Magnetic Reconnection

1.1 Introduction

Magnetic reconnection is the dominant process for dissipating magnetic energy in the universe. It therefore has dynamical importance in a broad range of space and astrophysical phenomena. Magnetic reconnection also has intrinsic scientific interest because the release of magnetic energy in a macroscopic system is linked to the dynamics of a narrow boundary layer, the "dissipation region", where dissipation facilitates the breaking of magnetic field lines. The complexity of reconnection and its scientific challenge results from the extreme disparity of spatial scales between the global system and the dissipation region. Further the dissipation region is often turbulent with electrons and ions displaying weakly-coupled, complex dynamics. The ongoing scientific issues related to magnetic reconnection span an enormous range of topics. In this document we focus on five of these: the rate of reconnection; the onset issue; the problem of cross-scale coupling in large systems; particle heating and acceleration; and reconnection in extreme environments. For each of these topics we discuss the science issues, recent progress and open issues, and discuss strategies for reaching scientific closure.

1.2 Key Scientific Challenges

Rate of Magnetic Reconnection

A key question about magnetic reconnection in astrophysical and laboratory plasmas is why the reconnection rate, or flux transfer rate, is so fast in comparison with the rate predicted by classical MHD theory. In the Sweet-Parker model the length of the dissipation region is determined by the macroscopic system size while the much shorter width is controlled by weak dissipation. Balancing plasma inflow with Alfvenic outflow in such a high aspect ratio dissipation region yields rates of reconnection that are far smaller than those inferred from observations. The exploration of reconnection in collisionless and nearly collisionless plasma has therefore focused on the structure and dynamics of the dissipation region, and important progress has been made through numerical simulations, observations from satellites, and dedicated laboratory plasma experiments. Two-fluid effects, resulting from the fundamentally different behavior of ions and electrons at small spatial scales, have been found to be important within the dissipation region [1-3].

Questions such as what provides the dissipation necessary to break the frozen-in condition in nearly collisionless plasma and what controls the width and length of the dissipation region are key foci of research. The relative roles of turbulence [4] and/or momentum transport as described by the off-diagonal pressure tensor [5] in balancing the reconnection electric field have not been established. NASA's MMS mission, a four spacecraft satellite mission, is designed to explore the fine-scale structure of the electron dissipation region and to answer these questions. Parallel measurements can be made in laboratory experiments and explored in 3-D reconnection simulations. Is the reconnection rate is determined solely by the microphysics of the dissipation region or also by the global boundary conditions? Such questions can be addressed in ongoing laboratory reconnection experiments such as MRX, VTF and SSX.

The Onset of Magnetic Reconnection

Magnetic reconnection often occurs in explosive events where magnetically stored energy is released on Alfvenic timescales. Examples are solar flares, magnetospheric substorms, and tokamak sawteeth. There has been much progress in understanding 2D, steady-state reconnection [1-3], but the time dependent problem is not well understood. In order for explosive energy release to occur, there must be a period of slow accumulation of magnetic energy followed by a sudden transition to fast reconnection. Of course, reconnection can also take place in a quasi-steady fashion (e.g., at the Earth's magnetopause and in the solar wind). Two distinct models have been proposed, based on the local versus global properties of the magnetic equilibria.

There is evidence that reconnection onset in the Earth's magnetosphere, where direct measurements are available, is linked to the width the current layer compared with the ion Larmor radius or skin depth. The magnetotail current sheet thins down to these scales prior to substorm onset and the THEMIS spacecraft observations suggest that at least some substorms are triggered by the onset of collisionless reconnection in the midtail region [6]. Further, current sheets wider than the ion skin depth in the solar wind compress at the Earth's bow shock and then undergo reconnection in the magnetosheath [7]. In the solar corona, where collisions are likely to be important at onset, it has been proposed that fast reconnection sharply onsets when the Sweet-Parker current layer approaches the ion Larmor radius or skin depth and there is some observational support from stellar data for this suggestion. In dedicated reconnection experiments in the laboratory a strong increase in the rate of reconnection occurs when the Sweet-Parker current layer width falls below the ion inertial length [8] and bursts of fast reconnection are observed when the width of the current layer approaches the ion Larmor radius [9]. Finally, although the width of the current layer has been a major focus of the exploration of reconnection onset, it remains an open question as to whether there are other local parameters that determine whether reconnection can take place.

In the corona it has also been suggested that the onset is driven by global rather than local dynamics. The breakout model [10] involves the reconnection of overlying magnetic field lines and subsequent reconnection and expansion of flux tubes. In the sawtooth crash and in the VTF reconnection experiment [9] observations suggest that the onset is spatially localized and then spreads so that even in cases where the magnetic field geometry is mainly 2D, 3D effects can be important for onset.

Cross-scale Coupling in Large Systems

During the past decade, much of the theoretical, computational and laboratory research on the basic physics of magnetic reconnection has been focused on relatively small systems in order to understand fundamental issues regarding the rate and structure of a single reconnection site. A variety of two-fluid and kinetic models predict fast reconnection rates that are weakly dependent on the system size or dissipation mechanism [1,5] but it is unclear how these results will extend to large-scale systems relevant to most astrophysical plasmas where the separation between the dissipation and macroscopic scales is enormous, of order 10^8 in stellar flares and 10^{10} in black hole accretion disks.

Given the huge range of scales, what controls the interaction between the dissipation scales and the global MHD evolution? Do the largest scales dictate the structure of the dissipation region or *vice versa*? There is growing evidence from both theory and simulations that in large-scale systems a single reconnection layer may spontaneously break-up into multiple interacting reconnection sites through the formation of secondary magnetic islands (or plasmoids). The behavior is similar in both collisional [11] and kinetic regimes [12]. An ongoing challenge is to understand how many islands are formed under various parameter regimes and how these islands modify the global reconnection rate and particle acceleration. Finally, astrophysical systems typically have many sources of turbulence, which is predicted to facilitate reconnection at a rate that is insensitive to the dissipation [13].

As the theory and simulation move forward on these questions, satellite observations from the Earth's magnetosphere, the solar wind and the solar corona are providing important constraints. In the solar wind the reconnecting current sheets are often highly planar [14] and the structure of the outflow jet is remarkably smooth in contrast to the some recent simulations showing highly distorted current sheets with embedded flux ropes around the x-line. Thus in order to relate simulation results to astrophysical contexts it is important to understand how the highly structured and transient plasma features in the vicinity of the dissipation region evolve downstream.

Reconnection Driven Heating and Particle Acceleration

The magnetic energy released during magnetic reconnection is converted into high-speed flows, heat and energetic particles (typically with energy spectra in the form of powerlaws). While the convective flows in reconnection outflows have been widely documented in situ satellite measurements in the Earth's magnetosphere and the solar wind and are well-described by the MHD jump conditions, the corresponding mechanisms for bulk plasma heating and particle acceleration remain poorly understood. Unraveling the mechanisms for heating and particle acceleration are essential to understand the role that reconnection plays in heating the coronae of stars and accretion discs and in driving their supersonic winds; in driving the relativistic jets from black holes and other compact objects; in powering giant radio galaxies; and in producing the cosmic ray spectrum. The evidence within the heliosphere is strong that the fraction of energy going into bulk heating and that is channeled into the energetic component during reconnection are not universal. In the case of impulsive flares roughly equal amounts of released energy appears in the form of thermal ions and electrons and energetic ions and electrons [15] with recent over-the-limb observations suggesting that the pressure of the energetic electron component can approach unity. Thus, the efficiency of conversion of magnetic energy into the energetic electron and ion components can be extraordinarily high. On the other hand, even the largest solar wind reconnection events, which have spatial extents of hundreds of Earth radii, exhibit bulk ion heating but no energetic ion component and no heating of electrons. The control parameter or parameters producing these stark differences have not yet been identified, making predictions of particle acceleration by reconnection problematic.

Because of their large parallel mobility, early models of reconnection-driven electron acceleration were based on the parallel electric fields that develop near a single magnetic x-line. However, parallel-electric-field models are inconsistent with the large numbers of energetic electrons seen in impulsive flares. In impulsive flares the electrons typically develop a thermal component (up to 10s of keV) and a powerlaw tail up to several MeV with a spectral index that varies with the flare intensity [16]. Observations [17] and modeling [18-19] indicate that in the complex magnetic fields on the sun, reconnection forms multiple magnetic islands that may be volume-filling and that particle heating and acceleration should be explored in this context. In a multi-island environment both parallel electric fields and Fermi acceleration in contracting islands [19] drive electron acceleration. The exploration of this multi-island reconnecting environment, which requires modeling reconnection in a 3-D kinetic system, remains in its infancy and is limited by available computational resources.

Ion heating in reconnection driven Alfvenic outflows has been well documented during reconnection in the Earth's magnetosphere and the solar wind [14]. Strong ion heating has been measured during reconnection events in laboratory reconnection with high mass ions gaining greater energy than low-mass ions [20]. The spectrum of energetic ions from impulsive flares extends up to the GeV/nucleon range in X-class flares [16] and the spectra of protons as well as trace ions have been well-documented by in situ satellite measurements in the solar wind. As in the case of electrons, super-Alfvenic ions may be efficiently accelerated during the contraction and merger of magnetic islands.

Reconnection in Extreme Astrophysical Environments.

Much of the work on magnetic reconnection has been for systems of relatively tenuous, low-energy-density, optically thin environments, which can be represented as a collection of non-relativistic charged particles whose numbers are conserved. However, magnetic reconnection has also been frequently invoked in astrophysical systems, especially in high-energy astrophysics, whose parameters can be extreme. Examples include accretion disks and their coronae and large-scale magnetospheres, jets, gamma-ray bursts (GRBs), pulsar magnetospheres and pulsar winds, and flares in soft gamma repeaters (SGRs). These systems require a number of new effects, including special relativity, radiation and pair creation.

Special-relativistic effect*s* are important when the reconnecting magnetic field is so strong that the magnetic energy density exceeds the rest-mass energy density of the upstream plasma. The corresponding Alfven speed and the reconnection outflow velocity approach the speed of light [21]. This situation is typical of astrophysical pair plasmas such as in radio-pulsar magnetospheres, which are believed to develop a large-scale equatorial current sheet beyond the light cylinder. Reconnection in this current sheet may produce the observed pulsed high-energy emission and coherent radio emission. Relativistic reconnection in pair plasmas may also power the giant magnetar flares in soft-gamma repeaters and the relativistic jets of gamma-ray bursts [22] and AGNs.

Radiation may affect reconnection through several mechanisms. Radiative cooling can affect the energy balance and hence the dynamics of the reconnection layer with different radiation cooling mechanisms acting in different astrophysical situations. In powerful events the dissipated energy density and the plasma temperature so high that radiation pressure enters the dynamics and can dominate the plasma pressure. Compton-drag resistivity due to electron-photon collisions as opposed to electron-proton collisions is important in several high-energy astrophysics situations [23].

Some astrophysical systems (magnetars, central engines of GRBs and supernovae) are believed to possess super-strong magnetic fields that exceed the critical quantum field of about 4 x 10^{13} Gauss, corresponding to the lowest electron Landau level energy equal to the electron rest mass. The magnetic energy density of such a strong magnetic field is so large that, when converted to radiation energy, it results in temperatures greater than the electron rest-mass energy of 0.5 MeV and electron-positron pair creation results [23]. The associated increase in the optical depth and also makes it highly collisional. How these processes affect the overall reconnection dynamics is unknown.

1.3 Major Opportunities

Multi-island magnetic reconnection and particle acceleration

Observations in the magnetosphere and corona and recent computer simulations suggest that over a broad range of collisionality reconnection at single large x-lines break up into multiple interacting islands or flux ropes. In systems with a guide field reconnection can take place at a variety of layers so that these magnetic islands may be volume filling. The conversion of energy in such a reconnecting system represents a paradigm shift from the single x-line picture of reconnection. Can we understand particle acceleration in such a complex, turbulent environment and therefore understand the extraordinary efficiency of particle acceleration in flares? What is the role of reconnection in producing the cosmic ray spectrum?

A number of existing satellites are providing in situ data in the magnetosphere (Themis, Cluster). Remote observations of solar flares from the Rhessi, Stereo, SDO and Hinode are providing evidence for fine-scale structure during impulsive flares. Future missions and in particular Solar Probe Plus will produce key in situ measurements in the low beta regime close to the sun, where the diagnosis of flare energy release and solar wind reconnection will be greatly facilitated. Simulations of reconnection and particle acceleration in a 2-D are providing important information on the spontaneous development and evolution of secondary magnetic islands and the physics of particle acceleration. However, exploring 3-D multi-island reconnection is a significant challenge even on the largest of present day computers because of the large separation of scales intrinsic to reconnection. The ongoing exploration of sawtooth events in the MST reversed field pinch is providing important data although diagnosing the dynamics of these events is difficult.

Bringing together observations from the range of satellite datasets to focus on the structuring and time variability of reconnection-driven energy release would facilitate progress in this area. The development of a dedicated laboratory experiment designed to explore 3-D multi-island reconnection and particle acceleration would provide critical data both in support of ongoing NASA missions and to provide closure on a problem of great importance in space and astrophysical systems. We recommend the formation of a National Working Group to explore possible geometries, parameters and diagnostics required for such an experiment. If a cost-effective design can be developed, the NWG would seek broad support for the construction of an experiment to explore these issues.

Magnetic reconnection in extreme environments

In many astrophysical environments, including pulsar and magnetar magnetospheres and jets, reconnection is in the strongly relativistic regime. Radiation pressure, cooling and drag and pair-production may also enter the dynamics close to the source regions of jets and gamma-ray-bursts (GRBs), and in magnetar magnetospheres. Thus, reconnection dynamics in these High-Energy-Density (HED) systems will be very different from that typically explored in heliospheric applications.

Satellite observations (Chandra, Fermi and Swift) are providing important constraints on jet structure and dynamics and the driver mechanisms of GRBs and magnetar flares. In Poynting-flux dominated jets the energy from fields dominates kinetic energy and can act as a source for energetic particles powering measured synchrotron emission. Because of the remoteness of most sources, however, the lack of resolution continues to limit progress. The understanding of relativistic reconnection is rapidly developing but at present the ability to benchmark these results is very limited.

A major effort to take advantage of advances in parallel computing to explore the strongly relativistic regime and to seek to implement a radiative transport model and pair production should be pursued. In parallel we suggest taking advantage of facilities in the HED community by pursuing a laser-driven reconnection experiment to explore reconnection in the relativistic regime. The laser facility at the University of Rochester has already demonstrated compression of magnetic fields to 10^7 G that produce Alfven speeds $c_A/c \sim 10\text{-}100$. The possibility of compressing an initial anti-parallel magnetic field configuration should be explored. Such a system would drive reconnection with outflows in the relativistic regime and could be used to benchmark the parallel modeling effort.

Explosive onset of magnetic reconnection

A fundamental question is why magnetic reconnection occurs as an explosion? The observations are nearly universal – the explosive onset of reconnection occurs in laboratory fusion experiments, magnetospheric substorms and solar and stellar flares. On the other hand, solar wind reconnection appears to be quasi-steady. What are the differences between these systems? Is there a universal mechanism for reconnection onset? Since the delayed onset of reconnection controls the storage of energy prior to release, answering this question may provide information on the size of energy releases that my be necessary to predict, for example, the size distributions of solar flares.

The VTF experiment at MIT exhibits the spontaneous onset of magnetic reconnection. While the onset occurs when the width of current layers approaches kinetic scales, consistent with expectations based on MRX data and as predicted in theory and simulations, the measurements suggest that the onset is intrinsically 3-D. Whether this result is generic remains an open issue. Recent advances have been made in understanding the onset of the sawtooth crash in the DIII-D tokamak experiment. THEMIS observations in the magnetosphere have suggested that substorm onset is linked to magnetic reconnection in the mid-tail. Simulation studies of reconnection onset in the magnetotail and solar corona are ongoing. In the solar case local criteria based on the transition from collisional to collisionless reconnection and geometrically based models are being pursued.

Establishing a consortium of scientists studying reconnection onset in the wide variety of laboratory and astrophysical systems would help focus the present largely-disconnected efforts. The establishment of such a consortium would also help raise the importance of the topic and thus encourage a broader effort of this area. Enhanced theoretical and modeling support for ongoing laboratory experiments would help maximize the scientific benefit of these experiments.

1.4 Impacts and Major Outcomes

Magnetic reconnection plays a central role in the dynamics of a wide variety of astrophysical systems. Magnetic fields and associated reconnection processes dominate the dynamics of the coronae of the stars and accretion discs. Magnetic reconnection is required for the dynamo to amplify the magnetic fields that are seen throughout the universe and is likely to be dynamically important in accretion discs. The role of magnetic reconnection in jets, magnetar flares and gamma-ray bursts continues to be explored. Over the past decade substantial progress has been made in identifying the mechanisms driving the surprising fast release of magnetic energy seen in explosive phenomena in the laboratory and space. However, there remain key areas that remain poorly understood and are critical for understanding and modeling the rich variety of astrophysical systems.

Within the heliosphere the evidence for strong plasma heating and particle acceleration during magnetic reconnection is substantial. However, unlike with shocks, there is no standard model of particle acceleration from reconnection. The absence of an accepted predictive model makes modeling of remote astrophysical systems, where observations provide less detail, challenging. The continuing development of more powerful computers combined with dramatic advances in remote sensing of solar dynamics with RHESSI, Hinode and SDO are fostering a dynamic scientific climate where significant progress in this area is likely, especially if a suitable laboratory experiment can be designed to further benchmark ideas from computations, theory and remote observations. Can a “standard model” for reconnection-based particle acceleration be developed? Such a model would dramatically change our ability to reliably model astrophysical systems.

Much of the progress on magnetic reconnection has been based on low energy density systems found within the heliosphere. In the extreme environments of magnetar and pulsar magnetospheres and the source regions of jets and gamma-ray bursts, radiation, relativistic effects and pair production are likely to strongly alter conventional reconnection scenarios. Understanding how reconnection dynamics changes in such environments is required to address even the most basic issues in such extreme environments. Reconnection experiments based on intense lasers combined with the development of new computational models would facilitate significant progress in this area.

1.5 Connections to Other Topics

Reconnection is a fundamental process describing the behavior of magnetic fields in plasma. Reconnection and its consequences are therefore a crucial element for describing other processes in magnetized plasma. The generic state of astrophysical fluids is often turbulent. In accretion disks, for example, the magneto-rotational instability drives the disks into a turbulent state that facilitates the angular momentum transport required for accretion. Magnetic reconnection is a dynamically important player. Magnetic reconnection is also an essential element during magnetic field generation via the dynamo. How are accretion and the turbulent dynamo modified by physics-based models of reconnection that differ greatly from the MHD treatment?

Launching astrophysical jets and outflows requires strong magnetic stresses. Simulations of jets exhibit magnetic field reversals that may reconnect and alter jet formation. Jets are also believed to be sources of high-energy particles. Observations suggest that both shocks and magnetic reconnection are efficient sources of energetic particles. What is the relative importance of the two acceleration processes in jets and other astrophysical phenomena? What are the astrophysical objects where one or another process dominates and how do they couple? Particles accelerated during reconnection could act as seed particles for shock acceleration.

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