GEM Focus Group Proposal

Physics of Plasma Boundaries

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1 Topic abstract

Plasma boundaries are, by definition, interfaces between regions with different plasma parameters. These boundaries generate a host of plasma wave and kinetic structures through instabilities powered by plasma inhomogeneities. They also serve to delineate distinct regimes of wave and particle dynamics. Magnetospheric plasma boundaries include the plasmapause, magnetopause, plume structures, plasma sheet boundaries, and dipolarization/injection fronts, all of which exhibit complex wave and particle dynamics. Recent advances in simulation capability as well as in space and laboratory instrumentation have opened the door to new aspects of plasma boundary physics and related nonlinear physics. Initial studies using these capabilities have found more questions than answers, making this topic ripe for focused scientific scrutiny. Further, the **universal nature of plasma boundaries** and their dynamics calls for this topic to be pursued promptly and with community enthusiasm.

2 Topic description

Recent advances in observational and simulation capability have revealed new aspects of plasma boundary physics. A coordinated effort among magnetosphere researchers (theoretical-, observational-, laboratory-, and simulation-focused) is required to gain a more complete understanding of how boundaries and their associated instabilities influence the macro-scale dynamics of the magnetosphere.

One recent advance has been the addition of the Magnetospheric MultiScale mission and the Van Allen Probes (and soon the ERG mission) to the Heliospheric observatory. These missions carry advanced instrumentation designed to regularly resolve kinetic-scale physics while producing high-quality context measurements of MHD-scale plasma process. These missions enable repeated crossings of magnetospheric plasma boundaries with unique multi-point perspectives. Therefore, these missions are uniquely suited to exploring the connections between macro- and micro-scale physics while resolving spatial/temporal ambiguities. The instrumentation, orbits, and multi-point nature of these missions allow researchers to establish quantitative observational definitions for plasma boundaries (e.g. the plasmapause, injection fronts) so that researchers can discuss similar features and phenomena with greater understanding.

A second recent advance has been the close link identified between macro-scale plasma boundaries the microphysics of kinetic-scale electric field structures and waves, including electron and ion phase space holes, electron and ion-acoustic double layers, nonlinearly steepened plasma waves, and kinetic Alfvén waves. These kinetic-scale structures and waves represent a whole class of plasma phenomena that may be significantly influencing magnetospheric plasma processes at meso- and macro-scales, **yet their production and impact on the magnetosphere has never been systematically quantified.**

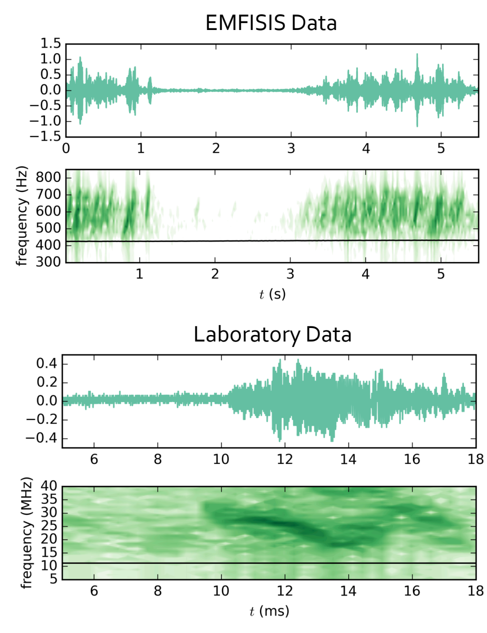

Figure 1: (Top) Bu component of Burst mode data taken from RBSP-B's EMFISIS instrument near a plasma boundary layer. Time series was recorded at 05:40:32.437892 UTC on 2012-11-14. (Bottom) Laboratory observation of Whistler Mode waves driven by plasma boundary layer. In both cases, electromagnetic waves are seen to be bursty with strong frequency chirping.

These structures and waves are found throughout the magnetosphere, including the plasmasheet boundary layer [e.g. *Matsumoto et al.*, 1994], polar cusp [e.g. *Franz et al.*, 1998], magnetosheath [e.g. *Cattell et al.*, 2002], auroral region [e.g. *Chaston et al.*, 2004], and inner magnetosphere [e.g. *Mozer et al.*, 2015]. Theoretical studies [*Johnson and Cheng*, 2001; *Artemyev et al.*, 2014] and observational event studies [*Ergun et al.*, 2001; *Chaston et al.*, 2014; *Mozer et al.*, 2014; *Agapitov et al.*, 2015a,b] have demonstrated **particle heating and acceleration in association with these structures and waves.**

A recent study by *Malaspina et al.*, 2015 systematically studied the connection between kinetic-scale structures and plasma boundaries (as defined by 5 - 30 keV electron flux gradients) in the inner magnetosphere (< 6.6 Re), finding that nearly all observed plasma boundaries had nearby kinetic-scale structures and that nearly all observed kinetic-scale structures occur near plasma boundaries.

> These studies demonstrate that kinetic-scale structures and waves are ubiquitous in the magnetosphere, capable of significant localized particle acceleration and heating, and are tightly linked with plasma boundaries.

Numerical self-consistent PIC simulations confirmed these results and provided additional information for kinetic-scale effects [*Drake et al.*, 2015]. This is indicative of the great potential of PIC simulations for studies of nonlinear wave-particles interactions.

A third recent advance is the ability to use laboratory plasmas to study boundary layer physics relevant to the magnetosphere. Recently, laboratory experiments of plasma boundary layers [*DuBois et al.*; 2013, *Tejero et al.*, 2011] have revealed that inhomogeneous plasma flows can lead to EMIC waves, lower-hybrid waves, and most recently whistler mode waves. Bursty, chirping whistler mode waves are produced coincident with the plasma boundary layer. The burstiness and frequency chirping clearly indicate nonlinear behavior. The modes are also nonlocal due to the fact that they are driven by a sharp plasma inhomogeneity. The nonlinear and nonlocal nature of these waves put the problem at the forefront of theoretical plasma physics where progress here could be relevant for many other plasmas including tokamak plasmas and astrophysical plasmas.

Laboratory experiments demonstrate how the essential physics of a space plasma phenomenon can be studied in detail under controlled conditions. They offer the ability to perform repeatable controlled experiments on the underlying plasma physics mechanisms that can lead to deeper understanding, more robust physics models, and more reliable space weather predictions.

3 Timeliness of focus group

This topic is ideally timed to utilize the ongoing high-quality measurements from the Van Allen Probes as they enter the extended mission phase, as well as the cutting edge observations from the Magnetospheric MultiScale mission and the upcoming ERG mission. These spacecraft, along with the additional missions in the Heliospheric observatory, are well positioned to address this topic as they fly through plasma boundaries repeatedly with the ability to observe both macro- and micro-scale physics.

Additionally, the topic is garnering attention in the community as structures and waves such as 'time domain structures' have recently been shown to be ubiquitous at plasma boundaries [*Malaspina et al.*, 2015]. In fact, recent studies of these wave structures have linked them to auroral particle precipitation [*Mozer et al.*, 2015]. And a first-light look at MMS data of magnetopause crossings shows that intense whistler-mode waves are generated in the vicinity of reconnection sites [*personal communication, R. Wilder*]. There is an urgent driving need for a contextual basis to be formed, within which these observations of boundary physics can be connected.

4 Goals & deliverables

This FG will strive to bring closure on the following science objectives throughout its tenure:

(1) Develop community-wide observational definitions for plasma boundaries.

(2) Quantify the spatial structure of plasma properties across the boundary and temporal dynamics of plasma boundaries in the magnetosphere.

(3) Predict and model waves and kinetic structures near boundaries based on local plasma and boundary properties.

(4) Quantify the significance of boundary dynamics and boundary-generated waves for particle acceleration and loss throughout the magnetosphere.

The pursuit of these goals will result in the following deliverables:

THEORY Within current theoretical framework, predict boundary structure and dynamics. Predict wave modes from boundary instabilities. Compare theory to simulation, laboratory studies, and observations to identify if any significant pieces of physics are missing.

SIMULATION Develop self-consistent simulation models to study the quasi-static spatial extent and then to study the slow-scale temporal dynamics of plasma boundaries; encourage modelers to use this information in existing plasma simulations. Aim to grow waves at simulated boundaries and look at the resulting effects on particle distributions. Compare the overall statistics of waves and particle effects to theory and observations.

LABORATORY Utilize laboratory plasmas to conduct controlled plasma boundary experiments relevant to magnetospheric physics. Likewise, use observation to provide a guide to experimental physics groups that are performing laboratory experiments of wave generation at plasma boundaries. Grow waves to compare to in-situ observations, and investigate the differences.

OBSERVATION Establish observational definitions for plasma boundaries to disseminate throughout the community such that researchers can discuss similar features and phenomena with greater understanding. Identify wave modes and kinetic structures localized to boundaries from observations using the Helisopheric observatory at our disposal. Determine the spatial extent and temporal dynamics of plasma boundaries from an observational perspective, and examine the connections to simulations and theory with both event-specific and statistical studies.

5 Relevance to existing Focus Groups

Tail-inner magnetosphere interactions (TIMI), 2012-2016: Dipolarization fronts and bursty bulk flows are common occurrences in the tail region. MMS will be in a prime position to observe these features, and likewise Van Allen Probes and THEMIS see particle injections frequently. The boundary physics FG will connect the large- and small-scale physics of these dynamic plasma boundaries, and may help to explain the particle energization that occurs at these sites.

Transient Phenomena at the Magnetopause and Bow Shock and Their Ground Signatures, 2012-2016: The magnetopause offers an incredible opportunity to systematically study boundary wave generation and particle effects. Our FG may shed light on this group's topics of transient phenomena such as ion foreshock observations and additional effects of FTE's.

Magnetic Reconnection in the Magnetosphere, 2013-2017: While the plasma boundary FG will not focus on magnetic reconnection, it can be a consequence of certain boundaries and many of the boundary effects described in this proposal are observed in the vicinity of reconnection. Additionally, dipolarization front boundaries are known to be a result of tail reconnection. Understanding the relationship between our topic and reconnection is important to both FGs.

Inner Magnetosphere Cross-Energy/Population Interactions (IMCEPI), 2014-2018: Many plasma boundaries exist in the inner magnetosphere that strongly delineate particle populations and dynamics across energies, such as plasmaspheric plumes and the plasmapause. Studing these boundaries can bring insight to particle population dynamics that we observe deep in the magnetosphere.

Quantitative Assessment of Radiation Belt Modeling, 2014-2018: There have recently been some links made between radiation belt dynamics and kinetic wave structures occurring at plasma boundaries. There is much to explore in the overlap between this FG and our proposed one.

6 Focus Group details and expected session topics

The term of effort will be 4 years, and will be associated with the Inner Magnetosphere Research Area.

We expect session topics to be organized around the four main deliverable categories described above: theory, simulation, laboratory and observation. We will work creatively to get researchers from all groups to discuss similar features and work together on notable challenge events. These challenge events may be particular times of wave observation at plasma boundaries, or they may instead be grouped simply by plasma boundary definition. Our mission is to craft the sessions such that theorists and observationalists alike can work collaboratively: from plasmapause studies to magnetopause studies, and the myriad other boundaries where such similar physics applies.

7 Co-Chairs

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  Expertise: particle dynamics & observation; MMS & Van Allen Probes
- Dr. David Malaspina, LASP - University of Colorado Boulder
  Expertise: wave dynamics & observation; MMS, Van Allen Probes, STEREO, Wind, Solar Probe Plus
- Dr. Chris Crabtree, U.S. Naval Research Laboratory
  Expertise: Theoretical plasma physics
- Dr. Oleksiy Agapitov, University of California, Berkeley
  Expertise: wave-particle interactions: NL and QL; test particles and PIC simulations; Van Allen Probes, THEMIS, MMS

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