**White Paper for *Frontiers of Plasma Science Panel***

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| Oral | X |
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| Title: | **Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena in Self-Organizing Plasmas** |
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**(Limit text to 3-pages including this form. Font Times Roman size 11.**
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## I. Magnetic Reconnection as a Fundamental Plasma Process

Magnetic reconnection - the topological rearrangement of magnetic field - underlies many explosive plasma phenomena over a wide range of scales in the universe and in laboratory fusion plasmas [1-3]. It plays pivotal roles in electron and ion heating, non-thermal particle acceleration to high energies, transport phenomena, and plasma morphology during magnetic and flow self-organization. **In heliophysics**, magnetic reconnection plays key roles in a wide range of phenomena from solar flares, coronal mass ejections, coronal heating, solar wind dissipation, interaction of interplanetary plasma with Earth and other planets' magnetospheres, dynamics of planetary magnetopheres such as magnetic substorms, and the heliospheric boundary with the interstellar medium. Magnetic reconnection is an integrated part of dynamo processes in generating and maintaining magnetic field in the sun and in planetary cores. **In astrophysics**, the importance of magnetic reconnection has been recognized during star formation out of molecular clouds, stellar flares, explosive phenomena from magnetars and pulsars, and cosmic ray acceleration. Magnetic reconnection is considered to occur in both coronae and interiors of magnetized accretion disks in proto-stellar systems and X-ray binaries, as well as in interstellar media

turbulence. Reconnection is also considered to be responsible for flares from Crab Nebula. Outside of the Milky Way, magnetic reconnection plays key roles in accretion disks in Active Galactic Nuclei around supermassive black holes where rapid accretion and hot coronae are observed. On even larger scales, magnetic reconnection may be important in extragalactic radio jets and lobes as they propagate and relax, and even in galaxy clusters. **In laboratory fusion plasmas**, magnetic reconnection occurs during sawtooth oscillations in tokamaks, (neoclassical) tearing mode growth, disruptive activity such as disruptions and possibly edge-localized modes, startup of Spherical Torus plasmas using Coaxial Helicity Injection, relaxation in Reversed Field Pinches and spheromaks, formation of Field Reversed Configurations by theta pinch or plasma merging. Magnetic reconnection may even play a role in inertial fusion plasmas which use magnetic field like in Z pinches or laser plasmas under externally imposed field. Thus, understanding reconnection is of fundamental importance for plasma physics and its contributions to our understanding of the universe and to the success of fusion energy.

## II. Major Scientific Challenges in Understanding Reconnection and Related Explosive Phenomena

Despite significant progress in the past decades, there exist a number of outstanding major scientific challenges to be addressed for a better understanding of reconnection phenomena within heliophysical, astrophysical and laboratory fusion plasmas:

**1. The multiple scale problem** [e.g. 3-7]: Reconnection involves coupling between the large MHD scale of the system size and the many orders of magnitude smaller dissipation scales such as ion and electron kinetic scales. Recent results suggest that plasmoid dynamics may couple these multiple scales efficiently as shown in "the phase diagram" in Fig. 1 where each phase represents a unique coupling mechanism of global MHD scale to local dissipation scales. Key questions include how the number of plasmoids (X-lines) scales with plasma size and Lundquist number, and how this scaling is influenced by a guide field.

**2. Reconnection rate** [e.g. 8-12]: Although two-fluid effects and kinetic physics have been shown to facilitate fast reconnection, the associated efficient dissipation, such as micro-turbulence, within the electron diffusion region is still elusive. How do these effects on local scales facilitate fast reconnection on the global MHD scales remains as an unanswered question.

**3. Partial ionization** [e.g. 13-16]: Important reconnection events often occur in weakly ionized plasmas, such as the solar chromosphere, whose heating requirements dwarf those of the corona. This introduces new physics associated with the neutral particles. Questions include whether increased friction slows reconnection or the enhanced two-fluid effect accelerates reconnection.

**4. The 3D Problem** [e.g. 17-21]: Numerous studies have focused on reconnection in 2D while natural plasmas are 3D. It is critical to understand which features of 2D systems carry over to 3D and which are fundamentally altered. New effects include instabilities due to variations in the third direction including those also in geometry, leading to the transition of "plasmoids" to complex, interacting "flux ropes", and the onset of magnetic stochasticity or turbulence, in addition to the effects due to exponentiation of field line separation in 3D. How fast reconnection is related to the self-organization phenomena such as Taylor relaxation as well as accumulation and conservation of magnetic helicity is a longstanding problem.

**5. Boundary condition** [e.g. 22-25]: It is not self-evident that reconnection physics in periodic systems can be straightforwardly applied to natural plasmas which are always non-periodic, and often line-tied at their ends as in solar flares. Whether the line-tied effects fundamentally alter the reconnection physics has profound importance in connecting laboratory to astrophysics.

**6. Onset** [e.g. 26-28]: Reconnection in natural and laboratory fusion plasmas often occur impulsively, with a rapid onset. Is the onset a local or global process, and is it a 2D or 3D phenomenon? It is unclear under what conditions the observed spontaneous reconnection takes place or whether these conditions are universal. Prior to onset, how magnetic energy is accumulated and stored is another important question.

**7. Energy conversion** [e.g. 29-36]: Reconnection is invoked to explain the observed conversion of energy to heat or to populations of non-thermal particles. To directly connect to observations, understanding the energy conversion process from magnetic field remains a major challenge.

**8. Flow-driven** [e.g. 37,38]: Reconnection has been considered to play important roles in flow-driven systems such as in stellar dynamo and accretion disks to saturate magnetic field and its associated turbulence. In return, reconnection can directly transport momentum or occur in a preexisting turbulence.

**9. Extreme condition** [e.g. 39]: Near compact objects, other extreme effects such as radiation and relativity can be important in determine reconnection process.

**III. Major Research Opportunities in Meeting Scientific Challenges**

Table below summarizes the capabilities to address the major reconnection questions by each approach: theory/simulation, observations (in situ and remote sensing), laboratory experiments (magnetized basic, magnetic fusion, and high energy density experiments). Green indicates the required capabilities are already in place or can be available by adequate investments from the corresponding funding agencies; yellow indicates difficult or impossible to achieve in the near future.

| Questions | Theory & Simulation | Observations | | Laboratory Experiments | | |
|---|---|---|---|---|---|---|
| | | *in situ* | Remote-sensing | Magnetized Basic | Magnetic Fusion | High Energy Density |
| Multi-Scale | | | | | | |
| Rate | | | | | | |
| Partial Ionization | | | | | | |
| 3D | | | | | | |
| Boundary | | | | | | |
| Onset | | | | | | |
| Energy | | | | | | |
| Flow-driven | | | | | | |
| Extreme | | | | | | |

**1. Theory and numerical simulation**. All major questions can be studied by theory and simulations using fluid, kinetic and hybrid models, and multi-fluid models that include kinetic effects through physics-based closure equations. Petascale computing resources have enabled modeling of 2D reconnection processes with realistic plasma parameters and system geometries. The exascale era promises to enable significantly more realism in 3D reconnection studies.

**2. Observations**. The newly launched Magnetospheric Multi-Scale mission and the scheduled Solar Probe Plus mission will provide unprecedented *in situ* measurements of magnetic reconnection and its related phenomena, such as coronal heating. The state-of-the-art remote sensing satellites such as Solar Dynamics Observatory and Fermi satellite continue to surprise us with new observations of explosive phenomena. These observations are intrinsically either local *in situ* or global morphological, but not simultaneously both, so that the problems such as multi-scale coupling are difficult to attack. Nonetheless, observations provide the ground truth of magnetic reconnection and its related phenomena in nature.

**3. Laboratory experiments**. With diversity in geometries and parameter regimes, experiments will continue to address some of the forefront questions in reconnection physics. The dedicated magnetized basic experiments are most mature, and their next generation facilities are poised to provide accessibilities in new reconnection phases with direct relevance to heliophysics and astrophysics. Magnetic fusion experiments provide accesses to collisionless reconnection in periodic geometries. High energy density plasmas by laser or Z pinch are emerging as a new platform, which can be used to uniquely attack a subset of the major reconnection problems. All of these experiments require adequate diagnostics and modeling in order to effectively contribute to solving reconnection problems.

In summary, magnetic reconnection is a fundamental process throughout the universe and laboratory fusion plasmas. Major research opportunities are identified in theory/simulations, observations, and laboratory experiments, to meet major scientific challenges. Using these approaches synergistically, multiple communities, with adequate support, should collaborate effectively through appropriate forms of partnership to maximize scientific productivity. Progress in understanding magnetic reconnection will also benefit fusion research as well as space weather research.

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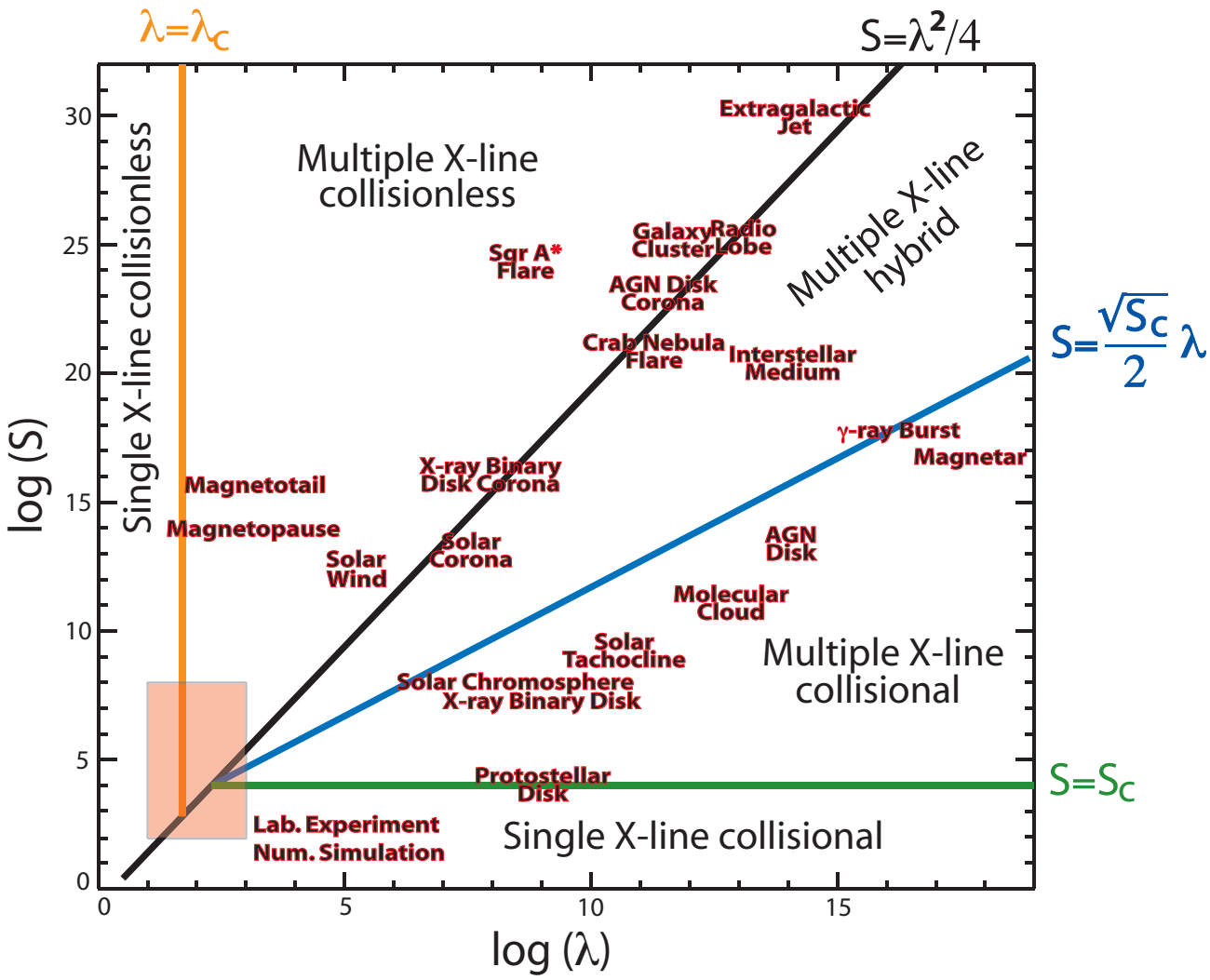


**Figure 1**. A phase diagram for magnetic reconnection. If either Lundquist number S or the normalized size, λ, is small, reconnection with a single X-line occurs in collisional or in collisionless phases. When both S and λ are sufficiently large, three new multiple X-line phases appear through plasmoid instabilities. Global MHD physics can effectively couple to local dissipation scales, which can be either collisionless or collisional, depending on parameters. There are some updates on this diagram by including effects such as electron pressure anisotropy [7]. Various heliophysical and astrophysical cases are also shown in their approximate locations in the diagram. Numerical simulations (using fluid, kinetic or hybrid approximations) and laboratory experiments (including magnetized basic, magnetic fusion, and high energy density plasma experiments) can already or are poised to access all reconnection phases directly relevant to heliophysical and astrophysical plasmas. Adapted from Ref.[3]: H. Ji & W. Daughton, Phys. Plasmas **18**, 111207 (2011).