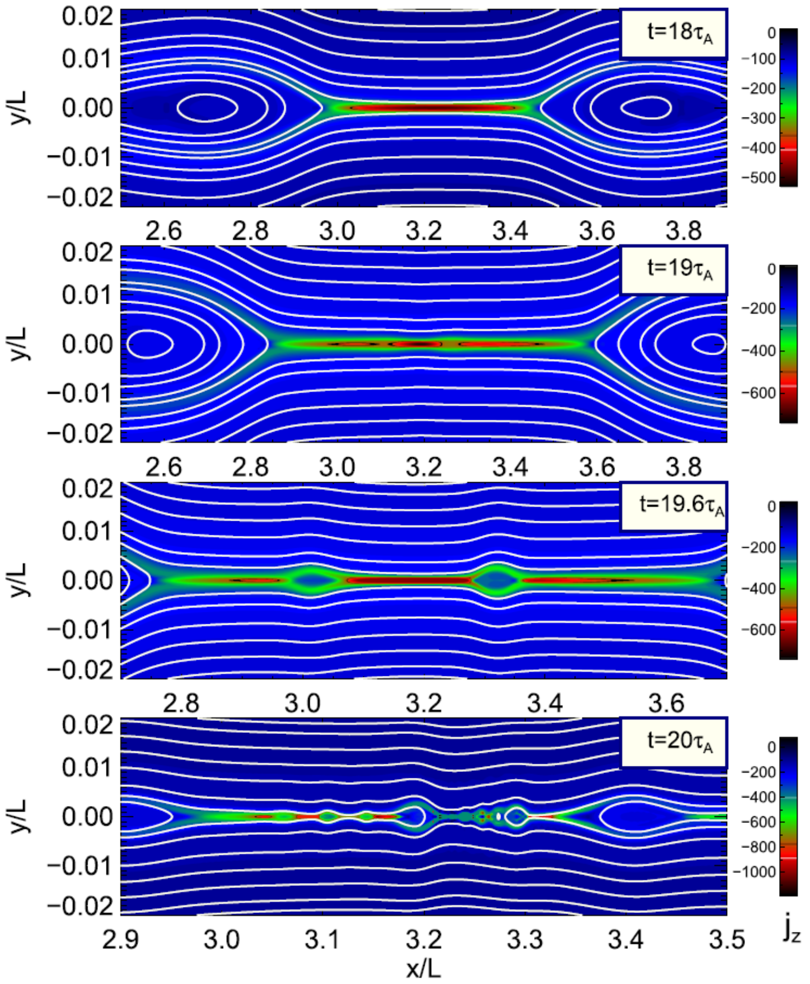

Figure 1. *Recursive formation of magnetic reconnection and magnetic islands on MHD to ever-smaller scales. After Tenerani et al. (2015).*

On MHD scales, it has been shown that the evolution of magnetic reconnection, at least in 2.5 dimensions, is recursive, giving rise to a hierarchy of magnetic reconnection and magnetic islands from larger to ever smaller scales, as shown in Figure 1 (Tenerani et al., 2015). This recursive formation of secondary magnetic reconnection and magnetic islands develops a turbulent regime in which the magnetic energy density shows a power law spectrum (Tenerani and Velli, 2020). Similarly, the formation of secondary reconnection and secondary islands have been found to exist in kinetic scales (Daughton et al., 2006; Drake et al., 2006; Lu et al., 2019a), which leads to a turbulent plasma environment (Daughton et al., 2011) with the magnetic energy density also showing a power law spectrum (Lu et al., 2019b). In-situ spacecraft in Earth's magnetotail have observed the formation of secondary islands in the reconnection diffusion region and the turbulent reconnection outflow (Wang et al., 2010; Lu, S. et al., 2020a), and magnetic islands have been found to constitute the turbulence in magnetic reconnection (Fu et al., 2017; Cheng et al., 2018). Other observations, however, show that magnetic reconnection-driven turbulence consists of magnetic holes (Ergun et al., 2020). Magnetic reconnection also forms reconnection ejecta (also referred to as reconnection fronts or dipolarization fronts) with plasma outflows and an increased normal magnetic field (e.g., Runov et al., 2015, 2018). Nevertheless, no matter the magnetic islands, the magnetic holes, or the reconnection eject, they all can trap particles and accelerate them in the turbulent reconnection. In addition to these coherent structures (e.g., magnetic islands, magnetic holes, reconnection ejecta), various waves, such as lower hybrid waves, electrostatic waves, whistler waves, and electron cyclotron harmonic waves, have also been observed in magnetic reconnection (e.g, Vaivads et al., 2004; Zhou et al., 2016; Cao et al., 2017; Li et al., 2020), which can also constitute the turbulence. In light of these findings, question (1) arises: **What waves and coherent structures are produced by magnetic reconnection to form**

turbulence? This question could have different answers at MHD and kinetic scales, and therefore, the answer could be different for the solar corona, the solar wind, and Earth's magnetosphere.

On the other hand, turbulence can also affect the process of magnetic reconnection. MHD theories have predicted that if the magnetic field is turbulent or stochastic, the rate of magnetic reconnection is increased dramatically (Lazarian and Vishniac, 1999). MHD simulations thereafter have verified that externally driven turbulence can indeed expedite magnetic reconnection (e.g., Loureiro et al., 2009; Yang et al., 2020). Similar to the externally driven turbulent reconnection, self-generated turbulent reconnection mediated by the formation of numerous magnetic islands (also referred to as plasmoids) has also been found to allow fast reconnection on MHD scales (e.g., Loureiro et al., 2007; Bhattacharjee et al., 2009; Pucci and Velli, 2014; Tenerani et al., 2015; Huang and Bhattacharjee, 2016). On kinetic scales, even without turbulence or plasmoids, collisionless magnetic reconnection can be fast by itself because of the Hall effect (e.g., Birn et al., 2001). Collisionless reconnection occurs because the magnetic field can be dissipated by particle kinetic effect, therefore, the reconnection electric field in Ohm's law is mostly balanced by the particle pressure tensor term (e.g., Pritchett et al., 2001; Lu et al., 2013). In spite of this, turbulence has also been suggested to play important roles in collisionless magnetic reconnection. Three-dimensional particle-in-cell simulations have shown that the development of strong turbulence makes significant contribution to the balance of Ohm's law, and therefore, the turbulence is strong enough to produce anomalous resistivity to allow occurrence of collisionless magnetic reconnection (Price et al., 2016). In collisionless reconnection, the formation of secondary islands can not only shape the turbulence in the reconnection region but also retain the fast reconnection, as suggested by Daughton et al. (2006). Moreover, as mentioned above, various kinetic-scale waves have been observed in magnetic reconnection. These waves do shape the turbulence in magnetic reconnection, but how they affect the process of magnetic reconnection is still unclear. For example, can these waves provide sufficient dissipation to trigger reconnection, and can they provide large enough anomalous resistivity to sustain the fast reconnection rate? So question (2) arises: **What are the effects of turbulence on the process of magnetic reconnection?**

In plasma environments that are already turbulent, magnetic reconnection can play a major role in the dissipation of turbulent energy from magnetic field to particles, as shown by both MHD (e.g., Servidio et al., 2009) and kinetic (e.g., Haggerty et al., 2017) simulations with prescribed, simplified configurations. The process of magnetic reconnection in turbulent plasmas has been show to occur self-consistently in global-scale kinetic simulations of Earth's magnetosheath (Karimabadi et al., 2014; Lu, Q. M. et al., 2020), as shown in Figure 3. In-situ spacecraft observations have confirmed the occurrence of magnetic reconnection in the turbulent plasma environment, such as the solar wind (e.g., Gosling et al., 2005; Phan et al., 2020), and Earth's magnetosheath (e.g., Retinò et al., 2007; Phan et al., 2018). In light of these studies, we would like to address question (3): **What is the role of magnetic reconnection in dissipation of turbulent energy in turbulent plasmas?** This question may also have different answers on different scales because magnetic reconnection in MHD and kinetic regimes are different (e.g., Birn et al., 2001; Pucci and Velli, 2014; Shi et al., 2019). Moreover, reconnection on the ion scales and electron scales are also different (Pyakurel et al., 2019; Lu, S. et al., 2020b). Therefore, this question needs to be investigated on different scales for different plasma environments separately.

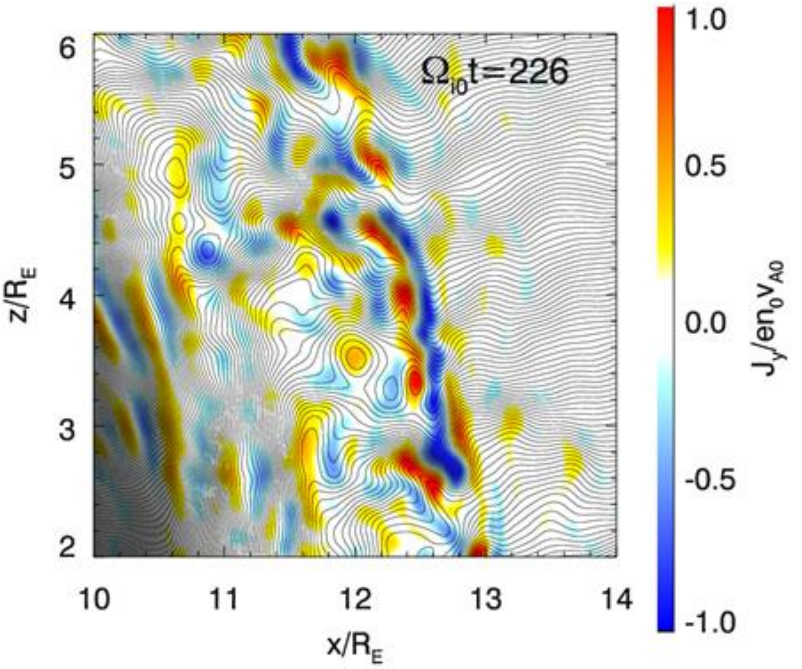

Figure 2. *Global hybrid simulation results zoomed into the magnetosheath region to show formation of magnetic reconnection and magnetic islands in the turbulent magnetosheath. Courtesy of Prof. Quanming Lu.*

To answer these three questions, we will analyze spacecraft observations of magnetic reconnection and turbulence in the solar corona, the solar wind, and Earth's magnetosheath and magnetosphere, including but not limited to spacecraft Parker Solar Probe, Solar Orbiter, Bepi Colombo, THEMIS, ARTEMIS, and MMS. We will perform two- and three-dimensional MHD, Hall-MHD, hybrid, and PIC simulations using various initial and boundary conditions that are representative in these plasma environments. The spacecraft observations and numerical simulations will be carried out synergistically. The simulation setup will be guided by the observational results; the simulation results will be used to help search for the observational events and interpret them; and the observational results will be used to prove (or disprove) the simulation results.

Added value:

The proposed ISSI-BJ International Team consists of experts in magnetic reconnection and turbulence. Team members will broaden their scope by discussions and collaborate work with other team members versed in different plasma environments as the discussion proceeds. Collaborative comparisons between data sets of different types, including imaging of densities and current sheets and in-situ electromagnetic field measurements, are much facilitated by the contemporary presence of the different experts, and the same is true for the analysis of simulations from the different plasma models. The three science questions will be addressed in the contexts of in the solar corona, solar wind, and Earth's magnetosheath and magnetosphere, hopefully leading to some degree of universality which shall add value to solar physics and magnetospheric physics. To answer these three questions, we will use plasma theories, simulations (MHD, Hall-MHD, hybrid, and PIC), and spacecraft observations, which shall add value to the advancement of research methods for space plasma physics.

Confirmed team members with one-page CVs appended:

1) **Artemyev, Anton** (University of California, Los Angeles, USA);
2) **Huang, Kai** (University of Science and Technology of China, China);
3) **Innocenti, Maria Elena** (Ruhr Universität Bochum, Germany);
4) **Lu, Quanming** (University of Science and Technology of China, China);
5) **Lu, San** (University of Science and Technology of China, China); he will sever as the leader of the International Team;
6) **Runov, Andrei** (University of California, Los Angeles, USA);
7) **Shi, Chen** (University of California, Los Angeles, USA);
8) **Tenerani, Anna** (The University of Texas at Austin, USA);
9) **Velli, Marco** (University of California, Los Angeles, USA);
10) **Yang, Zhongwei** (National Space Science Center, Chinese Academy of Sciences, China)
11) **Wang, Rongsheng** (University of Science and Technology of China, China);
12) **Zimovets, Ivan** (Space Science Institute, Russia).

All core team members have committed to their presence during the proposed periods of activity at the institute.

Schedule of the project:

We propose to hold two one-week-long meetings, each involving 12 team members and several students and young scientists. The first meeting will be in October 2021, and the second meeting will be held in September or October 2022. The exact dates of the meetings may be adjusted depending on specific circumstances and the progress in the resolution of the specific science questions identified in the proposal. Final report: January 1, 2023.

Expected outputs:

Although we have MHD, Hall-MHD, hybrid, and PIC simulation models, we shall develop them to accommodate to study the proposed science questions. We shall publish research articles based on the collaborations between team members on the three science questions, and we shall publish a comprehensive review paper at the end of the project. Another important output is that we shall develop a software or graphic user interface (GUI) to visualize the 3-D simulation results, which can well present slices, iso-surfaces, streamlines, field lines, etc. All simulation results (for the MHD, Hall-MHD, hybrid, and PIC simulations) share be prepared as data products in the format that is compatible for the software/GUI. We shall make the data products and the software/GUI publically available.

Facilities required:

Standard ISSI facilities (WiFi, projector, etc.) will be sufficient to hold our meetings. Telecon facilities will be required to allow participation of team members who are unable to travel.

Financial support requested from ISSI:

The standard financial support package for teams will be adequate for our project.

Affiliations, addresses, telephones and e-mails of all participants are appended.

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