White Paper for *Frontiers of Plasma Science Panel*

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Title:	**Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection through Collaborative Research on Reconnection Layer**
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1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

1. Magnetic Reconnection for Collaborative Research with Space Observations

Magnetic reconnection – the breaking of magnetic field lines resulting in a global topological change – is one of the most important processes in magnetized plasmas. Despite its prevalence and importance, the inherent complexity and non-linearity of the magnetic reconnection process has greatly inhibited our understanding of reconnection despite over half a century of study [Zweibel and Yamada 2009, Yamada *et al.* 2010]. In order to unravel the key physics underlying the reconnection process, laboratory plasma physicists, computational and theoretical physicists, and space and astrophysicists have greatly increased cross-discipline collaboration over the past couple of decades. This close collaboration has proven to be extremely effective and is reflected both in the dramatic increase of literature published on magnetic reconnection [e.g. Phan *et al.* 2007, Chen *et al.* 2008, Drake *et al.* 2009, Daughton *et al.* 2011, Yoo and Yamada 2012, Roytershteyn *et al.* 2012, Chen *et al.* 2012, Phan *et al.* 2014], as well as through the increased number of interdisciplinary conferences and meetings such as American Geophysical Union special sessions, American Physical Society symposia, and the IPELS (Inter-relationship between Plasma Experiments in the Laboratory and Space) series of conferences.

Along with this increase in cross-collaboration, modern technologies have greatly increased the diagnostic capabilities of both laboratory experiments and space satellites. Similarly, the rapid advancement of computational power available to researchers has allowed computational physicists to closely model both lab and space plasmas. Now the reconnection research has reached a point where it is

possible to directly and quantitatively compare the measured profiles of various plasma and reconnection parameters across laboratory experiments, space observations, and simulations. This progress has resulted both in remarkable agreement on some processes (e.g. the recently published energy partitioning studies performed both in the Magnetotail [Eastwood *et al.* 2013] and in laboratory experiments and simulations [Yamada *et al.* 2014]) and glaring discrepancies on others (e.g. the structure of the electron diffusion region as measured in experiments [Ren *et al.* 2008, Ji *et al.* 2008, Dorfman *et al.* 2008], and as predicted by simulations [Roytershteyn *et al.* 2010]). Both of these cases, agreement and discrepancy have proven to be important in advancing and guiding reconnection research, yet were only made possible by close cross-discipline collaboration. Therefore, in order to further advance the field of reconnection research, the scope of this collaboration should be greatly increased. Important issues are the structure of the electron current layer and what breaks the frozen-in condition during reconnection. Asymmetric reconnection is now a major focus at the magnetopause. In the remainder of this whitepaper, several new and forthcoming opportunities for high importance and high impact cross-discipline research will be outlined.

2. Major Scientific Challenges and Opportunities:

Despite significant progress in the past decades, there exist a number of outstanding major scientific challenges and opportunities for a better understanding of reconnection phenomena in space, astrophysical and laboratory plasmas.

Discipline / Measurement	**Laboratory**	**Simulation**	**Space**
Field	✓	✓	✓
Particle Distribution	Limited (to n_e, T_e, and T_i)	✓	✓
Location of X line	✓	✓	Difficult to Determine
Controlled Studies	✓	✓	Uncontrolled
Realistic Parameters	✓	Limited parameter regimes in 3D (m_i/m_e, $\omega_{pe}/\omega_{ce}<5$)	✓

Table 1 Relative strength and limitation of laboratory, simulation, and space measurements.

Table 1 summarizes the advantages and disadvantages of laboratory, simulation, and space reconnection studies in terms of the available information and controllability. In principle, each research environment can provide all the information needed to study the detailed physics of the electron diffusion region during reconnection, but is generally limited by practical considerations. In real laboratory plasma conditions exist in a controllable environment, but information on particle distributions is limited. Kinetic simulations can provide highly detailed information at all spatial locations simultaneously, but are limited in terms of realistic parameters such as the spatial sizes or ion to electron mass ratio, especially in three dimensions. Space data provides *in situ* measurements including detailed particle information, but it is generally difficult to determine the relative location of the X-line and to study magnetic reconnection in a controllable way. The strategy proposed here is to use the strengths of one venue to supplement the weaknesses of the others in order to achieve a better understanding of the crucial physics governing dynamics in the reconnection layer.

Major scientific challenges include 1) identifying the structure of the electron and ion diffusion region, 2) what breaks the magnetic field lines in the electron diffusion region, 3) what is the role of electrostatic and electromagnetic fluctuations in the reconnection process, and 4) how electrons and ions are energized in the diffusion region, and how the partitioning of energy flows is.

Space measurements: These themes of collaborative research are timely due to the existence of the major space mission, MMS (Magnetospheric Multiscale). MMS was launched recently to study the kinetic structure and the particle (particularly electron) dynamics of magnetic reconnection layers in the earth magnetosphere. The MMS mission is the first space mission to be able to make measurements at spatial scales extending down to the electron skin depth, $d_e = c/\omega_{pe}$. The measurements of particle distribution function at a 30 ms cadence will be valuable for understanding electron kinetic effects during reconnection, since this fine temporal and spatial resolution is very difficult to achieve in laboratory. In addition to MMS, there is also extensive database from other multi-spacecraft missions such as THEMIS and CLUSTER, which will be useful to complement MMS measurements to provide reconnection observations in the magnetosphere. A strong advantage of space satellite observations is that they can provide detailed data on particle distribution for three directions. With their energy analyzers already providing very useful information, the laboratory research would enormously benefit from it.

Laboratory experiments can provide systematic measurements of the reconnection structures to validate theories and simulations as well as to have an important impact on interpreting space satellite measurements and analysis. Laboratory experiments can measure the macro- and microscopic spatial structures of the reconnection layer, as well as both electrostatic and electromagnetic fluctuations. Laboratory experiments can also investigate the fine scale structure of symmetric and asymmetric reconnection layer as well as the electron and ion dynamics as a function of the externally applied guide field and the density asymmetry across the current sheet due to the versatility of the experiments. By comparing signatures of the electron and ion diffusion regions from laboratory experiments with data from spacecraft, the relative location of spacecraft can be decided, which contributes to the success of the space mission. The ability of laboratory experiments to simulate spacecraft crossings of the reconnection layer has been reported [Yoo and Yamada 2012].

Numerical simulations are also an essential part of this collaborative research by providing data sets with different boundary conditions, plasma parameters, and system sizes. Despite significant similarities, several careful checks should be made in the comparison between space and laboratory data. In particular, laboratory plasmas can have finite collisionality as compared to the extremely collisionless regime of the magnetosphere, and the boundary conditions of the laboratory experiment might contribute to some details of the reconnection process. To properly address these possible discrepancies, as well as the obvious issues associated with scaling laboratory results to astrophysical scales and vice-versa, simulation is a necessary component to the success of our study. Numerical simulations are also useful to study microphysics related to electron and ion kinetic effects due to the fine resolution of data.

3. Summary:

Magnetic reconnection is at the heart of the physics governing our space environment and is one of the most fundamental processes in magnetized plasmas. Collaborate research to study fine-scale structures of the diffusion region is a key to understanding this important fundamental process by compensating shortcomings of each research discipline. Through this collaborative research, exciting new physics behind the electron and ion diffusion region should be revealed.

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