

Magnetic Reconnection

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 finally discuss strategies for reaching scientific closure.

Rate of Magnetic Reconnection

A key question on 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 [1] the length of the rectangular shape dissipation region is determined by macroscopic boundary scale while the much shorter width is controlled by weak dissipation. Balancing plasma inflow with Alfvénic 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 [2]. It has been established that two-fluid effects, resulting from the fundamentally different behavior of ions and electrons, are important within the critical layer where reconnection occurs [3-10]. Important 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 important foci of theoretical and computational research as well satellite missions in the heliosphere and dedicated laboratory reconnection experiments.

Important developments on these topics are as follows:

- In numerical simulations, dedicated laboratory experiments and space satellite data, Hall effects have been verified by observations of an out-of-reconnection plane quadrupolar component of the magnetic field [4-8]. These observations provide experimental evidence for the decoupling of the motion of ions and electrons at the very small spatial scales of the dissipation region.

- In laboratory reconnection experiments the shape of the dissipation region changes dramatically as the collisionality of plasma is varied. In a collisional plasma, a rectangular-shaped Sweet-Parker reconnection layer is identified with a slow reconnection rate. In the collisionless regime, the shape of the reconnection layer changes to a Petschek-like, double-wedge shape with strong Hall fields and a much higher reconnection rate [8]. The transition occurs when the width of Sweet-Parker current layer falls below the ion inertial scale. In simulations similar behavior is seen [9,10] although in low resistivity MHD simulations the dissipation region breaks up into many small islands [11]. The reconnection rate in this multi-island regime is still being explored.

- In simulations the rate of reconnection is found to be insensitive to the electron mass and therefore the mechanism that breaks the frozen-in condition [3,6] and this has been interpreted as resulting from the dispersive character of whistler and kinetic Alfvén waves [6]. It should be emphasized that a weak dependence on the dissipation mechanism cannot be ruled out.

- Key mechanisms for breaking the frozen-in condition in collisionless reconnection have been investigated. In 2-D systems momentum transport (through the off-diagonal pressure tensor) facilitates a balance between the reconnection electric field and the plasma current [3]. Current driven turbulence has been seen in laboratory experiments [12], space [13] and 3-D simulations [14,15]. Although a correlation was found between the reconnection rate and the amplitude of electromagnetic waves in laboratory experiments, a causal relationship is yet to be found. The role of this turbulence in balancing the reconnection electric field is therefore not yet clear.

- Many astrophysical systems are turbulent and it has been suggested that this ambient turbulence could facilitate fast reconnection even in the absence of resistivity or other dissipation mechanisms [16]. Recent 3-D MHD simulations with forcing of turbulence around the magnetic reversal have demonstrated that fast reconnection, insensitive to the plasma resistivity, developed in this turbulent system [15]. Whether turbulence convecting into the dissipation region from upstream, a more realistic scenario, also leads to fast reconnection remains to be explored.

Some Important Outstanding problems:

Even with these notable advances, many important questions remain. While the Hall term appears to render the rate of reconnection insensitive to the dissipation mechanism, it does not by itself cause energy dissipation or break magnetic field lines. While the mechanisms for breaking field lines (turbulence and momentum transport as described by the off-diagonal pressure tensor), the relative roles of the two mechanisms have not been established. The widths of the electron current layers measured in the

laboratory [17] and in space [18] are somewhat wider than in 2-D simulations, suggesting that turbulence may be broadening the layers. 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 in laboratory experiments and larger-scale 3-D reconnection simulations will facilitate the resolution of this important problem.

An important question to also address is whether the reconnection rate is determined solely by the microphysics of the dissipation region or also by the global boundary conditions? To understand these key issues, we need to investigate the relationship between the local reconnection dynamics and global boundary conditions. Do these boundary conditions simply alter the upstream plasma parameters with the reconnection rate being determined by those upstream parameters or do boundary conditions affect reconnection in a more subtle way? Such questions will be addressed in ongoing laboratory reconnection experiments such as MRX, VTF and SSX.

Astrophysical systems are generally much larger than the microphysical scales such as the ion skin depth and ion gyro-radius. Most of the work on reconnection in the past, both numerical and experimental, have investigated relatively small systems – with scales of 10-100 times the ion inertial length. Scientists have been exploring reconnection in progressively larger computational domains. In the collisionless limit the rates of reconnection appear to be independent of the system size, although the mechanism that limits the length of the electron dissipation region continues to be debated [6-7]. The scaling behavior of reconnection with a guide field is much less well developed and in this case there is evidence that the dissipation region forms secondary islands that may be volume filling [19]. Because of the 3-D nature of this problem exploring reconnection scaling with system size with simulations will be a major challenge.

Important new data on reconnection with a guide field is likely to come from NASA's Solar Probe Plus mission, which will explore reconnection within ten solar radii of the sun. Predictions are that reconnection in this region will be dominated by a strong guide field and that the ambient beta will low. The instrument suite is designed to identify island structures and particle acceleration locally and in the corona. Thus, the combination of this new source of satellite data with simulations should facilitate significant progress in the guide field reconnection in an environment that is likely to be characterized by multi-island interactions.

The investigations of magnetic reconnection in space will require multi-scale measurements that sample both the minute diffusion region and the large-scale reconnection inflow and outflow regions, as being planned in the upcoming MMS mission. To enhance the effectiveness of new space-based satellite missions for studying reconnection, we advocate for a new generation of magnetic reconnection experiments, large-scale, versatile devices that can explore reconnection over a wide range of collisionality.

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The Onset of Magnetic Reconnection

Magnetic reconnection often occurs in explosive events where large amounts of magnetically stored energy are released rapidly at Alfvénic timescales. Well known examples of storage-release dynamics are solar flares [1], magnetospheric substorms [2], and tokamak sawteeth [3]. There has been much progress in understanding 2D, steady-state reconnection [4], but the time dependent problem—necessary to account for explosive reconnection—are 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. This transition—the so-called “trigger problem”—has been explored in 2D both analytically [5–7] and numerically [8,9] using ideas such as nonlinear mode excitation and bistability. We emphasize also that while the explosive release of magnetic energy during reconnection often gains the most attention reconnection can also take place in a quasi-steady fashion. Examples are at the Earth’s magnetopause and in the solar wind.

Much of the work on collisionless reconnection onset in the Earth’s heliosphere, where direct measurements are available, has focused on the role that the current layer width compared with the ion Larmor radius or skin depth plays in controlling reconnection onset. It is well known that the magnetotail current sheet thins down to around these scales prior to substorm onset. The recent evidence from the THEMIS spacecraft that at least some substorms are triggered by the onset of collisionless reconnection in the midtail region supports this idea [10]. Multisatellite measurements that show that current sheets wider than the ion skin in the solar wind are compressed across the Earth’s bow shock and then undergo reconnection in the magnetosheath further support these basic ideas [11]. Simulations also suggest that collisionless reconnection onsets strongly when

the thickness of the current layer approaches the ion skin depth [12,13] or the ion sound Larmor radius in the case of reconnection with a guide field [14].

In the case of reconnection in a collisional system such as the solar corona, it has been suggested that fast reconnection sharply onsets when the Sweet-Parker current layer approaches the ion skin depth [13] and there is some observational support from stellar data for this suggestion [15]. Further support comes from dedicated reconnection experiments in the laboratory where a strong increase in the rate of reconnection occurs when the Sweet-Parker current layer width falls below the ion inertial length [16].

However, recent simulations and models have demonstrated that resistive MHD reconnection at resistivities relevant to the corona are dominated by multiple islands rather than a simple Sweet-Parker layer [17, 18]. Thus, the onset transition becomes more complex, warranting further study. In the case of onset in the corona it has also been suggested that the onset is driven by global rather than local dynamics. The tether-cutting [19] and the breakout model [20] both involve the reconnection of overlying magnetic field lines and subsequent reconnection and expansion of flux tubes. In both case of these models, of course, the onset of fast collisionless reconnect must also ultimately take place. The electric field in flares exceeds the Dreicer runaway field by a large margin so the final stages of energy release must be collisionless.

Recent measurements of sawteeth in tokamaks suggest that the onset of the crash is linked to increasing magnetic shear at the reconnection layer and therefore the local increase of the reconnecting magnetic field [21]. Observations [22– 24] have further demonstrated that the sawtooth onset is spatially localized both toroidally and poloidally and that the temperature profile flattening is well organized as opposed to stochastic [25]. The spatially localized onset of the sawtooth crash suggests that even in cases where the magnetic field geometry is mainly 2D, 3D effects can be important for the onset of reconnection. Similarly, observations of reconnection on the sun have also indicated the presence of strong 3D effects in magnetic reconnection [26]. Dedicated laboratory experiment has also been applied to the study of spontaneous reconnection onset. In MRX the Hall effect and fast reconnection is observed when a low collisional regime is approached [27]. In the VTF reconnection experiment bursts of fast reconnection are observed [28]. The onset of reconnection occurs when the width of the current layer approaches the ion sound Larmor radius as suggested by theory. However, reconnection starts at one toroidal location and then spreads toroidally to the rest of the device. The exploration of 3-D dynamics during reconnection onset and comparison with these observations should be a focus of future computational studies.

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 independent parameters that determine whether reconnection can take place independent of the current layer. One such parameter is the plasma beta. In the solar wind, where the large number of reconnection events has now provided sufficient data to explore the parameter dependence of these events, high beta seems to suppress weak shear magnetic reconnection [29]. Ideas such diamagnetic stabilization have been proposed to explain finite beta stabilization [30] but need further development since the suppression of finite beta reconnection could prevent reconnection in astrophysical systems where beta is often high.

Investigations of the onset problem have raised further questions that must be addressed:

- 1) Why does reconnection often occur as an explosion (flares, substorms, sawteeth and disruptions in the laboratory while appearing steady at the Earth's magnetopause and in the solar wind)?
- 2) Is reconnection onset locally determined or a consequence of global dynamics? Are 3D effects fundamental to the onset of reconnection in nature?
- 3) What physical processes control the onset of collisionless reconnection? Are wide current sheets in collisionless plasma always stable (e.g., the heliospheric current sheet)?
- 4) Do ambient pressure gradients impact stability, particularly in plasmas with beta of order unity (e.g., the solar wind)?
- 5) Does the transition from Sweet-Parker (collisional) to Hall (collisionless) reconnection control onset during flares?

Given the complexity of these questions significant progress will require a coordinated effort that includes spacecraft observation of events on the Sun, in the solar wind, in the Earth's day side magnetopause and magnetotail as well observations in well diagnosed basic laboratory experiments. Numerically, the onset problem has been considered in fully kinetic simulations in 2D. However, for numerical studies in 3D full kinetic simulations are still not possible while at the same time retaining sufficient separation of the macroscopic and kinetic scales. Hall MHD codes are likely to play an important role in these investigations.

For the study of 3D onset problem dedicated laboratory experiments have the advantage that the phenomena can be studied under controlled conditions while retaining all 3D and kinetic effects. The direct measurement of the magnetic and electric fields as well as key plasma parameters allows for a detailed characterization of the onset dynamics. However, a significant drawback is that the system size of present day laboratory facilities is limited to a few ion skin depths. Physically larger facilities are desirable for minimizing and understanding the effects of the finite plasma boundaries.

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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. Presently, it remains unclear how these idealized results will extend to large-scale systems relevant to most astrophysical plasmas. This is true for both collisional parameter regimes where the resistive MHD model remains valid and kinetic regimes in which the resistive layers fall below the ion kinetic scales. In either case, the separation between the dissipation and macroscopic scales can be mind-boggling. In a large fusion machine or in the Earth's magnetosphere, typical macroscopic scales are $\sim 10^3$ times larger than the ion kinetic scale, while in the solar corona this ratio can exceed $\sim 10^8$ and for stellar flares and black hole accretion disks may approach $\sim 10^{10}$. Furthermore, in kinetic regimes there is clear evidence [1-4] that electron scale layers are expected to form within the ion scale reconnection layers, leading to an even larger scale separation. Within these regimes, a variety of two-fluid and kinetic models predict fast reconnection rates that are weakly dependent on the system size or dissipation mechanism [5-9], but the range of feasible simulation sizes is still quite limited in comparisons to astrophysical scales. Furthermore, it is not clear which applications actually reach ion scales where these effects become important.

For collisional reconnection regimes, the thickness of the Sweet-Parker dissipation layer scales as $\delta_{sp} \sim (\eta L_{sp})^{1/2}$ where η is the resistivity and L_{sp} is the length of layer. The reconnection rate is determined by the aspect ratio of the layer $\delta_{sp} / L_{sp} \sim S^{-1/2}$ where $S = 4\pi V_A L_{sp} / (\eta c^2)$ is the Lundquist number. Assuming that the layer length L_{sp} scales with the macroscopic system size implies Lundquist numbers around $S \sim 10^{14}$ in the solar corona, while in magnetars, collapsar models of gamma-ray bursts and core-collapse supernovae $S \sim 10^{18}$. This implies an enormous separation between the resistive and macroscopic scales, which imposes formidable challenges to understanding the cross-scale coupling. Although the Sweet-Parker solution is well established for low Lundquist numbers $S < 10^4$, the scaling of collisional reconnection in the high S regime remains uncertain due to secondary reconnection instabilities and turbulence.

Given the huge range of scales in collisional and kinetic regimes, *what is the interaction between the local dissipation scales and the global MHD evolution?* Do the largest scales dictate the structure of the dissipation region or is the large-scale dynamics controlled by the dissipation region? In principle, the coupling between these disparate scales could go in both directions, with the small-scale features influencing the macroscopic dissipation and time dependence, and/or the large-scale magnetic geometry influencing the structure and development of new reconnection layers. In recent years, 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). This same basic expectation now appears to hold in both collisional [10-15] and kinetic regimes [16-18], and for both anti-parallel and guide field geometry. One of the forefront challenges is to understand precisely how many islands are formed under various parameter regimes and how these islands modify the global reconnection rate, time dependence and particle acceleration. Within resistive MHD regimes, there is evidence that the reconnection rates are much faster [12,14] than simple Sweet-Parker estimates, but there remains considerable uncertainty in extrapolating to the limit of asymptotically large S . Another important consideration is that the formation of plasmoids may rapidly lead to the break down of resistive MHD [18-19], even for regimes that were previously thought to be collisional. The reason is that the new reconnection layers that form between islands are considerably thinner than the original Sweet-Parker layer. Depending on the parameters, these new layers may also be unstable to plasmoids leading to a hierarchy of reconnection layers that eventually approach ion kinetic scales [10,20], where two-fluid and kinetic effects begin to dominate [5, 21-22]

At the present time, most studies of this type have been limited to simple two-dimensional geometries, but in three-dimensions (3D) there is considerably more freedom to form both primary and secondary magnetic islands, since a full spectrum of modes are permitted to grow at the resonant surfaces within the sheared magnetic geometry. In the real 3D world, both primary and secondary magnetic islands correspond to flux ropes, which can interact in variety of complex ways not possible in simplified 2D simulation models [23-24]. If secondary island formation proves robust, one would expect large-scale reconnection layers to breakup into a complex hierarchy of interacting flux ropes (and perhaps lead to fully turbulent reconnection). The path

forward requires a much better understanding of how these secondary reconnection instabilities proceed in both collisional and kinetic regimes and as function of the ambient guide field. Does a single large x-line eventually dominate or does the dynamics always involve a hierarchy of interacting reconnection sites? As the theory and simulation move forward on these questions, satellite observations from the Earth's magnetosphere and the solar wind may provide some valuable observational constraints. For example, recent reconnection observations in the solar wind seem to suggest that at large distances (tens of thousands of ion skin depths) downstream of the x-line, the reconnecting current sheets are often highly planar and the structure of the outflow jet is remarkably smooth. This is in contrast to recent 3D simulations showing highly distorted current sheets with embedded secondary islands in the region surrounding 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 diffusion region evolve downstream.

In addition to secondary reconnection instabilities, in kinetic parameter regimes there are a wide variety of other plasma instabilities that may potentially influence the large-scale evolution. These include Buneman and streaming instabilities, the lower-hybrid drift instability, lower-hybrid waves, non-linear structures such as phase space holes, instabilities driven by temperature anisotropy or flow shear. At the present time, various research groups are exploring many of these possibilities using theory, simulation and small-scale laboratory experiments. However, it remains an outstanding challenge to demonstrate how these small-scale processes may lead to significant amounts of anomalous dissipation and influence the global evolution. For large-scale fluid modeling of reconnection, it would be highly desirable to capture these effects in terms of anomalous resistivity or viscosity, but progress towards this goal has been slow.

Another important consideration is that large-scale astrophysical systems are in many cases likely to be turbulent. Given the research results discussed above, it seems plausible that large 3D reconnection layers may quite naturally and self-consistently develop into fully turbulent reconnection scenarios. However, it is also possible that pre-existing turbulence excited by other sources may have a profound effect on the reconnection dynamics. In the past decade, promising results have been reported by imposing turbulence within MHD models [25-27]. As these research efforts move forward, it is important to reconcile these results with high-S simulations in which the fluctuations are driven self-consistently by instabilities within layer.

To make progress on these various issues and confidently apply the results to astrophysical applications, will require a coordinated effort between theory, simulations, laboratory experiments and satellite observations. While each of these approaches have some significant strengths and weaknesses, these can be overcome by working together. For example, linear theory can provide valuable predictions regarding the secondary instabilities that should be expected within elongated reconnection current layers, but do not provide any information regarding the nonlinear feedback. The formation and stability properties of kinetic scale layers are currently being studied within dedicated reconnection experiments such as MRX [3], where high-resolution measurements can be

repeated under well-controlled conditions. Unfortunately, at the present time these devices are not sufficiently large to access regimes where secondary islands may become important, and are often more collisional than applications in space. Satellite observations of reconnection in the magnetosphere offer the advantage of high time resolution measurements of the fields and particle distributions within highly collisionless reconnection layers. However, since there are only a small number (~1-4) of satellites available for each crossing, it can be challenging to develop a comprehensive picture of complex time dependent phenomena. Thus while magnetic islands and an assortment of different waves have been observed near reconnection sites, their precise role remains speculative. Numerical simulations will continue to play a central role in understanding the nonlinear evolution and in the future should allow researchers to *bridge the gap* between laboratory experiments and space observations. For example, promising approaches such as collisional kinetic simulation [19-20] can rigorously transition between collisional MHD and fully collisionless regimes. This should allow plasma processes that are studied and verified within controlled laboratory experiments to be more effectively extrapolated to collisionless parameters regimes and to quickly understand the influence of different macroscopic drivers and boundary conditions.

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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 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 understanding 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 great powerlaw in the sky. The evidence within the heliosphere is strong that the fraction of energy going into bulk heating and that 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 [1, 2] with recent over-the-limb observations suggesting that the pressure of the energetic electron component can approach unity [3]. 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, large-scale magnetic x-line. Energetic electrons consistent with such models have been seen during the crash of sawteeth in tokamaks [4]. However, parallel-electric-field models are inconsistent with the large numbers of energetic electrons seen in impulsive flares [5] – the current resulting from the flux of electrons in a single narrow stream stretching from the corona to the chromosphere would produce a magnetic field that is many orders of magnitude larger than the coronal field. 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 [6]. Electrons in flares can be accelerated efficiently in compressible MHD turbulence but a mechanism for producing this turbulence at the required efficiency has not been identified. There has been increasing recognition on the basis of observations [7, 8] and modeling [9–11] that in complex magnetic fields as found on the sun, reconnection forms multiple magnetic islands that are 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 [9, 12] drive electron acceleration. Both of these mechanisms drive the parallel pressure and the contracting islands are predicted to bump against the firehose instability threshold, which shuts off reconnection and produces an upper limit on the spectral index of the particle flux of 1.5 [9]. 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 Alfvénic outflows has been well documented during reconnection in the Earth’s magnetosphere and the solar wind, where “heating” often consists of counterstreaming ion beams [13, 14]. The measured increment in the ion temperature typically falls below predictions based on Petschek’s slow shocks. Moreover, even the largest PIC reconnection simulations do not produce the switch-off slow shocks that were expected to bound reconnection outflows [15]. The narrow boundary layers that bound the reconnection exhausts in simulations cause the ions crossing into the exhaust to act like “pickup” particles and gain an effective thermal velocity equal to the Alfvénic outflow velocity [16, 17]. In the case of the low beta corona, the resulting temperature increments of around a keV/nucleon are substantial. The pickup process therefore may be important for seeding ions to the super-Alfvénic regime. In laboratory experiments in the Madison Symmetric Torus (MST), a reversed-field-pinch configuration, strong ion heating has been measured during reconnection events, with high mass ions gaining greater energy than low-mass ions [18]. In the SSX experiment strong heating of ions in the outflow jets have also been measured [19]. Solar wind and laboratory reconnection events are providing a wealth of data. Further exploration of this data should enable scientists to untangle the role of slow shocks versus “pickup” processes in heating reconnection exhausts.

The spectrum of energetic ions from impulsive flares extends up to the GeV/nucleon range in X-class flares [6] and the spectra of protons as well as trace ions have been well-documented by in situ satellite measurements in the solar wind [5, 20]. As noted earlier, there is no evidence for an energetic ion component during solar wind reconnection events. An important observation in impulsive flares is the abundance enhancement of high mass-to-charge (M/Q) ions. The resonant acceleration of ions in reconnection-driven MHD turbulence has been offered as a mechanism for accelerating high energy ions and as a source of the abundance enhancements [5, 21]. As in the case of electron acceleration, the driving mechanism for this turbulence remains unclear. On the other hand, the dynamics of ions in a 3-D multi-island reconnection environment [10] remains an attractive model for ion acceleration since the generation mechanism for this “turbulence” is part of the reconnection energy release process. As in the case of electrons, super-Alfvénic ions should be efficiently accelerated during the contraction and merger of the magnetic islands that make up this turbulence. In simulations of the reconnection of the heliospheric sectorized magnetic field Fermi reflection in merging islands was the dominant driver of ion energy gain [22]. It has been suggested that reconnection-driven ion acceleration rather than shock acceleration is the source of the 10 – 100 MeV anomalous cosmic rays that populate the heliosphere [22, 23]. An important question is therefore whether reconnection-driven ion acceleration can be represented as a first order Fermi process. If so, as in the case of shock acceleration, explaining the ubiquitous powerlaw spectra of energetic particles becomes straightforward [9, 22, 24].

The exploration of particle acceleration during reconnection using natural reconnection events is challenging because the most energetic events take place in the low beta environment of the sun where in situ measurements are not possible. The occasional energetic electron reconnection events seen in the magnetotail have provided useful in situ data for identifying acceleration mechanisms but the limited number of such events limits progress. An important goal of the laboratory astrophysics community should be to explore the feasibility of an experiment to explore multi-island reconnection and particle acceleration. The theory and modeling of reconnection driven particle acceleration is now sufficiently well developed that a number of significant ideas and questions have been posed. Now is the time therefore to ask whether a well-designed experiment could be constructed to address these key questions. The successful design of the MRX experiment, which was successful in demonstrating that theoretical ideas about the importance of the Hall magnetic field were correct, is an example of how the close interaction between theory and experiment can produce breakthroughs in physics.

A reconnection-driven particle acceleration experiment would have to be substantially larger than the existing MRX, VTF, SSX, RSX and Caltech interacting loop experiments since sufficient magnetic flux would be required to ensure that energetic ions could be contained and at the same time interact with multiple reconnection sites. Thus, such an experiment would have to be a national facility. While the cost of such an experiment would be substantial in comparison with present dedicated laboratory reconnection experiments, its cost would be a small fraction of that of NASA satellite missions that are designed to address similar scientific issues.

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Reconnection in Extreme Astrophysical Environments.

Most of the magnetic reconnection research so far has been driven by our desire to understand magnetic dissipation in various space, solar, and laboratory plasmas, with applications to solar flares, substorms in Earth magnetosphere, and sawtooth disruptions in tokamaks. Importantly, all of these are relatively tenuous, low-energy-density, optically thin environments, adequately described as a collection of non-relativistic charged particles whose numbers are conserved.

Magnetic reconnection has also been frequently invoked in a large variety of astrophysical contexts, especially in high-energy astrophysics. Examples include accretion disks and their coronae and large-scale magnetospheres, jets, gamma-ray bursts (GRBs), pulsar magnetospheres and pulsar winds, flares in soft gamma repeaters (SGRs), etc. (see [1, 2] for review.) Not surprisingly, physical insights obtained from solar-, space- and lab reconnection studies have often been applied to these astrophysical systems. However, it is important to appreciate that the Universe is vast and very diverse. The range of physical conditions found in various astrophysical environments far exceeds that found within our solar system. In particular, there are some astrophysical phenomena in which, on the one hand, reconnection has been hypothesized to play an important role

and, on the other hand, the physical parameter regimes are really very different from those in solar flares, Earth's magnetosphere, and laboratory plasmas. Therefore, a straightforward extrapolation of the conventional reconnection scalings to some of these extreme systems is not justified. If we want to understand how these systems really work, we thus have to develop new theories of magnetic reconnection, taking into account several key physical processes that are not conventionally included in traditional reconnection studies. Among the most important of these additional effects are: (1) special relativity; (2) radiation; (3) pair creation.

(1) *Special-relativistic effects* are important when the reconnecting magnetic field is so strong and the plasma is so tenuous that the magnetic energy density exceeds not only the pressure, but also the rest-mass energy density of the upstream plasma. Then, the corresponding Alfvén speed and hence the reconnection outflow velocity approach the speed of light, and one needs to understand the role of various special-relativistic effects, e.g., Lorentz contraction and time dilation [3,4,5].

This situation is especially relevant to astrophysical pair plasmas, with one of the most important and cleanest examples being radio-pulsar magnetospheres, which are believed to inevitably open up and develop a large-scale equatorial current sheet beyond the light cylinder. Reconnection in this current sheet may be an important factor in producing the observed pulsed high-energy emission and perhaps even the coherent radio emission. At larger distances, in the so-called pulsar wind region, magnetic reconnection has sometimes been invoked to resolve the famous “sigma problem” --- very efficient conversion of magnetic energy to particle energy [6,7,8]. In addition, relativistic reconnection in pair plasmas is conjectured to be responsible for powering the spectacular giant magnetar flares in soft-gamma repeaters [9,10,11] and it may also be important to relativistic jets of gamma-ray bursts [12,13,14,15,16] and AGNs [17].

Among the key questions that will be addressed, and hopefully resolved in the next few years are: What factors control both the outflow velocity and the reconnection rate in relativistic reconnection? Does reconnection fundamentally change behavior in the regime of relativistic inflows and outflows? How the released energy is partitioned? How efficient is non-thermal particle acceleration? Does pair reconnection remain fast even without traditional Hall fields? Is there observational evidence for fast reconnection in such systems? Are there any robust observational signatures of relativistic reconnection?

Relativistic aspects of extreme astrophysical reconnection are probably the easiest to understand, as compared to the other two aspects discussed below. In fact, even though our understanding of relativistic reconnection is still not mature and far behind that of non-relativistic reconnection, this topic has probably already grown out of its infancy stage and should be considered as being in its “youth” stage. A significant amount of work has already been done both on its fundamental physics issues [3,4,5,18,19,20] and on astrophysical applications [14,15,16,17].

We should realistically expect significant theoretical and computational progress in this area in the near future, with relatively modest modifications to the existing numerical and

analytical models. In fact, most of the modern PIC codes used to study non-relativistic collisionless reconnection are intrinsically relativistic and so can be (and are being) applied to relativistic reconnection problems. In addition, recent advances in developing resistive relativistic MHD algorithms [21] instill hope that more progress will be made on collisional relativistic reconnection. However, laboratory investigations of relativistic reconnection are not yet on the horizon, but perhaps we should start thinking about them.

(2) *Radiation* may affect reconnection profoundly in several fundamental ways, none of which have been adequately explored so far. In particular:

(a) Prompt radiative cooling in both optically thin and optically thick regimes greatly affects the energy balance and hence the dynamics of the reconnection layer. Different radiation cooling mechanisms may be important in different astrophysical situations, e.g., (1) synchrotron and synchrotron-self-Compton in GRB, AGN, and Blazar jets [17]; (2) external inverse-Compton cooling of energetic electrons by powerful ambient soft radiation fields in coronae of black holes accreting at a large fraction of the Eddington limit, both in galactic X-ray sources and in AGNs [22]; (3) radiation diffusion out of an optically-thick pair-dominated reconnection layer in the context of magnetar flares and GRB central engines [11,16]. We believe that any serious effort in this area will require approaching the reconnection problem as a radiative-transfer problem [11].

(b) Radiation pressure: in some of the most spectacular high-energy astrophysics phenomena, the dissipated energy density, and hence the plasma temperature, is so high that radiation pressure (that scales as T^4) starts to play an important role. Examples include reconnection in central parts of black-hole accretion disks; central engines and inner parts of GRB jets; and gamma-ray flares in magnetospheres of magnetars. In most extreme cases (magnetar flares and GRBs) radiation pressure is likely to completely dominate over the plasma pressure.

(c) Compton-drag resistivity (due to electron-photon collisions as opposed to electron-proton collisions) is important in several high-energy astrophysics situations (accretion disk coronae of accreting black holes [22], magnetar flares [11], and GRB jets [11,16]).

To the best of our knowledge, the above fundamental aspects of magnetic reconnection in the presence of powerful radiation fields have not been adequately explored so far, even though they are critical for a number of outstanding problems in modern high-energy astrophysics. There is a clear astrophysical motivation for investing resources in this fundamental research area to assure rapid progress. To some degree, this progress will be facilitated by the advent of new computational and experimental tools developed recently in the emerging area of High-Energy-Density Physics (see below).

(3) *Pair Creation*: (this fundamental physics issue is closely related to the previous one -- radiation effects). It is currently believed that some astrophysical systems --- most notably magnetars and central engines of Gamma Ray Bursts and Supernovae --- possess super-strong magnetic fields, i.e., fields exceeding the critical quantum field of about 4×10^{13} G.

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 huge (of order 10^{28} ergs/cm³) that, when converted to radiation energy (with density aT^4), it results in temperatures greater than the electron rest-mass energy of 0.5 MeV. In a situation like this, copious electron-positron pair creation inevitably occurs [11,16], which results in a great increase of the optical depth across the reconnection layer and also makes it highly collisional [23]. How these processes affect the overall reconnection dynamics is still not clear.

Connections to High-Energy-Density (HED) Physics:

The above discussion demonstrates that many astrophysical phenomena call for developing a better physical understanding of magnetic reconnection in High-Energy-Density environments in which magnetic field, plasma, and radiation are all important and strongly coupled to each other. We suggest that studying reconnection in HED plasmas should become an important new direction in future reconnection research. Indeed, HED Physics (HEDP) and Laboratory Astrophysics (HEDLA) represent a new and exciting branch of modern physics [24]; they study the properties of matter at extremely high energy densities where radiation pressure is important. HEDP is currently enjoying a period of rapid growth fueled in part by the availability of new very powerful laser-plasma and Z-pinch experimental devices, such as NIF, Hercules, Vulcan, Omega, and the Z-machine. In addition, there has been a lot of progress on the computational side, with the development of advanced radiation-MHD codes. The advent of these new experimental and computational capabilities calls for the exploration of fundamental plasma physics processes, including magnetic reconnection. So far, there has been only a handful of disjoint experimental [25,26] and theoretical [11,16,23] investigations of various aspects of HED reconnection, and we believe that a more coherent and organized effort in this important new area of fundamental research is needed.

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Ties with other working groups

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. As the numerical modeling has become one of the essential tools for studying processes in astrophysical systems, the proper modeling of magnetic reconnection in numerical simulations has become a burning issue. Code diffusivity introduces its own reconnection and therefore understanding whether numerical reconnection renders the results of simulations unreliable requires much better understanding of the reconnection physics. Thus we expect synergetic interaction and collaboration between reconnection experts and other members of the plasma astrophysics community.

1. *Turbulence and reconnection*: The generic state of astrophysical fluids is often turbulent. This turbulence has been documented with in situ measurements of interplanetary and magnetospheric magnetic fields [1, 2] and interstellar observations [3, 4, 5, 6, 7, 8, 9, 10, see also 11 for a review]. This turbulence is a consequence of the numerous sources of free energy and from the large Reynolds numbers of astrophysical fluids. Pre-existing turbulence may change the reconnection rate but at the same time reconnection can induce turbulence [12, 13, 14, 15]. Moreover, the properties of turbulence vitally depend on the ability of magnetic field lines to reconnect [12].
2. *Reconnection and particle acceleration in shocks*: Shocks are an accepted mechanism of First Order Fermi acceleration of particles [16, 17, 18]. Recently the First Order Fermi acceleration has been identified as a process taking place during reconnection [19, 20, 21, 22]. What is the relative importance of the two acceleration processes? What are the astrophysical objects where one or another process dominates? One can also visualize a situation when the acceleration in reconnection acts to boost the energies of particles sufficiently so that shocks can accelerate them further. For instance, this may be a very important process for the pre-acceleration of electrons [23, 24, 25].
3. *Magnetic Dynamo*: Magnetic reconnection is an essential element of magnetic field generation via the dynamo process. Turbulent magnetic diffusion, which is a key component of the mean field dynamo is only justified in the kinematic regime when the magnetic field back-reaction is negligible [26]. Can magnetic reconnection in turbulent

fluids be fast enough to justify the diffusivities that are usually attributed to turbulent diffusivity in the mean field dynamo? Is magnetic diffusivity fast only in collisionless fluids? Do we expect to see the differences in dynamo operation for collisional ISM and collisionless coronal gas? Turbulent magnetic dynamo is another process of the crucial importance [27]. How is the turbulent dynamo modified by realistic and physics-based reconnection?

4. *Momentum transport*: Magnetic fields connecting different elements of accretion disks are essential for producing momentum transport [28, 29]. The radial extent to which magnetic fields can couple the motion of the accretion disk plasma affects the efficiency of the momentum transport. In the presence of the magneto-rotational instability the disks become turbulent and therefore it is essential to understand reconnection in turbulent plasmas. Are the magnetic reconnection rates different in the collisional disks bodies and collisionless disk halos? How does the local plasma beta influence reconnection? The answers to such questions are required to correctly implement reconnection in numerical simulations of accretion.

5. *Jets and Outflows including structure formation*: Launching astrophysical jets and outflows requires magnetic stresses. Simulations of jets show magnetic field reversals. All this requires understanding the properties of magnetic reconnection. In addition, jets are believed to be sources of high-energy particles? Can this be the consequence of reconnection rather than shocks?

6. *Magnetized Dusty Plasmas*: Magnetized dust carrying most of the charge of the system is a common phenomenon in dense environments of molecular cloud cores. Removal of magnetic fields from the cloud cores is an essential process that can take place via magnetic reconnection. Can magnetic reconnection be efficient in such rather special systems where the dust carries most of the charge? The dust size distribution is known to evolve in astrophysical environments [30]. For the physics of dust coagulation and shattering the velocities of dust particles are important. Can magnetic reconnection accelerate charged dust the same way that it accelerates energetic particles?

7. *Interface and Shear Instabilities*:

These instabilities are affected by the magnetic field and, as a result, the dynamics of the magnetic field and associated reconnection can be important. The non-linear stages of MRI, Rayleigh-Taylor, Richtmyer-Meshkov, Vishniac and other instabilities in magnetized plasma involve strong magnetic field entangling the evolution. The dynamical results will depend on the reconnection speed.

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