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Preface for frontiers of magnetic reconnection research in heliophysical, astrophysical, and laboratory plasmas

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I. INTRODUCTION

Magnetic reconnection[1,2]—the topological rearrangement of magnetic field—underlies many explosive phenomena across a wide range of natural and laboratory plasmas.[3] It plays a pivotal role in electron and ion heating, particle acceleration to high energies, energy transport, and self-organization. Reconnection can have a complex relationship with turbulence at both large and small scales, leading to various effects that 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 interplanetary plasma with magnetospheres, dynamics of planetary magnetospheres such as magnetic substorms, and the heliospheric boundary with the interstellar medium. Magnetic reconnection is integral to the solar and planetary dynamo processes. In astrophysics, magnetic reconnection is an important aspect of star formation in molecular clouds, stellar flares, explosive phenomena from magnetars and pulsars (including Crab Nebula), and even for acceleration of cosmic rays at ultra-high energies. Magnetic reconnection is thought to occur in both coronae and interiors of magnetized accretion disks in proto-stellar systems and x-ray binaries as well as in interstellar medium turbulence. Magnetic reconnection is believed to occur in the centers of active galactic nuclei, where matter is accreted onto supermassive black holes. On even larger scales, magnetic reconnection may be important in extragalactic radio jets and lobes, and even in galaxy clusters. Magnetic reconnection might occur during the recently discovered fast radio bursts as well as play a role in understanding and predicting observations of multi-messenger astronomy and event-horizon telescopes. In laboratory plasmas, magnetic reconnection is known to occur during sawtooth oscillations in tokamaks, neoclassical tearing mode growth, disruptions, the startup of Spherical Torus plasmas using coaxial helicity injection, relaxation in reversed field pinches and spheromaks, the formation of field reversed configurations by theta pinch or plasma merging, and possibly in edge-localized modes. Magnetic reconnection may play a role in magnetized inertial fusion plasmas such as Z pinches or laser plasmas. Thus, understanding magnetic reconnection is of fundamental importance for plasma physics and significantly contributes to our understanding of the Universe and to the success of fusion energy research.

Most of these examples mentioned above are summarized in the context of reconnection phase diagram,[3] which is updated in Fig. 1. The solid black line separating phases between "multiple X-line collisionless" and "multiple X-line hybrid" is replaced by a dashed black line because the Sweet Parker current sheet cannot be formed in plasmas above the triple point in the phase diagram before it is unstable to plasmoid instability. This point was reflected in the revised phase diagrams by Cassak and Drake[4] and Karimabadi and Lazarian[5] and was made by N. Loureiro at the recent US-Japan Workshop on Magnetic Reconnection held in May 2022. Another dashed black line going through the triple point is added based on the scaling of the current sheet thickness marginally stable to plasmoid instability with respect to the Lundquist number, $S^{-1/3}$. This scaling is predicted theoretically[6] and confirmed numerically in 2D MHD simulations[7] for the onset of plasmoid instability, although the reconnection phase diagram is meant to capture different multiscale physics during fully nonlinear (quasi-)steady reconnection. Also updated is the region occupied by the upcoming Facility for Laboratory Reconnection Experiments (FLARE) project.[8]

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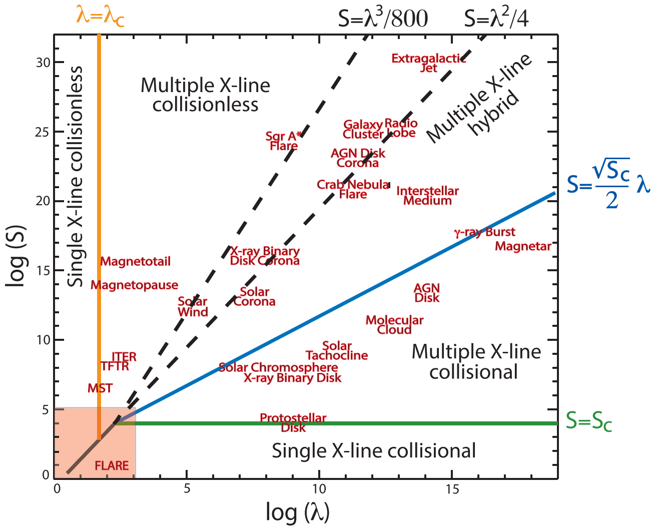

FIG. 1. The updated reconnection phase diagram from Ji and Daughton. A dashed black line replaces the original solid black line, while another dashed black line is added based on the scaling of the marginally stable current sheet thickness with respect to the Lundquist number, $S^{-1/3}$. Also updated is the region occupied by the upcoming FLARE project. Adapted with permission from H. Ji and W. Daughton, Phys. Plasmas **18**, 111207 (2011). Copyright 2011 AIP Publishing.

II. HISTORY OF MAGNETIC RECONNECTION RESEARCH

Magnetic reconnection has a long research history to match its broad importance in plasma physics. It evolved in the following three major stages of the research.[2] The first stage began in 1950s with the MHD description of the plasma for the development of basic concept of magnetic reconnection motivated by the solar flare observations. The focus was on the reconnection rate, at which the magnetic energy is released to plasma, and representative models include the Sweet-Parker model predicting slow rate and the Petschek model predicting fast rate. However, quantitative tests of these models did not exist numerically until 1980s and in the laboratory until 1990s. The Sweet-Parker model is valid at relatively low Lundquist numbers, while the Petschek model requires strong anomalous resistivity within the diffusion region, which has not yet been verified neither in kinetic simulations nor in experimental and observational tests.

The next major stage of the reconnection research began in 1990s when physics beyond MHD was recognized to be important for fast reconnection in collisionless plasmas, facilitated by the availabilities of numerical models of the Hall MHD, two-fluid and full kinetic descriptions of the plasma, and the *in situ* measurements of key quantities in near-earth space. Observationally, relevant fast reconnection was, indeed, realized by these numerical models, which were subsequently verified in space observation and laboratory experiments first on ion kinetic scales then on electron kinetic scales, despite the lack of first principles analytic theories. While these advances are highly relevant to certain applications (magnetospheres, solar wind, etc.) where kinetic-scale reconnection is known to occur, the applicability to much larger systems such as the solar corona remains unknown.

The third major stage of the reconnection began in 2000s when the idea that sufficiently stretched current sheets even in the collisional MHD regime can lead to fast multi-scale reconnection via spontaneous plasmoid instability or general 3D turbulence. Through a hierarchy of self-similar current sheets, the large ideal scales, at which free magnetic energy is accumulated, are efficiently coupled to the local dissipation scales, either collisional or collisionless, to generate globally fast reconnection. Conceptually, some of these multi-scale scenarios have been successfully tested numerically and have been conveniently organized as multiple X-line phases in the reconnection phase diagrams,[2,3] which have been serving as a guide for further experimental[8] and numerical[9] explorations.

III. MINI-CONFERENCE ON FRONTIERS OF MAGNETIC RECONNECTION

As the reconnection research is transitioning from the stage 2 to stage 3, a group whitepaper was submitted to Plasma 2020 and Astro 2020 Decadal Surveys,[10] where new challenges have been summarized, and opportunities in all three approaches (numerical, laboratory, and observational) have been explored. (For completeness, a further expanded group whitepaper[11] submitted to the Heliophysics 2050 workshop held in May 2021 is referenced here to vision the next three decades until 2050 to finally solve the multi-scale reconnection problem.) New ideas and progress continue to emerge in recent years on the advanced topics like reconnection onset and nonthermal particle acceleration.[2] Encouraged by these new developments, we have organized a mini-conference at 2020 American Physical Society Division of Plasma Physics annular meeting on the latest developments and future prospects of this field.

In this mini-conference, we invited frontier researchers from each of the above three communities (plasma physics, heliophysics, and astrophysics) to present their latest results and their future prospects in five half-day sessions: (1) basic reconnection physics, (2) reconnection in magnetosphere, (3) reconnection in the laboratory, (4) reconnection in astrophysics, and (5) reconnection on the sun. Each of these sessions consists of invited talks and contributed talks. Below, we briefly summarize each of these five sessions with useful references wherever exist to benefit our reader.

A. The basic reconnection physics session

This session began with Xiaocan Li of Dartmouth College as an invited talk in the main meeting program on power-law formation of accelerated electrons during nonrelativistic reconnection in 3D, extending previous studies mostly based on 2D reconnection.[12] This talk was followed by Patrick Kilian of Los Alamos National Laboratory on acceleration mechanisms of nonthermal particles during trans-relativistic reconnection.[13] The importance of perpendicular electric field was pointed out during the later phase of simulation in accelerating particles. Gregory Werner of University of Colorado presented initially hot pair plasma acceleration during relativistic 3D reconnection where particles are still robustly accelerated acceleration but via a more complex dynamic behavior.[14] Yi-Min Huang of Princeton University discussed plasmoid-mediated reconnection in Hall MHD, while Andrey Beresnyak of Naval Research Laboratory discussed turbulent reconnection also in Hall MHD. William Daughton of Los Alamos National Laboratory presented results on turbulent reconnection in mesoscale systems. Derek Schaeffer of Princeton University presented experimental results of fast reconnection in highly extended current sheets with an aspect ratio on the order of 100 in large-β laser

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plasmas followed by the corresponding numerical simulations by William Fox of Princeton Plasma Physics Laboratory.[15] Bruno Coppi of MIT presented the idea of magnetic reconnection when significant electron temperature gradient exists in the reconnection region with substantial differences between parallel thermal conduction to perpendicular thermal conduction.[16]

B. The magnetospheric reconnection session

James Burch of Southwest Research Institute gave an overview talk on the progress made by the Magnetospheric MultiScale (MMS) mission since 2015 in understanding asymmetric reconnection in magnetopause[17] and symmetric reconnection in magnetotail[18] as well as various plasma waves associated with these events. Paul Cassak of West Virginia University summarized progress and theory challenges in reconnection kinetic physics in the MMS era. Li-Jen Chen of NASA Goddard Space Flight Center presented latest results on MMS observation of lower-hybrid drift waves (LHDW) during reconnection[19] and simulation studies of reconnection in the shock turbulence.[20] This was followed by Shan Wang of University of Maryland on the MMS observations of reconnection at Earth's bow shock and further by Naoki Bessho of University of Maryland on the corresponding kinetic simulations.[21] Kendra Bergstedt of Princeton University reported statistical properties of a turbulent reconnection event in magnetotail by MMS as well as the associated energy dissipation.[22] Amy Keesee of University of New Hampshire presented on the observed structures in ion temperature profiles measured by the remote-sensing energetic neutral atom imaging system, compared with the *in situ* measurements by MMS.[23] Finally, Andrew McCubbin of University of Iowa explained a new technique called field-particle correlator[24] to analyze detailed energy transfer processes in phase space during reconnection.

C. The laboratory reconnection session

Jan Egedal of University of Wisconsin-Madison summarized progress in studying magnetic reconnection by a strong drive through shocked flux pileup[25] in a laboratory setting where LHDW modulations of electron-scale reconnecting current sheets were studied and compared well with 3D simulations.[26] Jongsoo Yoo of Princeton Plasma Physics Laboratory summarized the progress in understanding LHDW in their electrostatic and electromagnetic versions, which explain well the MMS observations.[27] In order to interpret the model to explain the laboratory results, finite collisions have been incorporated but without leading to significant changes in the predicted growth rate. These favorable results justify close comparative research between laboratory experiments and space observation on the subject of LHDWs during magnetic reconnection and are reported in a paper[28] included in the Special Topic, "Frontiers of Magnetic Reconnection Research in Heliophysical, Astrophysical and Laboratory Plasmas," in *Physics of Plasmas*. Sayak Bose of Princeton Plasma Physics Laboratory reported latest results from guide field reconnection on Magnetic Reconnection Experiment.[29] Hantao Ji from Princeton University summarized statistical properties of multiscale reconnection in plasmas with high Lundquist numbers and large normalized sizes. Analytic and numerical research was performed to study the guide effect on plasmoid distribution in plasmoid-mediated multiscale reconnection. Different power laws have been predicted depending on the assumptions on plasmoid merging, which should have important implications on energization processes especially on particle acceleration. These results are reported in a paper[30] included in the "Frontiers of Magnetic Reconnection Research in Heliophysical, Astrophysical and Laboratory Plasmas" Special Topic. Adam Stanier of Los Alamos National Laboratory summarized efforts[9] to numerically simulate laboratory experiments[26] as well as the upcoming FLARE project.[8] Hiroshi Tanabe of University of Tokyo reported effective ion heating by merging Spherical Tori with ion temperature proportional to energy of the reconnected field component.[31] Finally, Gennady Fiksel presented results of energy energization during reconnection at high-β laser-produced plasma.[32]

D. The astrophysics reconnection session

Magnetic reconnection under extreme astrophysical conditions has been a hot research topic in recent years. Alexander Philippov of Flatiron Institute (now at University of Maryland) began this session by reviewing the growing evidence of the importance of relativistic magnetic reconnection in powering observed emission from black holes and neutron stars, including pulsars.[33] Global particle modeling of pulsars by Benoit Cerutti of Centre National de la Recherche Scientifique and University of Grenoble revealed the dominance of plasmoid-dominated turbulent reconnection in pulsar wind leading to efficient nonthermal particle acceleration.[34] Dmitri Uzdensky of University of Colorado provided an overview of the reconnection process under extreme astrophysical conditions, including radiation, collisions, and QED effects.[35] Fan Guo of Los Alomas National Laboratory expanded the research of relativistic turbulent magnetic reconnection into 3D on the subject of particle acceleration,[36] vastly different from their 2D counterparts. Reported by Lorenzo Sironi of Columbia University, magnetic reconnection can efficiently accelerate particles to relativistic regimes in sheared flow environment such as in astrophysical jets.[37] This was followed by Luca Comisso of Columbia University who showed interplay between reconnection and turbulence in magnetically dominated plasmas.[38] Xiaocan Li made his second presentation as a contributed talk mainly on the interpretation of his 3D simulation results.[12] Finally, Hui Li of Los Alamos National Laboratory discussed 3D turbulence by both the externally driven and self-generation processes.[39]

E. The solar reconnection session

The final session of this mini-conference is about reconnection in the solar atmosphere. The first talk was given by Bin Chen of New Jersey Institute of Technology on detailed electron acceleration measurements during solar flares by radio spectral images from the recent telescope arrays.[40] This was followed by a talk by Spiro Antiochos of NASA Goddard Space Flight Center on theory and simulation of energy release of magnetic field via magnetic reconnection in the solar corona. Harry Arnold of University of Maryland (now at NASA) presented results of electron acceleration based on a numerical model in the macroscale system by taking into account reconnection on large scales while kinetic particle physics at large energies.[41] Qile Zhang of Los Alamos National Laboratory presented new results on particle acceleration in nonrelativistic regimes via flux rope kink instability.[42] Amitava Bhattacharjee of Princeton University summarized progress in spectral observation and modeling of plasmoid-mediated reconnection onset in the solar atmosphere.[43] Fred Driscoll of UC San Diego

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presented his ideas on diagnosing current sheets in solar wind. Finally, Walter Gekelman of University of California, Los Angeles presented methodologies in locating reconnection regions in a complex 3D field geometry, using a large dataset taken in the laboratory.

IV. CONCLUSIONS

This mini-conference served as a snapshot of the magnetic reconnection research status in November 2020 during the time period when the field is transitioning from the stage 2 focusing mostly on physics beyond MHD to the stage 3 on multiscale physics of reconnection connecting global MHD scale to local dissipation scale. The timing was particularly well as it was around the mid-point between the 2018 US-Japan Workshop on Magnetic Reconnection (MR2018)[44] held in September 2018 and the 2022 US-Japan Workshop (MR2022) held in May 2022. The five half-day sessions covered five different but interconnected aspects of the subject with representative talks highlighting state of the art in each aspect. Nonetheless, these presentations and discussions were still not comprehensive and certainly incomplete due to the breadth and depth of the field. Therefore, readers are encouraged not only to follow up with cited references here but also to check out relevant books[45,46] and reviews.[1,2] In particular, the most recent "roadmap" review[2] in part by authors of this Preface presents forward-looking prospects of the field emphasizing multiscale physics, onset, and particle acceleration and heating. The utilization of multiscale experiments and exascale computing in the upcoming decades should accelerate the progress toward the complete solution of magnetic reconnection problem not only in its understanding but also in its prediction of both onset and consequences, as outlined in the group whitepaper[11] submitted to the Heliophysics 2050 workshop.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Hantao Ji: Writing – original draft (equal). **William Daughton:** Writing – review and editing (equal).

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