White Paper for *Frontiers of Plasma Science Panel*

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Title:	The next magnetic reconnection frontier: realistic, first-principles kinetic simulations or reconnection in large 3D systems with and without radiation.
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1 page of references and 1 page of figures may also be included. *Submit in PDF format.*)**

• ***Computational magnetic reconnection frontier: achievements and challenges.***

Magnetic reconnection is a fundamental plasma physics process of magnetic field rearrangement and relaxation; its primary outcome is rapid conversion of magnetic energy into thermal and nonthermal particle energy (Zweibel & Yamada 2009; Yamada et al. 2010). This energy conversion is established as the main mechanism behind many explosive phenomena in space and laboratory plasmas, e.g., Earth magnetospheric substorms, solar flares, and tokamak sawtooth disruptions. Moreover, in recent years reconnection has been increasingly recognized as an important mechanism for powering high-energy (X-ray and gamma-ray) flaring emission in many astrophysical objects, like Gamma Ray Bursts (GRBs); accretion disks, their coronae, hot accretion flows, and relativistic jets from accreting black holes (BHs) in Active Galactic Nuclei (AGN), including blazars, and galactic X-ray Binary (XRB) systems; pulsar magnetospheres and pulsar wind nebulae (PWNe); and magnetar flares in Soft-Gamma Repeaters.

This broad recognition of the importance of reconnection in governing energy release in magnetized plasmas has led to a significant intense research effort over the past decades aimed at understanding it. Advanced ***numerical simulations*** constitute a very important component of this effort, along with dedicated laboratory experiments, in-situ spacecraft measurements in the Earth magnetosphere, solar flare observations, and analytical theory (see Hantao Ji's white paper). Modern simulation studies employ a variety of plasma-physical frameworks, ranging from kinetic particle-in-cell (PIC) simulations, to various hybrid and two-fluid models, to single-fluid resistive MHD. These studies are rapidly improving over

time as more advanced numerical algorithms and more powerful computers are becoming available and, as a result, our understanding of reconnection has improved dramatically in recent years.

However, the present state-of-the-art simulations of reconnection still fall somewhat short of being realistic, for the following reasons. Firstly, as has become clear in recent years [Loureiro et al. 2007, 2012, Daughton et al. 2009, Bhattacharjee et al. 2009, Samtaney et al. 2009, Huang & Bhattacharjee 2010], reconnection processes behave qualitatively differently in modest-size systems and large systems. This is because thin and long, high-aspect-ratio current layers in large systems become unstable to secondary instabilities (e.g., the secondary tearing, or plasmoid, instability) and get quickly disrupted. As a result, classical laminar, quasi-stationary reconnection, seen in smaller systems, is replaced in large systems with a new, highly-dynamic reconnection regime exhibiting complex hierarchy of multiple interacting secondary structures of different sizes, such as plasmoids and flux ropes [Shibata & Tanuma 2001, Uzdensky et al. 2010]. It is important to note that all of space and astrophysical reconnecting systems, and most of tokamak plasmas are indeed in this ***large-system plasmoid-dominated regime***.

Secondly, while there have been some pioneering simulations of reconnection in ***three dimensions (3D)***, most of them were rather limited in their system size and thus inapplicable to realistic systems; the great majority of reconnection studies so far have been done in two dimensions (2D). The real world is of course 3D and with 2D studies we can never be sure that what they teach us is relevant to real Nature. The large-system plasmoid-dominated reconnection regime becomes even more complex and turbulent-like in 3D, characterized by complex interaction of 3D flux ropes and activation of yet another set of instabilities (e.g., the kink). In fact, recent theoretical work [e.g., Boozer 2012] and existing 3D simulations [Daughton et al. 2011] present a very compelling case for dramatic differences in 2D and 3D.

Finally, reconnection in many real astrophysical systems should take place in a radiative regime where effects like radiative cooling or radiation pressure play an important and, sometimes, even dominant role. ***Radiative magnetic reconnection*** represents a newly emerging frontier in plasma astrophysics and is only now beginning to be investigated systematically [Jaroschek & Hoshino 2009, Cerutti et al. 2013, 2014].

- ***Next ten years: developing reliable predictive simulation capabilities to study realistic 3D magnetic reconnection in space/astrophysically-relevant large-system regime.***

Right now, we are on the verge of being able to ***completely solve the magnetic reconnection problem in 2D****, to get a deep, comprehensive understanding of it, and in the next decade we should be able to say the same about 3D!* Present computational capabilities allow us to reach comfortably systems sizes that are sufficiently large to ensure that we are in the asymptotic large-system regime, and even with reasonably large, approaching realistic, ion-to-electron mass ratio, but only in 2D. This means that gaining a complete and thorough understanding of 2D reconnection over a broad range of parameters, including the questions of energy partitioning, nonthermal particle acceleration, transition to plasmoid turbulence, etc., is now finally within our grasp and should be accomplished in just the next few years.

However, as argued above, one can never be fully satisfied with the toy-model 2D picture, and one eventually has ***to move to realistic full-3D studies***. The good news is that with the expected continuing rise in the computing power over the next 10 years or so, roughly by two orders of magnitude, not only modest-size 3D simulations [like those done today, e.g, Daughton et al. 2011, Cerutti et al. 2014, Sironi & Spitkovsky 2014, Guo et al. 2014], but also asymptotically large 3D simulations will become accessible. This means that, in about 10 years, our numerical studies of reconnection (and, hopefully, other plasma processes of similar or lesser complexity, e.g., shocks) will transition from being academic, basic-physics pursuits, aimed at just obtaining physical insight, to finally becoming realistic "engineering" models characterized by high degree of realism and a ***real, quantitative predictive power***. Through several well-designed simulation campaigns, we should be able to map out the dependence of key reconnection output parameters (e.g., reconnection rate, energy partitioning between species, main parameters of accelerated

particle distribution) as functions of a few input system parameters. This, in turn, will transform such simulations into useable tools of, e.g., astrophysical modeling that will establish strong, reliable links between observations and theory. This will also yield a full understanding of the role of reconnection in magnetic fusion devices and will thus help advance this important DoE mission.

However, progress does not just come by itself. While the prospects of achieving the above goals in the next decade are quite realistic, making it a reality will require a concerted, unrelenting effort by the research community and ***committed unwavering support from the DoE*** and other funding agencies.

First, one will of course need to invest continuously in ***growth and improvement of computing infrastructure***. While necessary, this, however, is not sufficient for accomplishing the ambitious goals set out in this paper. With the increasing degree of realism obtained in studies of plasmoid-dominated reconnection in large 3D systems, the ***expected level of physical complexity will rise*** dramatically. This means that new scientific questions will be asked and the notion of what we call a "comprehensive understanding of reconnection" will evolve. (For example, even defining reconnection rate properly is a nontrivial issue in 3D!) New, more sophisticated numerical diagnostics tools and data analysis methods will be called for. For example, characterizing the chaotic, turbulent reconnection in large 3D systems will probably require developing statistical methods for analyzing simulation results, extending the 2D studies of statistical probability distributions of the emerging secondary structures like plasmoids [e.g., Uzdensky et al. 2010, Fermo et al. 2010, Loureiro et al. 2012, Huang et al. 2013]. In addition, whereas most studies of particle acceleration in reconnection have analyzed only the total particle energy spectra, integrated over the entire system and over all directions, future analyses, motivated by astrophysical and space applications, will have to be more detailed, e.g., looking into the angular distribution of accelerated particles [Cerutti et al. 2012] and their spatial inhomogeneity. All this means that an increasingly greater effort, especially human intellectual effort, will need to be devoted to diagnostics and analysis of the simulations. In other words, as our simulations become more realistic and more complex, we will be spending more time thinking about what the results mean and how they can help us understand space and astrophysical phenomena.

One of such new diagnostic tools of utmost importance to astrophysics, which is being developed now will be developed in the next few years, is the capability to including radiation effects and to compute ***observable radiative signatures of reconnection*** --- time-resolved orientation-dependent photon spectra, energy- and direction-dependent light curves, images, movies, etc. This capability is extremely important because it will enable one to study reconnection in physical regimes that are actually expected in astrophysical environments and also will enable one, at last, to relate the results of such simulations to the actual astronomical observations.

- ***Summary of the impact of the computational magnetic reconnection research on plasma science.***

The research outlined in this paper will qualitatively change our view of magnetic reconnection --- one of the most important basic plasma phenomena, ubiquitous in nature --- from it being seen as an enigmatic phenomenon that is perhaps too challenging and complex to comprehend with any reasonable degree of confidence, to a process that is essentially completely, quantitatively understood with high degree of confidence and a real predictive power. It will no longer be an unpredictable, anything-goes tooth fairy, and will instead become a trusted and reliable friend. This will have a huge effect on magnetic fusion, space physics, and, in combination with the development of radiative signatures capability, astrophysics, because we will be able to reliably establish, by reverse-engineering this process, the ambient plasma parameters of the reconnecting systems, that are only accessible via remote telescopic observations of the light emitted by the reconnection region. Thus, reconnection, instead of being part of the problem will become part of the solution – it will be a (reliable!) measurement tool that should find broad application in astrophysics. But, importantly, for this rosy picture to become a reality, we need strong and constant support from DoE and other agencies.

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