A Project Information

- **Title:** Super-Alfvénic propagation of energy released during magnetic reconnection in the Earth's magnetotail.
- **Project ID:** UDEL0002
- **Submission date:** September 14, 2015.
- **Project Lead:** Michael Shay, University of Delaware
- **NSF Award:** Collaborative Research: Super-Alfvénic propagation of energy released during magnetic reconnection in the Earth’s magnetotail, Award # AGS-1219382, 9/1/2013 - 8/31/2016, Program Officer: Janet Kozyra, PI: Michael Shay, University of Delaware.
  Note: Dr. Shay will be applying for a no-cost extension of this grant, leading to an end date of 8/31/2017.

B Overview of the Project

Magnetic reconnection plays a fundamental role in magnetotail dynamics, reconfiguring magnetic topology to release stored magnetic energy. An important unsolved question regarding magnetic reconnection concerns the nature of the energization of plasma and the energy propagating away from the reconnection site, with implications for our understanding of transient magnetotail phenomena such as bursty bulk flows, dipolarization fronts, and substorms. The bulk ion flows accelerated by reconnection have been measured directly by spacecraft observations and have been linked to the generation of aurora. However, the propagation speed of this energy is limited to the Alfvén speed. Less well understood, however, are the heating of the plasma due to reconnection and the super-Alfvénic flows of energy associated with kinetic electrons dynamics which tend to occur near the magnetic separatrices. The quadrupolar magnetic fields in this region associated with Hall dynamics have been shown to be the manifestation of a kinetic Alfvén wave (KAW) which propagates super-Alfvénically parallel to the magnetic field, generates substantial Poynting flux which can exceed that due to the bulk ion flows, and is associated with energetic electrons streams which compose the Hall currents. For this study we seek to answer the following questions:

- What controls the velocity and the energy carried by the Kinetic Alfvén Wave (KAW) as it propagates away from magnetic reconnection.
- What role does the KAW play in the heating and energization of electrons and ions?

This question will be addressed using P3D, the fully electromagnetic particle-in-cell code (PIC) through systematic simulations of magnetic reconnection. This is the first systematic study of the properties of the KAW and the role that it plays in magnetic reconnection.

**Relationship with NWSC Community Science Objectives:** Magnetic reconnection is present throughout the Heliosphere and plays an important role in such diverse phenomena as coronal heating, the acceleration and heating of the solar wind, and the interaction of the solar wind with the Earth. Understanding the nature of energy propagation away from reconnection is necessary for future predictive models of space weather. In terms of the “HPC dimensions of Earth System Modeling,” (*NWSC Science Justification*, Figure 2.1) this work represents “New Science” and “Better Science.” New science because the interplay of the KAW and reconnection has not been carefully examined, and better science because this is the first study to utilize a complete kinetic plasma simulation for systematic studies of this phenomena.
C Science Objectives

C.1 Background

Magnetic reconnection plays a fundamental role in magnetotail dynamics, reconfiguring magnetic topology to release stored magnetic energy. An important unsolved question regarding magnetic reconnection concerns the nature of the energy propagating away from the reconnection site. First, while it is known that this propagating energy can take the form of substantial plasma heating, the process by which this occurs is not well understood because simple closure models of plasma equations of state are not valid in the nearly collisionless magnetosphere. Second, the speed with which this energy flows has significant implications for our understanding of transient magnetotail phenomena such as bursty bulk flows, dipolarization fronts, and substorms. To determine the role that reconnection is playing in these phenomena, it is important to determine where and when magnetic reconnection initiates. Because spacecraft rarely pass directly through the x-line, reconnection onset usually is determined by remote observations. Tracing back in time and space to reconnection onset requires a good understanding of both the path that the reconnection signals propagate along as well as their speed.

These issues highlight the need to examine the fastest propagating “signals” from reconnection and the form of energy that they take. One such possibility, which is the focus of this proposal, is the quadrupolar Hall magnetic field associated with collisionless reconnection. This signature has been shown to be the manifestation of a kinetic Alfvén wave (KAW), which propagates super-Alfvénically parallel to the magnetic field and generates substantial Poynting flux which can exceed that due to the bulk ion flows. This KAW is also associated with energetic electrons and heated plasma that propagate super-Alfvénically. The quadrupolar magnetic field and energetic electrons, denoted “KAW/EE” in this proposal, are located close to the magnetic separatrix. The basic physical properties of this KAW/EE as it propagates away from the x-line are the focus of this proposal.

Furthermore, our recent publication as part of this project has found that a large scale parallel electric potential forms which is associated with the Hall magnetic field and thus the KAW [1]. This potential acts to hold in the hot electrons in the reconnection exhaust. The heating of these electrons in the exhaust has been found (in another publication in this project) to scale with the inflowing Alfvén speed [5], consistent with satellite observational studies [2]. This potential efficiently accelerates and heats electrons but partially inhibits ion heating [1]. Therefore, it can act as an energy transfer mechanism between ion and electron heating. This new finding provides a linkage between the heating of plasma during magnetic reconnection and the structure and propagation of the KAW. Therefore, we propose to run computer simulations to examine the following questions: (1) What is the propagation speed and scale sizes of the separatrix kinetic Alfvén wave and associated energetic electrons (KAW/EE); (2) How do its properties change as it propagates away from the x-line?; (3) How much energy does it carry and in what forms?; and (4) How is its energy attenuated as it propagates away from the x-line?

D Computational Experiments and Resource Requirements

Simulations will be performed using a state of the art simulation code: a kinetic particle-in-cell (PIC) code P3D [3, 6]. This code is parallelized using MPI routines with 3-D domain decomposition and displays reasonable scaling with increasing processor number. P3D is used by scientists throughout the United States and is now hosted by GitHub in the private repository P3D-PLASMA-PIC on GitHub.com.

D.1 P3D: Kinetic particle-in-cell

The code P3D is a kinetic particle-in-cell code which can simulate collisionless plasma system including all relevant kinetic physics. This code is fully electromagnetic; that is, it includes light waves and plasma
oscillations. The field equations for this code are

\[
\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},
\]  
\[
\frac{\partial \mathbf{E}}{\partial t} = c^2 \left[ \nabla \times \mathbf{B} - \mathbf{J}_i + \mathbf{J}_e \right],
\]

where \( \mathbf{J}_i \) and \( \mathbf{J}_e \) are the ion and electron bulk currents which are determined by summing the individual particles onto the grid. Time has been normalized to \( t_o = \Omega_i^{-1} = (eB_o/m_i c)^{-1} \), with \( B_o \) chosen as the initial lobe magnetic field. Length has been normalized to \( L_o = c/\omega_{pi} = c\sqrt{m_i/(4\pi n_o e^2)} \), with \( n_o \) equal to the initial current sheet density minus the lobe density. The velocities therefore are normalized to the Alfvén velocity, \( \tau \) is the normalized speed of light: \( \tau \equiv c/(L_o/t_o) = c/c_A \).

The individual particle equations of motion are

\[
\frac{d\mathbf{x}_{ij}}{dt} = \mathbf{v}_{ij},
\]
\[
\frac{d\mathbf{v}_{ij}}{dt} = \left[ \mathbf{E} + \mathbf{v}_{ij} \times \mathbf{B} \right],
\]
\[
\frac{d\mathbf{x}_{ej}}{dt} = \mathbf{v}_{ej},
\]
\[
\frac{d\mathbf{v}_{ej}}{dt} = -\frac{1}{m_e/m_i} \left[ \mathbf{E} + \mathbf{v}_{ej} \times \mathbf{B} \right],
\]

where \( \mathbf{x}_{ij} \) and \( \mathbf{v}_{ij} \) are the position and velocity of the \( j \)th ion particle. The particle electron positions and velocities are denoted similarly. The values of \( \mathbf{E} \) and \( \mathbf{B} \) at the location of each particle are interpolated from nearby grid points. Because grid-scale electron plasma oscillations have a smaller frequency than grid-scale light waves, the field can be sub-stepped. The discretization for the fields has a uniform cell size and is static over the simulation. Derivatives in space are taken using a 3 point second order accurate scheme. The time stepping scheme for the fields is a second order accurate trapezoidal leapfrog scheme. The individual particles exist between grid points and their velocities and positions are leapfrogged with respect to one another to achieve second order accuracy in time.

P3D is a mature production level code that has been benchmarked carefully and whose scaling properties have been optimized. As part of our Accelerated Scientific Discovery program of simulations on Yellowstone, P3D was shown to scale very well up to 16,384 cores, as shown in Fig. 2.

D.2 Computational Time Required

Magnetic reconnection simulations using P3D will be performed for this study. The initial configuration is an equilibrium of sheared magnetic fields, which is unstable to magnetic tearing and the resultant reconnection [4]. This project has so far been successful in determining the properties of and some of the physics which controls the heating of the plasma during magnetic reconnection and the effect of the KAW on this energization [5, 1]. A large number of simulations with system size \( L_x \times L_y = 204.8 \times 102.4 c/\omega_{pi} \) and \( 4096 \times 2048 \) grid points have been performed; Shay et al., 2014 has a table describing many of them [5].

However, it is clear from our experience that in order to study the propagation, damping, and dispersion characteristics of the KAW during reconnection it will be necessary to use larger system sizes and perform a scaling study of the affect of \( m_i/m_e \). In Fig. 1(a) and (b) are shown preliminary studies of the KAW. The 2D plots show the variation of \( B_z \) along magnetic field lines (l) for different magnetic field lines (horizontal axis). Due to the quasi-steady nature of the reconnection, the slope of the top-most contours represent the velocity of the KAW structure as it propagates away from the magnetic field line. Fig. 1(a) is a typical simulation we have in hand \( 204.8 \times 102.4 c/\omega_{pi} \) with \( 4096 \times 2048 \) grid points, and Fig. 1(b) is for a system 4 times larger. Both systems have \( m_i/m_e = 25 \). The larger simulation in (b) has a roughly constant slope.
Figure 1: Necessity for large simulation sizes and scaling with \( \frac{m_i}{m_e} \). (a) and (b) \( B_z \) propagation along field lines. Simulation in (b) is 4 times larger than simulation in (a). Horizontal axis is location where field line crosses center of exhaust and \( l \) is distance along field line. Due to quasi-steady period of reconnection, horizontal axis also represents time using field line velocity \( v_0 \). The slope of the top-most contours represents parallel propagation velocity of KAW. (c) Electron heating rate \( M_{Te} \) dependence on electron mass from Ref. [5]. Solid line is best fit and asterisk is value measured from satellite observations [2].

for the top-most contours, while the smaller system in (a) does not. Clearly, only the larger system would be adequate to determine the KAW velocity. Doubling the box size to \( L_x \times L_y = 409.6 \times 204.8 \) is expected to be sufficiently large for the KAW properties to stabilize.

In addition, our results in hand imply that \( \frac{m_i}{m_e} \) can play a role in modifying the properties of the KAW and the heating of the plasma. Fig. 1(c) shows heating rates versus mass ratio for a study of electron heating during magnetic reconnection. The heating rates become reduced as \( \frac{m_i}{m_e} \) decreases. But, by performing a scaling with mass ratio, we were able to estimate the properties of electron heating for realistic electron mass, which compares favorably with satellite observations [2]. For this reason, although most simulations will have \( \frac{m_i}{m_e} = 25 \), a smaller number of more expensive simulations with \( \frac{m_i}{m_e} = 100 \) and 400 are planned.

A typical two dimensional simulation with mass ratio \( \frac{m_i}{m_e} = 25 \) and a system size \( (L_x, L_y) = (204.8, 102.4) \), requires \( 4096 \times 2048 \) grid points and around a billion particles for 100 particles per grid cell. These simulations are typically run until a time of about \( t \approx 100 \) in normalized time units, which necessitates about 10,000 time steps per run. Each run typically takes on the order of 2 hours on 1024 real cores on Yellowstone, which requires around 2100 core hours per simulation. This gives a code efficiency of \( 2.5 \cdot 10^{-8} \) hours/(grid-cells * time-steps). This value is used to estimate the time necessary to perform the simulations for this study. The code scales quite well on Yellowstone up to 16,384 processors, as shown in Figure 2. As discussed regarding Fig. 1a-b, a system size of \( 409.6 \times 204.8 c/\omega_{pi} \) is expected to be sufficient to give adequate time to probe properties of the KAW.

Note that significant optimizations have been implemented into P3D, which have increased efficiency recently. Key items have been more efficient particle stepping routines and particle sorting routines. Since the bulk of the computational time involves particle evolution in time, these have led to significant improvements. Furthermore, a more efficient initialization of the system allows a faster onset of magnetic reconnection with fewer secondary islands generated. For that reason, the core hours per grid scale per timestep have decreased significantly in the past several years.

The KAW is known to depend strongly on the Alfvén speed and the angle of propagation between the wave and the magnetic field. The upstream reconnection magnetic field \( B_r \) controls the Alfvén speed and the out of plane magnetic field \( B_y \) controls the angle of propagation, so we vary these with three values...
each: \( B_r = \{1/\sqrt{5}, 1, \sqrt{5} \} \) and \( B_g = \{0.0, 0.1, 0.5\} \). The speed of the KAW is also dependent on plasma \( \beta = 8\pi nT/B^2 \), while the linear Landau damping of the wave can be affected by the electron to ion temperature ratio \( T_e/T_i \). It is important to simulate \( T_e/T_i \gg 1 \) and \( T_e/T_i \ll 1 \). Running three different temperatures for both ions and electrons will allow an adequate variation of parameter space to examine the effects of \( \beta \) and temperature ratio, giving: \( T_e = \{0.02, 0.2, 2.0\} \) and \( T_i = \{0.02, 0.2, 2.0\} \).

Varying these 4 parameters over three values each requires \( 3^4 = 81 \) simulations with \( m_i/m_e = 25 \) and \( 8192 \times 4096 \) grid points, at a cost of about 17,000 hours per simulation. This set of simulations will allow an exhaustive study and understanding of the variation of KAW properties over a wide range of conditions. It is expected that these systematic simulations will allow a determination of the basic physics controlling the character, propagation speed, and change in time of the KAW properties.

However, the electron mass may also modify KAW properties, so a scaling study is necessary on the electron mass ratio. Changing the electron mass ratio is difficult. The grid scale \( \Delta \propto \sqrt{m_e/m_i} \) because the electron Larmor radius, inertial length, and Debye length must be resolved. Therefore, reducing \( m_e/m_i \) by a factor of 4 requires twice as many grid points in each direction, and the time step to be halved, which means that a simulation requires about 8 times more computational resources.

For this reason, it will be necessary to use the physics learned from the more modest \( m_e/m_i \) simulations to determine the parameter regime to study. It is estimated that about 10 simulations at \( m_e/m_i = 100 \) will be necessary to understand the scaling of KAW with mass ratio and verify that the \( m_i/m_e = 25 \) scaling persists. 10 simulations will allow at least three of the four parameters \( B, B_g, T_e, \) and \( T_i \) to be varied between two values each. In the previous study of the effect of KAW and reconnection on electron heating, a single focused \( m_i/m_e = 400 \) simulation allowed the extension of the electron heating prediction to realistic mass ratios, as shown in Fig. 1c. Therefore, we plan on a single focused \( m_i/m_e = 400 \) run again. The results from previous simulations will be examined to choose the optimum parameters for this quite expensive simulation.

PIC simulations are extremely memory intensive owing to the large number of individual particle data that must be stored. Each \( m_i/m_e = 25 \) simulation requires around 100GB of storage, with \( m_i/m_e = 100 \) and \( m_i/m_e = 400 \) using 400 GB and 2TB respectively. With the number of simulations described above, these runs will require about 30TB of archival storage. We estimate that about we will need access to about 1/2 of this data at a time, so we request 15TB of project space.

A table showing the different simulations with the requested Yellowstone hours is shown below. Note that because our simulations are valid for a range of locations in the heliosphere, it is not possible to give the core-hours per simulated year or other time period. Instead, we have given them per inverse ion-cyclotron time \( (\Omega_{ci}^{-1}) \). Although the inverse ion-cyclotron time can vary greatly throughout the heliosphere, the core hours it takes to simulate one of these times will not.

### Resources Requested

<table>
<thead>
<tr>
<th>Study</th>
<th>System Size (Grids)</th>
<th>Time Steps</th>
<th>Core hours per simulation</th>
<th>Total Approx Core Hours</th>
<th>Archival Space/sim (TB)</th>
<th>Total Archival Space (TB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_i/m_e = 25 ) 3-values each of ( B_r, B_g, T_e, ) and ( T_i ).</td>
<td>( 8192 \times 4096 )</td>
<td>200</td>
<td>20000</td>
<td>16,777</td>
<td>1,400,000</td>
<td>0.2</td>
</tr>
<tr>
<td>( m_i/m_e = 100 ) focused parameter sweep on 3 of 4 parameters</td>
<td>( 16384 \times 8192 )</td>
<td>200</td>
<td>40000</td>
<td>134,218</td>
<td>1,300,000</td>
<td>0.8</td>
</tr>
<tr>
<td>( m_i/m_e = 400 ) focused simulation</td>
<td>( 32768 \times 16384 )</td>
<td>200</td>
<td>80000</td>
<td>1,073,742</td>
<td>1,100,000</td>
<td>3.2</td>
</tr>
<tr>
<td>Total (Rounded)</td>
<td></td>
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</table>

### D.3 Data Analysis and Visualization

The initial analysis of data will be performed using IDL and python. 5000 core hours each for 4 users are requested on the Geyser and Caldera clusters, giving a total of 20,000 core hours requested.
E Data Management Plan

Kinetic particle-in-cell (PIC) computer simulations are extremely storage intensive. The reason is due to the necessity of simulating 100 ions/electrons per grid cell, with 6 floating point numbers stored for each ion and each electron. Therefore, even the smallest simulation to be run as part of this study will generate 200GB of data. Therefore we request:

- 30TB of additional storage space on HPSS archive.
- 15TB of large-scale project file space on CISL's GLADE Resource

The 30TB of storage space on HPSS is necessary to store the simulation particle and fields data. For each simulation, about 1/5 of the data is grid point fluid data which is used extensively for analyzing the simulation results. About 4/5 of the data is individual particle data which is used less frequently to create distribution functions of the kinetic particles. For the coming year, it will be necessary to have access to all of the fluid data on a flexible immediately available access like CISL's GLADE Resource, which amounts to about 6TB of space. In addition, it will be necessary to have a significant number of runs with the particle data available to examine distribution functions. Therefore, we request an additional 9TB on the CISL GLADE Resource. This comes to a total of 15TB of large-scale project file space on CISL's GLADE Resource.

The basic data management plan is as follows. When the simulation completes, all data will be immediately copied to mass storage. In addition, the grid point fluid data will be immediately copied to the GLADE large project storage. The particle and fluid data will remain for a few weeks on the scratch space for flexibility in restarting simulations as necessary. Finally, a subset of the particle data will be downloaded to the GLADE large project storage in order to analyze particle distribution functions.

F Accomplishment Report on Past Use of CISL Resources

F.1 Accomplishments Associated with This Project

Students: The following graduate and undergraduate students were supported under this NCAR allocation

- Colby Haggerty, a graduate student at the University of Delaware.
- Prayash Pyakurel Sharma, a graduate student at the University of Delaware
- Christian McHugh, an undergraduate student at the University of Delaware. Christian is now a graduate student in Physics at University of Texas, Austin.
- Rungployphan Kieokaew, a visiting undergraduate student from Thailand. Rungployphan is now a graduate student at the University of Exeter, United Kingdom.

Publications: The following refereed publications are the result of research under this project:


The physical processes that control the partition of released magnetic energy between electrons and ions during reconnection is explored through particle-in-cell simulations and analytical techniques. We demonstrate that the development of a large-scale parallel electric potential controls the relative heating of electrons and ions. The potential
develops to restrain heated exhaust electrons and is located near the Hall magnetic field near the separatrices. It enhances electron heating by confining electrons in the region where magnetic energy is released. Simultaneously the potential slows ions entering the exhaust below the Alfvén speed expected from the traditional counterstreaming picture of ion heating. Unexpectedly, the magnitude of the potential and therefore the relative partition of energy between electrons and ions is not a constant but rather depends on the upstream parameters and specifically the upstream electron normalized temperature (electron beta). These findings suggest the fraction of magnetic energy converted into the total thermal energy is independent of upstream parameters.


This paper describes the efforts of our Inter-Disciplinary Scientist (IDS) team to (a) establish the large-scale context for reconnection diffusion region encounters by MMS at the magnetopause and in the magnetotail, including the distinction between X-line and O-line encounters, that would help the identification of diffusion regions in spacecraft data, and (b) devise possible strategies that can be used by MMS to capture and transmit burst data associated with diffusion region candidates. The interplay between satellite observations and computer simulations play an important role in achieving the above goals. We also discuss automated burst trigger schemes that could capture various reconnection-related phenomena. The identification of candidate diffusion region encounters by the burst trigger schemes will be verified and improved by a Scientist-In-The-Loop (SITL). With the knowledge of the properties of the region surrounding the diffusion region and the combination of automated burst triggers and further optimization by the SITL, MMS should be able to capture most diffusion regions it encounters.


Electron bulk heating during magnetic reconnection with symmetric inflow conditions is examined using kinetic particle-in-cell (PIC) simulations. Inflowing plasma parameters are varied over a wide range of conditions, and the increase of electron temperature is measured in the exhaust well downstream of the x-line. The degree of electron heating is well correlated with the inflowing Alfvén speed $c_{Ap}$ based on the reconnecting magnetic field through the relation $\Delta T_e = 0.033 m_i c^2_{Ap}$, where $\Delta T_e$ is the increase in electron temperature. For the range of simulations performed, the heating shows almost no correlation with inflow total temperature $T_{tot} = T_i + T_e$ or plasma $\beta$. An out-of-plane (guide) magnetic field of similar magnitude to the reconnecting field does not affect the total heating, but it does quench perpendicular heating, with almost all heating being in the parallel direction. These results are qualitatively consistent with a recent statistical survey of electron heating in the dayside magnetopause (Phan et al, Geophys. Res. Lett., 40, doi:10.1002/grl.50917, 2013), which also found that $\Delta T_e$ was proportional to the inflowing Alfvén speed. The net electron heating varies very little with distance downstream of the x-line. The simulations show at most a very weak dependence of electron heating on the ion to electron mass ratio. The study highlights key properties that must be satisfied by an electron heating mechanism: (1) Preferential heating in the parallel direction; (2)
Heating proportional to $m_i c_{Ai}^2$; (3) At most a weak dependence on electron mass; and (4) An exhaust electron temperature that varies little with distance from the x-line.

F.2 Accomplishments Associated with Other Projects

The following refereed publications are associated with the CISL project P35751011 entitled, “Three dimensional studies of magnetic reconnection and self-generated turbulence in the Heliosphere.”


- Note: The following publication included simulations performed using NCAR-CISL resources, but we failed to acknowledge this in the manuscript. We apologize for the oversight and have taken steps to ensure that it will not happen again.


G References


**H Figures and Captions**

Figure 2: Scaling of the fully electromagnetic kinetic particle-in-cell code P3D on Yellowstone. P3D shows very good scaling up to 16,384 cores on Yellowstone.