White Paper for 2024 Heliophysics Decadal Survey

Major Scientific Challenges and Opportunities in Understanding Magnetic Reconnection and Related Explosive Phenomena in Heliophysics and Beyond

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Abstract

Magnetic reconnection underlies many explosive phenomena in the heliosphere and in laboratory plasmas. New research capabilities in theory/simulations, observations, and laboratory experiments provide the opportunity to solve the grand scientific challenges summarized in this whitepaper. Success will require enhanced and sustained investments from relevant funding agencies, increased interagency/international partnerships, and close collaborations among the heliophysics, astrophysics, and laboratory plasma communities. These investments will deliver transformative progress in understanding magnetic reconnection and related explosive phenomena including space weather events.

I. Magnetic Reconnection: A Fundamental Process throughout the Universe and in the Lab

Magnetic reconnection – the topological rearrangement of magnetic fields – underlies many explosive phenomena across a wide range of natural and laboratory plasmas [1-4]. It plays a pivotal role in electron and ion heating, particle acceleration to high energies, energy transport, and self-organization. Reconnection has a complex relationship with turbulence at both large and small scales, leading to various effects which are only beginning to be understood. In heliophysics, magnetic reconnection plays a key role in solar flares, coronal mass ejections, coronal heating, solar wind dissipation, the interaction of the solar wind with planetary magnetospheres, associated dynamical phenomena such as magnetic substorms, and the behavior of the heliospheric boundary with the interstellar medium. Magnetic reconnection is also involved in solar and planetary dynamo processes. Reconnection is believed to play significant roles around compact objects, in the interstellar medium, galactic dynamos, and beyond. In short, magnetic reconnection is ubiquitous in the Universe, influencing space weather events that have significant societal impact, explosive phenomena under extreme astrophysical environments, and laboratory fusion plasmas intended to generate carbon-free energy. Understanding magnetic reconnection is therefore a priority not only for heliophysics but also for our understanding of the distant Universe, for the success of fusion energy, and for development of accurate space weather models.

The long history of magnetic reconnection research can be divided into three phases [4]. The first phase lasted from the 1950s to 1990s, primarily based on the MHD description of the magnetized plasma, which is valid for large system sizes and is represented by the Sweet-Parker and Petschek models of reconnection. The central question was about the reconnection rate, which had been widely observed to be fast by solar observations, such as Yohkoh, and laboratory fusion experiments, such as tokamaks. Laboratory basic plasma experiments including the Large Plasma Device (LAPD), University of Tokyo Spherical Torus 3 (TS-3), and Magnetic Reconnection Experiment (MRX) also contributed to the progress at this phase, e.g., by quantitatively confirming the validity of the Sweet-Parker model in collisional plasmas.

The second phase began in the 1990s and is still ongoing, focusing on the physics beyond MHD in search of fast reconnection mechanisms and associated dynamics. This research has been primarily based on the in-situ measurements of spacecraft in near-Earth space, such as Cluster, THEMIS, and Magnetospheric MultiScale (MMS) missions, as well as numerical models ranging from Hall MHD and two-fluid to hybrid and full kinetic treatments of electrons and ions. Laboratory experiments including the MRX, Swarthmore Spheromak Experiment (SSX), Reconnection Scaling Experiment (RSX), Versatile Toroidal Facility (VTF), PHAse Space MApping (PHASMA), and Terrestrial Reconnection Experiment (TREX) have also contributed significantly to our understanding of kinetic reconnection on both ion and electron scales. These non-MHD reconnection results support fast reconnection as observed but only are valid on local kinetic scales, which are diminishingly small compared to the system scale in heliophysics.

In parallel to the second phase, the third phase of magnetic reconnection research has begun in the last two decades to identify the critical multiscale physics that couples widely separated global MHD system scales and local kinetic dissipation scales. Progress in determining such couplings is necessary to understand and predict reconnection onset and energetic consequences. Several proposed theoretical concepts have been explored, including plasmoid instability of elongated current sheets and 3D turbulent reconnection. There exist abundant opportunities in the coming decade in multiscale observation, exascale computing, data science, and multiscale laboratory experiments, which can work in concert towards finally solving important problems about magnetic reconnection in heliophysics and beyond. This white paper articulates major scientific challenges in the third phase of reconnection research, and opportunities in the coming decade in meeting these challenges by supporting collaborative programs across agencies between NASA, DoE, and NSF.

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

1. The multiple scale problem [e.g., 3-21]: Reconnection involves coupling between the fluid or MHD scale of the system and the kinetic ion and electron dissipation scales that are orders of magnitude smaller. This coupling is currently not well understood, and the lack of proper treatments in a self-consistent model is the core of the problem. Reconnection phase diagrams [e.g., 3,4; Fig. 1] illustrate possible coupling mechanisms to achieve fast reconnection based on plasmoid dynamics. Electron and ion pressure anisotropy can play important roles on scales much larger than their kinetic scales [e.g., 8, 4]. Key questions include: how do plasmoid dynamics scale with key parameters such as the Lundquist number and effective size; how is this scaling influenced by a guide field; are other coupling mechanisms, such as 3D turbulent reconnection, important; and how does reconnection respond to turbulence and associated dissipation on scales below or above the electron scales?

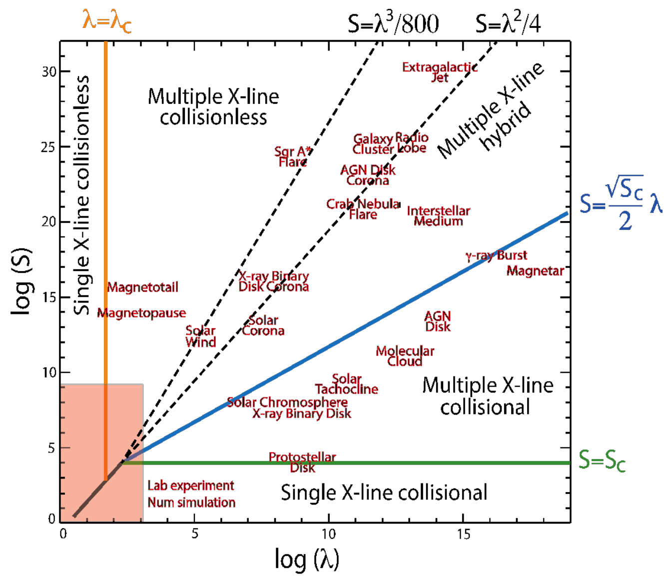

Fig. 1. *Reconnection phase diagram in Lundquist number S and the normalized size λ (to ion kinetic scales). Numerical simulations and laboratory experiments can access all reconnection phases directly relevant to heliophysical and astrophysical plasmas. Adapted from H. Ji & W. Daughton, Phys. Plasmas* ***29****, 070401 (2022).*

2. The 3D problem [e.g., 17-26]: 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. Effects that require topological analysis include instabilities due to variations in the third direction leading to complex interacting flux ropes, potentially enhancing magnetic stochasticity; field-line separation in 3D; and effects of 3D turbulence. How fast reconnection is related to self-organization phenomena such as Taylor relaxation, as well as the accumulation of magnetic helicity, remains a longstanding problem with important implications for, e.g., coronal heating and eruptions.

3. Energy conversion [e.g., 27-44, 80-83]: Reconnection is invoked to explain the observed conversion of magnetic energy to heat, flow, and nonthermal particle energy. A major challenge in connecting theories and experiments to observations is the ability to quantify the detailed energy conversion and partitioning processes. Competing theories of particle acceleration based on 2D and 3D reconnection have been proposed, but there is no consensus on the origin of the observed power laws in particle energy distributions.

4. Boundary conditions [e.g., 45-48]: It is unclear whether an understanding of reconnection physics in periodic systems can be directly applied to natural plasmas, which are non-periodic and often line-tied at their ends such as in solar flares. Whether line-tying and driving from the boundaries fundamentally alter reconnection physics has profound importance in connecting laboratory physics to heliophysics. It is also crucial to learn how reconnection works in naturally occurring settings that have background flows, out-of-plane guide magnetic fields, and asymmetries.
5. Onset [e.g., 49-55]: Reconnection in heliophysical, astrophysical, and laboratory plasmas often occurs impulsively, with slow energy build up followed by a rapid energy release. Is the onset a local, spontaneous (e.g., plasmoid instability) or a globally driven process (e.g., ideal MHD instabilities), and is the onset mechanism a 2D or 3D phenomenon? How do collisionality and global magnetic topology affect the onset conditions? A related question is how magnetic energy is accumulated and stored prior to onset, e.g., in filament channels on the Sun and in the lobes of Earth's magnetotail.
6. Partial ionization [e.g., 56-61]: Reconnection events often occur in weakly ionized plasmas, such as the solar chromosphere (whose heating requirements dwarf those of the corona) and the protosolar nebula, introducing new physics from neutral particles. Questions include whether reconnection is slowed by increased friction or accelerated by enhanced two-fluid effects.
7. Flow-driven [e.g., 53,62,63]: Magnetic fields are generated by dynamos in flow-driven systems such as stars and planets, and reconnection is part of the dynamo process. Reconnection can also occur as a result of flow-driven instabilities such as Kelvin-Helmholtz instability. Key questions include: where does reconnection occur in such systems; how fast does it proceed; how does reconnection influence the associated turbulence and field growth?
8. Turbulence and shocks [e.g., 15-18,71-76]: Reconnection is closely interconnected to other fundamental plasma processes such as turbulence and shocks, which in turn produce heliophysical phenomena such as solar energetic particles. Alfvénic turbulence can accelerate reconnection in the absence of plasmoids and kinetic effects. Reconnection outflow can become turbulent, modifying the reconnection processes. Reconnection can also occur in upstream or downstream shock-generated turbulence. It is essential to understand reconnection when it transitions to a turbulent state, the role of turbulence in reconnection in 2D and 3D settings, as well as the turbulent and shock acceleration of energetic particles. A possible role for magnetic reconnection in modifying the turbulent cascade is another avenue for studies.
9. Related explosive phenomena [e.g., 39,50,77] Global ideal MHD instabilities (e.g., kink, torus, ballooning) can either drive or result from reconnection (e.g., solar coronal mass ejections, geomagnetic storms/substorms, and dipolarization fronts in the magnetotail). Understanding how, and under what conditions, such explosive phenomena take place, as well as their impact, remain major scientific challenges. Physics insights from the study of reconnection under extreme astrophysical conditions [e.g., 78] should be beneficial as well.

III. Major Research Opportunities in Meeting Scientific Challenges

Magnetic reconnection research utilizes three distinctly different but mutually complementary approaches:

1. Theory, numerical simulation, and data science. The major questions outlined above are ripe for studies with fluid, kinetic, and hybrid models, as well as novel, rapidly emerging numerical methods that blend fluid and kinetic descriptions. Exascale computing will allow us to finally attack these questions in fully 3D systems that approach realistic plasma parameters. Dedicated programs from NASA and NSF, including collaboration with DoE which currently hosts exascale computing facilities, are needed to leverage these advances over the next decade. Joint programs will best support the required development of next-generation analytical and numerical models and the application of new numerical technology and theoretical understanding to the reconnection challenges. Data science techniques, currently under rapid development, can potentially increase our capabilities in processing large amounts of data for scientific understanding, developing new toolsets in knowledge discovery, and practical forecasting of space weather events related to reconnection. Data science also offers new methods to link numerical simulations to observations and laboratory experiments [e.g., 79].

2. Observations. Over the next decade, unprecedented remote sensing observations from missions such as SDO (Solar Dynamics Observatory), IRIS (Interface Region Imaging Spectrograph), Goode Solar Telescope of Big Bear Solar Observatory, Expanded Owens Valley Solar Array (EOVSA), Fermi, Solar Orbiter, and the upcoming MUSE (Multi-slit Solar Explorer) mission, as well as in situ measurements from missions such as MMS, Parker Solar Probe, BepiColombo, the upcoming IMAP, TRACERS and HelioSwarm missions, and proposed missions such as MagCon, will deliver a wealth of critical new insights on reconnection. The modeling and theory programs proposed above will be ideally positioned to take advantage of these data for advancing and validating understanding.

3. Laboratory experiments. Ground truth in new understanding is ultimately provided by comparing theory and models with observations and laboratory experiments. Dedicated basic reconnection experiments have greatly matured, and next-generation facilities, such as FLARE [4], are poised to provide access to all reconnection phases with direct relevance to heliophysics. New diagnostics are needed to provide kinetic-scale measurements at the distribution function level [e.g., 80]. Magnetic fusion and high-energy-density experiments provide unique platforms to address certain major questions. In concert with theory and simulation, dedicated programs from the DoE and NSF are needed to support the next-generation experimental facilities and diagnostic instrumentation that are essential for achieving closure between theory and experiment.

Each of the above approaches has both advantages and shortcomings. Observations are limited in accessibilities and desired spatiotemporal resolutions. Theory and simulations are necessarily limited by computational resources, simplifying assumptions, and achievable parameters. Similarly, laboratory experiments are limited by achievable parameters and by necessary boundary conditions. However, combining these approaches in a mutually complementary way is particularly powerful in solving many heliophysics problems.

Figure 2(a) illustrates the three phases of reconnection research. In phase I, remote-sensing observations and fluid simulations were dominant contributors to physics on system scales. In phase II, in-situ space observations, lab measurements, and particle simulations have been and will continue to be main contributors to physics understanding on kinetic scales. In phase III, coupling mechanisms between system scales and local scales are the key. As an example, we suggest that this bridge between the discoveries of phases I and II can be approached via the mesoscale of fluid-scale plasmoids, from local scales in geospace and in the lab, and from system scales by solar and heliospheric observations and fluid simulations. Figure 2(b) proposes connecting local and system scales in terms of a continuous distribution of plasmoid size. On local scales, plasmoids apparently follow exponential scaling in space [81-83] and in the lab [84,85]. The next step in geospace and in the lab is to reach fluid-scale plasmoids, which can serve as the foundation for extending self-similar mesoscale power-law physics towards system scales. On the system scale, plasmoids also apparently follow exponential scaling [86], and the next step in solar and astrophysical observation is to extend self-similar mesoscale power-law physics towards local scales [12,87]. The physical basis for proposing this challenging undertaking is the well-established existence of power law distributions resulting from processes that manifest self-similar behavior. For example, flare-accelerated nonthermal particles have long been known to exhibit power-law energy spectra [27,88,89], which thus indicate that a self-similar physical mechanism, such as Fermi and betatron processes in multiscale plasmoids [32,44], accelerates those particles across a wide energy range [Fig. 2(a)]. Theory, simulation, and data science should play critical roles in developing capabilities of understanding and predicting such self-similar physics across all scales.

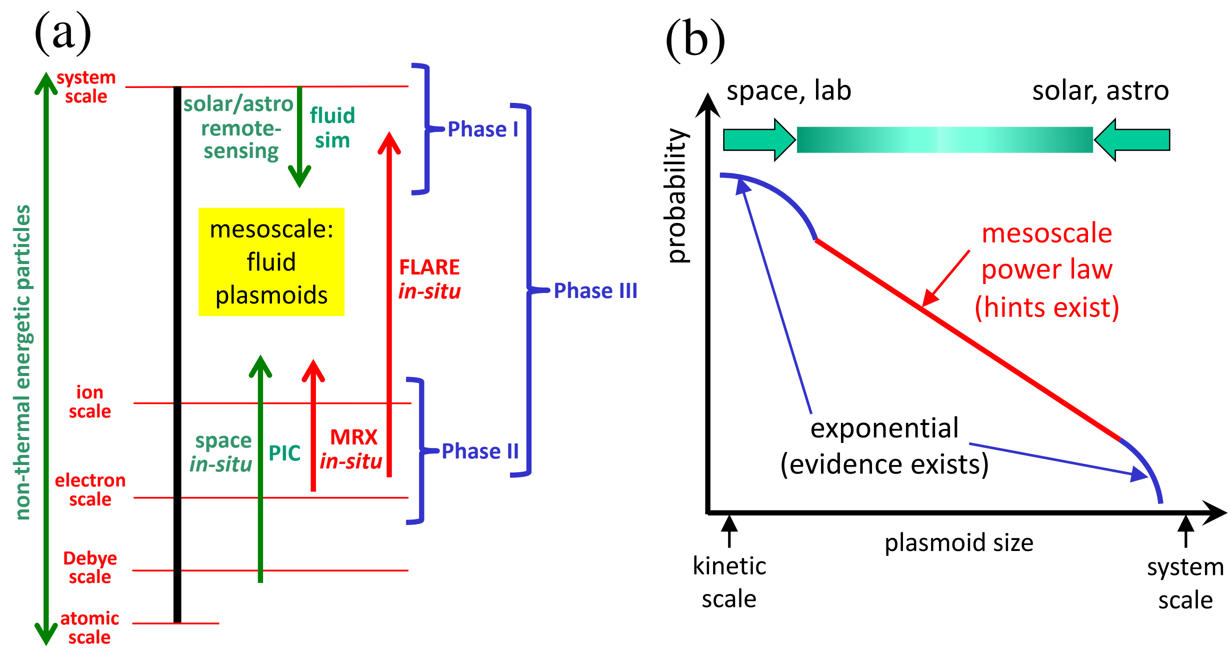

Fig. 2. *(a) Approaches in reconnection research during each phase. (b) Connecting local kinetic scales and system fluid scales via self-similar physics in the form of mesoscale fluid plasmoids. Adapted from H. Ji's presentation on August 8, 2022 at the TESS (Triennial Earth-Sun Summit) meeting.*

IV. Conclusions and Recommendations

In summary, magnetic reconnection is a fundamental process in heliophysics, across the Universe, and in laboratory fusion plasmas. New research capabilities in theory/simulations/data science, observations, and laboratory experiments will allow us to solve the grand scientific challenges briefly summarized in this white paper. Success will require enhanced and sustained investments from relevant funding agencies and private industry, increased interagency/international partnerships, as well as close collaborations among the heliophysics, astrophysics, and laboratory plasma communities. The successful DRIVE (Diversify, Realize, Integrate, Venture, Educate) science centers are good models for such collaborations, expanded to include interagency cooperation among NASA, DoE, DoD, and NSF. These investments will deliver transformative progress in understanding magnetic reconnection and related explosive phenomena in heliophysics, which will advance many areas of critical practical importance, such as space weather.

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