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Physical processes in the cusps: Plasma transport and energization—Final report

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The cusp Focus Group was originally part of the Global Interaction Campaign started in 2004 which was interested in fields and particles from the solar wind to the plasma sheet, with an emphasis on processes that mediate their transport. In 2006, following the reorganization of the GEM activities into focus groups, the dayside component of the Global Interaction Campaign (Reconnection Dynamics, cusp and LLBL) was divided into three focus groups: 1) Foreshock, bow shock and magnetosheath, 2) Dayside magnetopause reconnection and 3) Cusp physics.

The main objective of the Cusp Focus Group is to bring together researchers from observations, modeling, and theory to coordinate research on longstanding problems in the cusp region from various angles. Specifically the Focus Group addresses the following topics.

1. Plasma transport into the cusp.
2. Energization of ions in diamagnetic cavities.
3. Origin of waves observed in the cusp and their role in particle scattering and acceleration.
4. Interaction of FTE's with the cusp.
5. The source region of energetic ions and electrons observed in the cusp.
6. Ionospheric signatures of such processes as Poleward Moving Auroral Forms

It was the ultimate goal of the workshops to enhance our understanding of the cusp physics, its coupling to other parts of the system such as the bow shock, magnetopause and the ionosphere and the important role it plays in dayside transport and energization. In the following we summarize the major advances made towards each of these objectives and the current state of our knowledge.

Plasma Transport into the Cusp

The efforts of the cusp Focus Group have jump started several projects to solve a long standing controversy about energetic ions in the cusp (CEP). Scientist from different fields including particle observations, wave analyses, and MHD simulations were brought together to bring their combined experience and tools to address acceleration and transport issues of CEPs.

While CEPs in the cusp are an observational fact, their origin remains an open issue. Three main source regions are discussed in the literature:

(a) Local acceleration by the turbu lence in a Cusp Diamagnetic Cavity (CDC).
(b) Transport of energetic ions into the cusp from the quasi-parallel bow shock.
(c) The Magnetosphere.

Studies favoring the bow-shock source for CEP ions have shown magnetic connections between the cusp and the quasi-parallel bow shock and documented IMF conditions that favor such connections [e.g., *Trattner et al.*, 2010a]. It was correctly pointed out during the GEM meetings that energetic ions from the bow shock on their way to the cusp should also be present in the magnetosheath and especially in the magnetospheric boundary layers. The subsequent transport studies

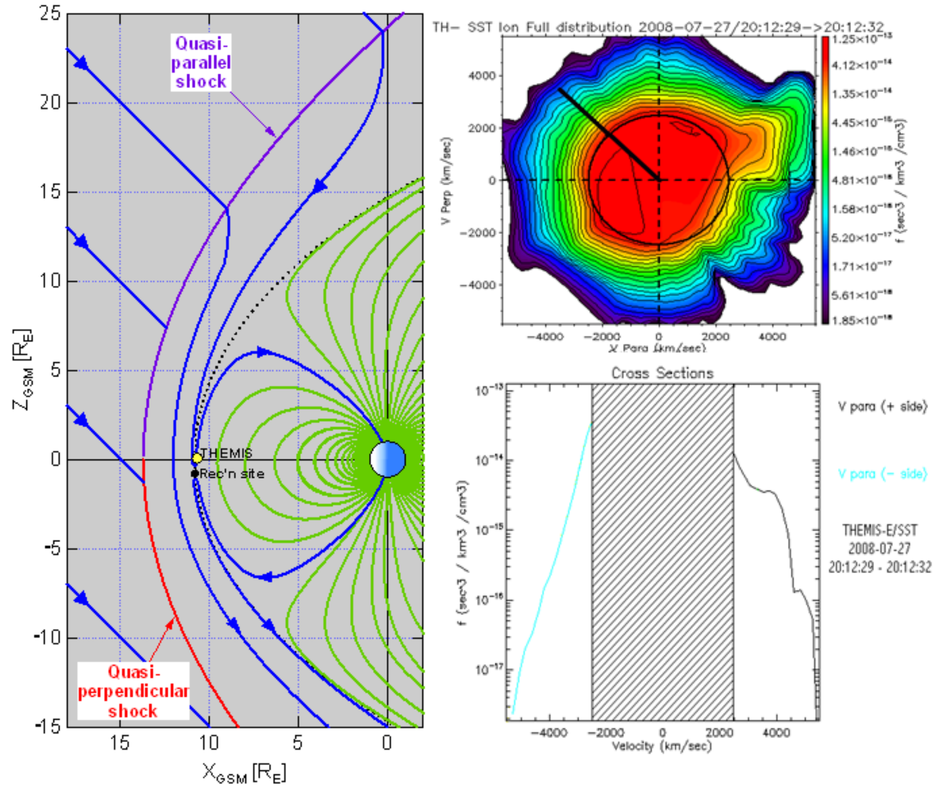

Figure 1: THEMIS located north of the reconnection site in the magnetosphere boundary layer observes energetic ions streaming into the cusp [*Petrinec et al.*, GEM 2010 workshop presentation].

of CEP ions were a direct consequence of the GEM cusp Focus Group discussions.

The observational evidence and their interpretation in terms of CEPs and their possible source regions remain controversial. T. Fritz reported examples of energetic ion anisotropies just outside the magnetopause in the magnetosheath observed by ISEE. The distributions invariably showed an anti-sunward convection anisotropy and provided no evidence for particles streaming sunward along magnetic field lines draped against the magnetopause [*Whitaker et al.*, 2007]. Fritz argued that the observations contradicted a picture presented earlier by *Fuselier et al.* [2009], which indicated that ions energized at the pre-noon bow shock might cross the magnetosheath and then flow sunward. *Fuselier et al.* [2009] showed in his presentation that the energetic ion population in the cusp behaves the same way as the bulk of the plasma and therefore is not accelerated in the cusp. IMF field lines draped around the magnetopause provide a connection between the reconnection region (and therefore the cusp) and the quasi-parallel bow shock region which allows shock accelerated ions to stream into the cusp. These ions are observed in the magnetosheath in an event observed by ISEE-2 adjacent to the magnetopause [*Phillips et al.,* 1993, Plate 1].

A Cluster cusp event observed on February 14, 2003, featuring extended cusp diamagnetic cavities (CDC) and a strong CEP flux was selected during the GEM meetings by Katariina Nykyri to study possible local acceleration processes in the cusp. The transport of CEP ions from the quasi-parallel bow shock for this event was investigated by *Trattner et al.* [2010b] using data from the Cluster CIS instruments. Applying analyzing tools to pinpoint the location of the reconnection site and IMF field line draping around the magnetopause revealed a reconnection site located poleward of the cusp and a quasi-parallel bow shock region in the southern hemisphere which is magnetically connected to the northern hemisphere cusp region. The 3D capability of the CIS instrument provided observations in the cusp cavity and the magnetopause boundary layer and showed an energetic particle distribution streaming into and towards the cusp, respectively, consistent with a bow shock source for cusp energetic particles [*Trattner et al.*, 2010b].

In a subsequent study by S. Petrinec, THEMIS observations near the magnetopause reconnection site are used to determine if shock-accelerated energetic ions can make it into the magnetosphere, and subsequently into the cusp. Figure 1 shows that the quasi-parallel bow shock during this event was located in the northern hemisphere (left panel). The THEMIS energetic ions are shown in the right panels of Figure 1 and stream in from the bow shock when the satellite was located north of the reconnection site. No energetic ions are detected at THEMIS when the satellite is located south of the reconnection site since the reconnection site cuts off the access to the northern hemisphere quasi-parallel bow shock region in agreement with a bow shock source for CEP ions. These examples of energetic ion transport represent important milestones in determining the source region of CEP ions.

In addition to studies about the origin of CEP ions, several participants in the cusp Focus Group presented studies on cusp ion structures. These studies combine simulation results with observations as shown by Conner, who used an MHD code to reconstruct cusp ion structures observed by the Polar satellite. Conner found that the observed model MHD cusp structures agree with observations but also depend strongly on the chosen virtual satellite orbit.

Newell reported on merging cusp bursts and showed auroral observations from the Polar UVI instrument including data from two DMSP satellite crossings at local noon during that event. The event is driven by southward IMF conditions during which the DMSP satellites detected two large Alfvénic electron bursts, one located at the poleward edge of the old cusp location and one at the equatorward edge of the new cusp location. Associated flow bursts contributed a significant fraction of the typical cross polar potential. Ion observations which showed low energy cutoffs revealed details of the timing sequence.

The oxygen heating rate in the cusp by Alfvénic structures was studied by Coffey using Polar TIDE observations. The heating rate, determined for each cusp crossing over a 3 month period, showed a strong correlation with BB-ELF emissions. One cusp crossing studied in detail showed the electric and magnetic field fluctuations were Alfvénic, and the electric field gradient satisfied the limit for stochastic acceleration. Comparison of the observed heating rate with others derived suggests that the stochastic acceleration mechanism was operational and the heating was due to a combination of different correlation time scales for effective heating between the particles and waves.

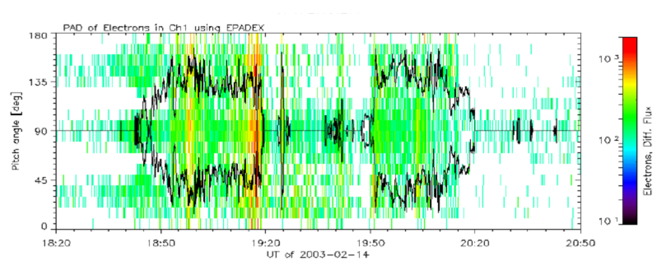

Figure 2: Energetic electron pitch angle distribution observed by the Cluster RAPID instrument inside a CDC [Nykyri et al., 2010c].

Energization of Ions in Diamagnetic Cavities

As mentioned above, one of the main pillars of the cusp Focus Group was the controversy regarding the origin of CEP ions. The GEM Cusp Focus Group provided the framework for bringing together researchers of various backgrounds to provide new ideas to solve the CEP controversy. In addition to studies about the transport of energetic ions into the cusp as described in the previous section, local acceleration studies involving wave analysis of the turbulence reported in CDCs as well as MHD simulations of CDCs with test particles were used to provide a broadened approach and view the controversy from different angles.

Of great interest to the community are the results from MHD simulations of CDCs presented by Otto and Pilchowski. The simulation used test particles to investigate ion acceleration in the funnel shaped, low magnetic field region. The simulation model was set for southward IMF and used electric and magnetic fields from local cusp simulations. Test particles are launched within the cavity and remain trapped for 50 minutes. The resulting energetic population is highly anisotropic with pitch angles peaking at 90° +/- 45°. The maximum energy gain reached by the ions is 70 keV while the maximum energy gain reached by electrons was 40 keV. The particle movement within the CDC is an oscillation between the boundaries (gyration and drift). Predicted spectra match those observed, suggesting a potential energ-zation mechanism for electrons and ions.

Nykyri et al. [2010 a, b, c] investigated the Cluster cusp crossing on Feb. 14, 2003 using data from the RAPID, PEACE, CIS and FGM instruments. Her investigations cover several research topics within the Cusp Focus Group, and specifically address "The Origin of Waves observed in the Cusp" and "The Source Region of Cusp Energetic Particles". The Cluster cusp crossing exhibits two diamagnetic cavities filled with high energy electrons, protons and helium with the particle flux decreasing as a function of distance from the CDC. By using the four Cluster satellites Katariina reported for the first time an actual spatial size of a diamagnetic cavity (about 1 R_E in the direction normal to the magnetopause). The turbulence in the cavity, thought to be one of the methods for accelerating ions, was identified as partly the back and forth motion of the cavity boundary over the satellite while most of it exhibits an FTE-like structure. The highest power in the magnetic field fluctuations is significantly below the ion cyclotron frequency. Of particular interest was the observation of energetic electrons at 90° pitch angles (Figure 2). Conservation of the first adiabatic invariant requires particles entering the weak field region within the CDCs from some external source to exhibit small pitch angles. Some re-processing of the particles within the CDC is required to explain particles with 90° pitch angles.

The size of a CDC in the high altitude cusp was also estimated by *Walsh et al.* [2008] using a combination of simultaneous Cluster and Polar satellites in the cusp. For the range covered by the satellites, the CDC seems to attain a thickness of 1.9 R_E thickness and a length of 9 R_E.

The apparent agreement between CEP ions and CDC is generally interpreted as evidence for a local acceleration region inside the cusp and was investigated by several studies. Fritz presented an ISEE-1/2 cusp crossing with orders of magnitude flux increase within the depressed and very turbulent diamagnetic cavity.

The energetic particles seem to originate from below the observing spacecraft streaming upward/outward. The electrons demonstrated a distribution peak at 90° pitch angle, indicative of being confined within a cusp minimum field

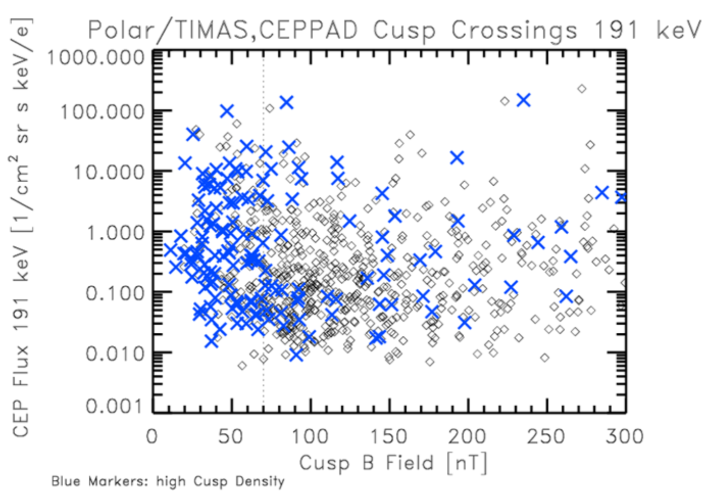

Figure 3: A correlation between the appearance of high CEP fluxes with the local magnetic field. High CEP fluxes are not limited to low field regions as predicted by the local acceleration model [*Trattner et al.*, GEM 2007c workshop presentation].

trap. The observations were interpreted as being consistent with a local acceleration source.

A statistical study by *Niehof et al.* [2005] also addressed the CDC - CEP correlation. The study is based on Polar data in the cusp. Out of 2117 satellite passes, 1192 cusp crossings were observed. In this cusp survey 734 CDC and 970 CEP events were recorded. Of those, 681 cusp crossings showed CDC and CEP events which led to the conclusion that CDC and CEP are directly related. The other source regions for CEP ions discussed in the literature (the quasi-parallel bow shock and magnetosphere) were also investigated and discussed in this study but showed no significant correlation.

In contrast, the cusp CEP- CDC correlation study performed by Trattner showed no relationship between the two observed cusp features. The study examined 1000 Polar cusp events to test the appearance of CDCs with those of CEPs. The appearance of CDCs is a function of high solar wind density and the altitude of the observing satellite. The diamagnetic effect of the magnetosheath plasma is enhanced during high density events [e.g., n > 15 cm^3] which causes the well known depression in the geomagnetic field at high altitudes where the geomagnetic field is already weaker. If CDCs and CEP events are related, significant fluxes of e.g., 200 keV protons should only be present during low field conditions in the high altitude cusp. As shown in Figure 3, high flux values for the 200 keV protons are present for all field conditions in the high altitude cusp and exhibit no correlation with depressed field conditions.

With these contradictory results it becomes obvious that more research is required to understand the origin of energetic particles in the cusp.

Interactions of FTE's with the Cusp

Since the discovery of Flux Transfer Events (FTEs) by *Russell and Elphic* [1979], questions regarding their generation, size, motion, evolution and dayside ionospheric signatures have prompted numerous investigations. Using a 2.5 D Hybrid simulation code, *Omidi and Sibeck* [2007] investigated FTEs marked by density enhancements. Showing considerable variations in size and speed, the FTEs originate in the low latitude dayside magnetopause and move poleward. When they reach the cusp, the density enhancements diminish and the events ultimately disappear (Figure 4). The interaction of FTEs with the cusp involves secondary reconnection and is quite complex, causing reconnection jets that inject plasma into the magnetosheath and the cusp with the latter leading to density enhancements in the cusp.

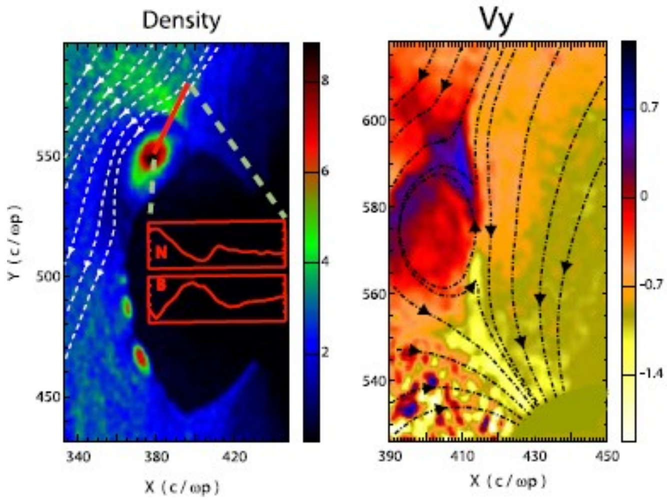

Figure 4: (left) Density and flow lines in the FTE rest frame before it encounters the cusp. The observed density enhancement and flow deflection is due to the slow mode bow wave. (right) The Y component of ion velocity and projection of the magnetic field lines in the X-Y plane. Plasma jetting into the magnetosheath and cusp due to reconnection is evident [*Omidi and Sibeck*, 2007].

Based on these studies and following up on questions from earlier GEM meetings on the cusp, *Sibeck et al.* [2009] investigated the fate of 20 R_E long FTE's originating along a component reconnection X-line through the subsolar point, and how they are (or are not) convected into the cusp regions for various IMF orientations. The Cooling et al. [2001] model for the motion of reconnected magnetic field lines was used to track the motion of the FTE's to determine if they reach the cusp. The probability that FTE's can reach the cusp is higher for southward IMF compared to northward IMF and is also more likely for weak IMF compared to strong IMF. The chance of an FTE reaching the cusp increases as the length of the reconnection line increases.

In a subsequent study Sibeck discussed hybrid simulations to determine if events generate density variations in front of an FTE and subsequently cause fast or slow shocks as discussed by Sonnerup. Only fast moving events exhibit such wakes (slow mode density enhance-ment), which should be visible on Cluster in front of fast moving FTE's as the satellites cross the magnetopause. Early in life an FTE starts out below Mach 1. It subsequently speeds up to a sonic Mach number of ~4. However, the FTE never gets into the fast (or slow) shock regime but stays below Alfvén Mach number 1.

Ionospheric Signatures

The cusp Focus Group covered also the foot points of the cusp in the ionosphere and the consequences of cusp ion precipitation on this layer.

Spacecraft traveling through the cusp at a variety of altitudes have consistently found the cusp to be filled with intense, often irregular power in the upper ULF frequency range. Some ground-based studies have observed narrowband waves in this same frequency range in the vicinity of the cusp foot point, but it has not been possible with magnetometers alone to either confirm or deny a cusp source for these waves. *Engebretson et al.* [2009] reported the first simultaneous, collocated observations of a set of induction magnetometers installed at three near-cusp sites on Svalbard and an all-sky auroral imager located at Longyearbyen. Data during northern winters of 2006–2007 and 2007–2008, when the cusp foot point was in darkness, showed occasional broadband noise when energetic particle precipitation occurred overhead, but on most days no broadband ULF power was observed above the noise level near noon when only soft cusp precipitation or poleward moving auroral forms occurred overhead. However, on 3 days, including 15 January 2007, several bursts of band-limited Pc 1-2 waves were observed in association with regions of intense soft precipitation that peaked near the poleward edge of the cusp. Their properties are consistent with an origin in the plasma mantle, as observed in a recent satellite-ground study by *Engebretson et al.* (2005). These observations confirm that even intense cusp precipitation is not effective in generating ion cyclotron waves that penetrate to the ground, if it is embedded within the central regions of the cusp, whereas regions of enhanced precipitation at the poleward edge of the cusp are associated with observed waves.

A study of multi-instrument observations of Pc 3-4 pulsations at cusp latitudes in Svalbard on September 18, 2006 was presented by Lu. The study of combined magnetometer, radar and satellite data shows that the strongest Pc 3-4 signal on the ground occurs 4°-5° equatorward of the cusp, and the location can be accurately determined from the radar backscatter. The study contradicts the direct cusp entry theory, which predicts strongest ground signal right under the cusp, but supports the ionospheric transistor theory by *Engebretson et al.* [1991].

A sequence of 3 patches of high-density (10^{12} m^{-3}) cold plasma on a horizontal scale-size of 300–700 km was reported by *Moen et al.* [2006]. The patches were observed near magnetic noon by the EISCAT VHF radar above Svalbard on 17 December 2001. The patches followed a trajectory towards the cusp inflow region. The combination of radar and all-sky observations demonstrates that the patches must have been segmented equatorward of the cusp/cleft auroral display, and hence their properties had not yet been influenced by cusp particle showers and electrodynamics on open flux tubes. The last patch in the sequence was intersected by radio tomography observations, and was found to be located adjacent to a broader region of the same high electron density further south. The patches occurred under moderately active conditions (Kp=3) and the total electron content (TEC) of the high-density plasma was 45 TEC units. The train of patches appeared as a segmentation of the tongue of ionization. The sequence of patches occurred in association with a sequence of flow bursts in the dusk cell return flow. It is proposed that reconnection driven pulsed convection is able to create sub-auroral patches in the region where high density mid-latitude plasma is diverted poleward toward the cusp. It is the downward Birkeland current sheet located at the equatorward boundary of the flow disturbance that represents the actual cutting mechanism [see also *Rinne et al.* 2007].

Lessard presented first results from a study on the cusp ion fountain using SCIFER rocket observations (apogee 1500 km) on Jan 18, 2008 following launch at 07:30:08 UT. The launch occurred from Norway over the EISCAT radar on Svalbard during the occurrence of a Poleward Moving Auroral Form (PMAF). Investigated were the relative significance of Joule heating, soft electron precipitation and waves in ion outflow processes including the altitude dependency of these processes. The observations showed ion outflow with the EISCAT radars during the event, in conjunction with soft electron precipitation. The Japanese spacecraft REIMEI took images during the launch.

Knipp presented a study on ionospheric energy deposition by reconnection. Ionospheric observations during northward IMF conditions and a large IMF By component showed localized energy deposition deep in the atmosphere. Such energy deposition changes the scale height in the atmosphere and provides localized heating not currently considered in models.

Deliverables

The cusp Focus Group was aiming for the following deliverables as outlined in the original Focus Group proposal

1) Enhanced understanding of cusp trans port and acceleration processes
2) Improved local and global models of re connection
3) Assessment of various models and their capabilities and limitations in capturing transport processes and the implications for GGCM models

The work within the focus group has greatly improved our understanding of cusp transport and acceleration processes and left us with new puzzles to be investigated in future studies. The development of new analyzing tools to determine the magnetic connection of the cusp region to the upstream region provides instantaneous knowledge and mapping of the bow shock conditions to the magnetosphere. These tools were used in correlation studies about the appearance of CEP events and their connection to one of the suspected source regions, the quasi-parallel bow shock [e.g., *Fuselier et al.,* 2009; *Trattner et al.*, 2010a] as well as in studies to track energetic ions in the magnetosheath on their way to the cusp [e.g. *Trattner et al.*, 2010b, *Petrinec et al.*, 2010]. The results from these studies support the bow shock source for CEP events.

However, the controversy about the source region is still alive with observations that are interpreted as evidence for a local acceleration source [e.g., *Niehof et al.,* 2005; *Whitaker et al.*, 2006, 2007; *Niehof et al.*, 2008; *Walsh et al.*, 2009, 2010]. Of particular interest was the observation of the 90° electron pitch angle distribution within a CDC [e.g., *Nykyri et al.*, 2010c] which will require more studies.

The magnetic connection and mapping studies from the cusp to the surrounding solar wind environment and the bow shock also led to the development of a model for the reconnection location at the dayside magnetopause during southward IMF conditions [*Trattner et al.*, 2007]. The study showed that during dominant IMF B_Y conditions, magnetic reconnection occurs along an extended

Line of Maximum Magnetic Shear across the dayside magnetopause (i.e., consistent with the tilted X-line, component reconnection scenario). In contrast, for dominant IMF B_Z (155° < atan(B_Y/B_Z) < 205°) or dominant B_X ($|B_X|/B$ > 0.7) conditions, the reconnection location bifurcates and was traced to high-latitudes, in close agreement with the anti-parallel reconnection scenario, and did not cross the dayside magnetopause as a single tilted reconnection line. This empirical model is currently being evaluated using confirmed locations of the reconnection line from the THEMIS mission in addition to MHD simulation models.

One of the great successes of the cusp Focus Group was the fusion of plasma analyzing teams with wave-particle interaction and simulations groups which led to some surprise discoveries. For the first time the actual size of the CDCs was estimated [e.g., *Walsh et al*., 2008; *Nykyri et al*., 2010a] and the turbulence inside a CDC was characterized [e.g., *Nykyri et al.,* 2010b]. The turbulence in the cavity was identified as partly the back and forth motion of the cavity boundary over the satellite while most of it exhibits an FTE-like structure. However, the highest power in the magnetic field fluctuations is significantly below the ion cyclotron frequency.

Test Particles within an MHD simulation environment resulted in energetic ion populations that are highly anisotropic with pitch angles peaking at 90° +/- 45°. The maximum energy gain reached by the ions is 70 keV while the maximum energy gain reached by electrons was 40 keV, which is supporting a local acceleration process. These contradictions need to be solved in future studies, e.g. including observed turbulences in the simulation environment of the CDC and also using Hybrid codes to study this kinetic process.

In conclusion, the Focus Group made substantial progress in understanding local particle processes in the cusp and particle transport into the cusps. These achievements were made possible by bringing together people from different backgrounds to share their views. We would like to thank all the contributors to the focus group.

References

A non-exhaustive list of published papers related to the Focus Group presentations (and references in this report):

Carlson, H. C., J. Moen, K. Oksavik, C. P. Nielsen, I. W. McCrea, T. R. Pedersen, and P. Gallop (2006), Direct observations of injection events of subauroral plasma into the polar cap, *Geophys. Res. Lett., 33*, L05103, doi:10.1029/2005GL025230.

Clausen, L. B. N., T. K. Yeoman, R. C. Fear, R. Behlke, E. A. Lucek, and M. J. Engebretson (2009), First simultaneous measurements of waves generated at the bow shock in the solar wind, the magnetosphere and on the ground, Ann. Geophys., 27, 357-371.

Coffey, V. N., Oxygen Ion Heating Rate within Alfvenic Turbulence in the Cusp at 1 Re Altitude, University of Alabama in Huntsville, *Ph.D. Dissertation*, 2009.

Cooling, B. M. A., C. J. Owen, and S. J. Schwartz (2001), Role of the magnetosheath flow in determining the motion of open flux tubes, *J. Geophys. Res., 106,* 18763-18775.

Engebretson, M.J., T. G. Onsager, D. E. Rowland, R. E. Denton, J. L. Posch, C. T. Russell, P. J. Chi, R. L. Arnoldy, B. J. Anderson, and H. Fukunishi (2005), On the source of Pc 1-2 waves in the plasma mantle, *J. Geophys. Res.,* 110, A06201, doi:10.1029/2004JA010515.

Engebretson, M. J., J. L. Posch, V. Pilipenko, and O. Chugunova (2006), ULF waves at very high latitudes, in *Magnetospheric ULF Waves: Synthesis and New Directions*, Geophysical Monograph Series 169, edited by K. Takahashi, P. J. Chi, R. E. Denton, and R. L. Lysak, American Geophysical Union, 137-156.

Engebretson, M. J., J. Moen, J. L. Posch, F. Lu, M. R. Lessard, H. Kim, and D. A. Lorentzen (2009), Searching for ULF signatures of the cusp: Observations from search coil magnetometers and auroral imagers in Svalbard, *J. Geophys. Res.,* 114, A06217, doi:10.1029/2009JA014278.

Fuselier, S.A., S.M. Petrinec and K.J. Trattner (2009), Comment on "Energetic particles sounding of the magnetospheric cusp with ISEE-1" by K.E. Whitaker et al., Ann. Geophysicae, 25, 1175-1182, 2007, *Ann. Geophys., 27*, 441-445.

Jacobsen, K. S., T. D. Phan, J. P. Eastwood, D. G. Sibeck, J. I. Moen, V. Angelopoulos, J. P. McFadden, M. J. Engebretson, G. Provan, D. Larson, and K. H. Fornaçon (2009), THEMIS observations of extreme magnetopause motion caused by a hot flow anomaly, *J. Geophys. Res.,* 114, A08210, doi:10.1029/2008JA013873.

Lockwood, M., J. Moen, A. P.van Eyken, J. Davies, K. Oksavik, and I. W. McCrea (2005), Motion of the dayside polar cap boundary during substorm cycles: I. Observations of pulses in the magnetopause reconnection rate, *Ann. Geophysicae, 23,* 3495-3511.

Lockwood, M., J. Davies, J. Moen, A. P. van Eyken, K. Oksavik, I. W. McCrea and M. Lester (2005), Motion of dayside polar cap boundary during substorm cycles: II. Generation of poleward-moving events and polar cap patches by pulses in the magnetopause reconnection rate, *Ann. Geophysicae,* 3513-3532.

Moen, J., Carlson, H.C. Carlson, K. Oksavik, C. P. Nielsen, S. E. Pryse, H. R. Middleton, I. W. McCrea, and P. Gallop (2006), EISCAT observations of plasma patches at sub-auroral cusp latitudes, *Ann. Geophysicae, 24,* 2363-2374.

Moen, J., N. Gulbrandsen, D. A. Lorentzen, and H. C. Carlson (2007), On the MLT distribution of F-region polar cap patches at night, *Geophys. Res. Lett.*, 34, L14113, doi: 10.1029/2007GL029632.

Moen, J., Y. Rinne, H.C. Carlson, K. Oksavik, R. Fujii, and H. Opgenoorth (2008), On the relationship between thin Birkeland current arcs and reversed flow channels in the winter cusp/cleft ionosphere, *J. Geophys. Res.*, doi: 10.1029/2008JA013061.

Moretto, T., D. G. Sibeck, B. Lavraud, K. J. Trattner, H. Reme, and A. Balogh (2005), Flux pile-up and plasma depletion at the high latitude dayside magnetopause during southward interplanetary magnetic field: a cluster event study, *Ann. Geophys.,* 23, 2259-2264.

Niehof, J. T., Fritz, T. A., Friedel, R. H., and J. Chen (2005), Structure of Cusp Diamagnetic Cavities, Eos Trans. AGU, 86(18), Jt. Assem. Suppl., JA414.

Niehof J. T., T. A. Fritz, R. H. W. Friedel, J. Chen (2008), Interdependence of magnetic field and plasma pressures in cusp diamagnetic cavities, *Geophys. Res. Lett.,* 35, L11101, doi:10.1029/2008GL033589.

Nykyri, K., A. Otto, E. Adamson, E. Dougal, J. Mumme (2010a), Cluster Observations of a Cusp Diamagnetic Cavity: Structure, Size and Dynamics, *J. Geophys. Res*., submitted July 1st.

Nykyri, K., A. Otto, E. Adamson, A. Tjulin (2010b), On the Origin of Fluctuations in the Cusp Diamagnetic Cavity, *J. Geophys. Res*., submitted July 1st.

Nykyri, K., A. Otto, E. Adamson, E. Kronberg, P. Daly (2010c), Cluster Observations of High-Energy Particle Properties in Cusp Diamagnetic Cavity, *J. Geophys. Res*., submitted July 1st.

Omidi, N., and D. G. Sibeck (2007), Flux transfer events in the cusp, *Geophys Res. Letters, 34*, L04106, doi: 10.1029/2006GL028698.

Petrinec. S., K.J. Trattner, S. a. Fuselier, T.D. Phan and V. Angelopoulos (2010), Case Study of Energetic Ions Near the Dayside Magnetopause Reconnection Site – Implications for Energization Sources, *GEM 2010 summer workshop*.

Phillips J.L., S.J. Bame, R.C. Elphic, J.T. Gosling, M.F. Thomson, and T.G. Onsager (1993), Well-resolved observations by ISEE 2 of ion dispersion in the magnetospheric cusp, *J. Geophys. Res.,98,* 13429.

Pilipenko, V. O. Chugunova, M. Engebretson, T. Yeoman, and M. Vellante (2009), Mechanisms of the cusp-related Pc 3-4 waves, in "Physics of Auroral Phenomena," Proc. 32nd Annual Seminar, Apatity, 89-92.

Rinne, Y., J. Moen, K. Oksavik, and H. C. Carlson (2007), On the occurrence of Reversed Flow Events in the Cusp Ionosphere Observed by the European Incoherent Scatter (EISCAT) Svalbard Radar, *J. Geophys. Res., 112,* A10313, doi: 10.1029/2007JA012366.

Rinne, Y., J. Moen, H. C. Carlson, and M. R. Hairston (2010), Stratification of east-west plasma flow channels observed in the ionospheric cusp in response to IMF B_Y polarity changes, *Geophys. Res. Lett.*, doi:10.1029/2010GL043307.

Russell, C.T., and R.C. Elphic (1979), ISEE observations of flux transfer events at the dayside magnetopause, *Geophys. Res. Letters, 6,* 33-36.

Sibeck, D. G., G. I. Korotova, V. Petrov, V. Styazhkin, and T. J. Rosenberg (2005), Flux transfer events on the high-latitude magnetopause: Interball-1 observations, *Ann. Geophys*., 23, 3549-3559.

Sibeck, D. G. (2009), Concerning the occurrence pattern of flux transfer events on the dayside magnetopause, *Ann. Geophys.,* 27, 895-903.

Sibeck, D. G. and R.-Q. Lin (2010), Concerning the motion of flux transfer events generated by component reconnection across the dayside magnetopause, J. Geophys. Res.,115, A04209, doi:10.1029/2009JA014677.

Trattner K.J., J. Mulcock, S.M. Petrinec and S.A. Fuselier (2006), Distinguishing between anti-parallel and component reconnection at the dayside magnetopause, *ESA Special Publication,* SP-598.

Trattner, K.J., S.M. Petrinec, W.K. Peterson, S.A. Fuselier and H. Reme (2006), Tracing the location of the reconnection site from the northern and southern cusps, *J. Geophys. Res.,* 111, A11211, doi:10.1029/2006JA011673.

Trattner K.J., J.S. Mulcock, S.M. Petrinec, S.A. Fuselier (2007), Probing the boundary between anti-parallel and component reconnection during southwards IMF conditions, *J. Geophys. Res., 112,* A08210, doi:10.1029/2007JA012270

Trattner K.J., S.M. Petrinec, S.A. Fuselier and W.K. Peterson (2010a), Cusp energetic ions as tracers for particle transport into the magnetosphere, *J. Geophys. Res.*, 115, A04219, doi:10.1029/2009JA014919.

Trattner, K.J., S.M. Petrinec, S.A. Fuselier, K. Nykyri and E. Kronberg (2010b), Cluster observations of energetic bow shock ions in the magnetsheath and the cusp, *J. Geophys. Res., submitted.*

Trattner K.J., S.M. Petrinec and S.A. Fuselier, CEP statistic, *GEM 2007 Summer Workshop*.

Walsh, B.M., T. A. Fritz, N. M. Lender, J. Chen, and K. E. Whitaker (2007), Energetic particles observed by ISEE-1 and ISEE-2 in a cusp diamagnetic cavity on 29 September 1978, *Ann. Geophys., 25*, 2633–2640.

Walsh, B.M., T. A. Fritz, J. Chen (2008), Properties of cusp diamagnetic cavity boundary, *Ann. Geophys., 26*, 3501–3509.

Walsh B. M., K. E. Whitaker, T. A. Fritz, J. Chen, and M. Klida (2009), Reply to S. Fuselier et al.'s comment on "Energetic particle sounding of the magnetospheric cusp with ISEE-1", by K.E. Whitaker et al., *Ann. Geophys., 25*, 1175-1182, 2007, *Ann. Geophys., 27*, 447-450.

Walsh B. M., T. A. Fritz, M. Klida, and J. Chen (2010), Energetic electrons in the exterior cusp: identifying the source, *Ann. Geophys., 28,* 983–992.

Whitaker, K. E., J. Chen, and T. A. Fritz (2006), CEP populations observed by ISEE 1, *Geophys. Res. Lett., 33*, L23105, doi:10.1029/2006GL027731.

Whitaker, K.E., T.A. Fritz, J. Chen, and M. Klida (2007), Energetic particle sounding of the magnetospheric cusp with ISEE-1, *Ann. Geophysicae, 25*, 1175.

GGCM modules and methods: 2005–2010 report

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1. Introduction

The numerical study and modeling of magnetic reconnection in the geophysical system presents several challenges. Chief among these difficulties is the resolution of both the dissipative and non-dissipative kinetic length scales that have been found to strongly affect both the reconnection rate and the geometries of the reconnection regions produced by numerical models.

The solar wind and magnetospheric plasmas possess a vanishingly small Spitzer resistivity. The Lundquist number, $S = LV_A/\eta$, provides a dimensionless characterization of a system's resistivity, and is given by the ratio of the Alfvén wave crossing time to the resistive diffusion time of a system with Alfvén speed uniform resistivity, η, and characteristic length L. This ratio can exceed 10^{10} in our system of interest, making the system effectively collisionless.

A second difficulty stems from the large scale of the geophysical system compared to the characteristic proton inertial length, $d_i = c/\omega_{pi}$ in regions where reconnection is likely to occur. The size of the geophysical system is on the order of 10,000 ion inertial lengths. Electron inertial effects represent an additional challenge since the electron skin inertial length is $(M_i/m_e)^{1/2} \cong 43$ times smaller than d_i.

Numerical work in the first half of the past decade produced great advances in our understanding of collisionless magnetic reconnection in small, systems with idealized geometries. Notably, the GEM Reconnection Challenge study concluded that the Hall term in Ohm's Law fundamentally altered the structure of the dissipation region during simulations of two dimensional, symmetric, spontaneous reconnection events.

The Hall term represents the decoupling of ion and electron motion, and the consequent departure from MHD behavior at length scales below the ion inertial scale. This Hall effect is non-dissipative, i.e. the Hall term itself *does not* break the frozen-in condition. However, the decoupling of the ions from the still frozen-in electrons allows reconnection to proceed much more rapidly provided the resistive length scale in the plasma is below d_i.

These findings indicated that a resistive length scale smaller than d_i is a sufficient (though not necessarily a necessary) condition for the existence and onset of fast, potentially dissipation independent reconnection in relatively small systems with large amounts of magnetic free energy. However, one must make a large leap to move from the GEM challenge parameters and initial condition to the 10,000 d_i magnetosphere with its strong, dynamic driving, asymmetric current sheets and complex three dimensional geometry.

The Modules and Methods focus group aims to make connections between these models of small, idealized systems (with reasonably realistic microphysics but unrealistic geometries and highly artificial boundary conditions) to global models, which have much more realistic geometry and driving but which generally employ more *ad hoc*, often grid-dependent dissipation models.

In broad terms we have sought to determine which kinetic effects matter most, and which may be more safely ignored if we wish to use global, MHD based codes to accurately model the locations and rates of magnetic reconnection observed in nature.

2. Scientific Objectives

The scientific objective of the focus group on GGCM Modules and Methods was to understand the physics of collisionless magnetic reconnection on magnetospheric length scales (100-10,000 ion inertial lengths). To this end, we have identified several broad questions (and a number of specific sub-questions) to be addressed by the focus group:

Q1: Can global resistive magnetohydrodynamics (MHD) codes accurately model magnetospheric reconnection?

Q1.1: What is the effective Lundquist number of the magnetosphere? (*What is the role of anomalous resistivity? Can anomalous resistivity be accurately modeled in resistive MHD codes? What are the roles of the post-MHD terms in the Generalized Ohm's Law?*)

Q1.2: How does the physics of reconnection depend on the *ad hoc* resistivity model used in global MHD codes? (*How does reconnection scale with resistivity in the high Lundquist number limit? What is the effect of numerical resistivity? Can we reproduce Petschek reconnection by localizing the plasma resistivity? What is the effect of current dependent resistivity?*)

Q1.3: How does dayside magnetopause reconnection work in global MHD codes? (*Is reconnection locally controlled or externally driven? Does the Cassak-Shay formula apply to the dayside magnetopause? What can resistive MHD tell us about the generation and topology of Flux Transfer Events (FTEs)?*)

Q1.4: How does magnetotail reconnection work in global MHD codes? (*Can global resistive MHD codes accurately model magnetic storms and substorms? How do simulated storms and substorms depend on the resistivity models used in resistive MHD codes?*)

Q2: How does the physics of collisionless reconnection observed in Particle-In-Cell (PIC) simulations scale up to reality?

Q2.1: How does the reconnection rate scale with the electron inertial length? (*Does the Hall effect render the collisionless reconnection rate independent of electron mass? Is the collisionless reconnection rate universally Alfvenic?*)

Q2.2: How does the reconnection rate scale with the ion inertial length? (*Does the Hall effect render the collisionless reconnection rate independent of the ion inertial length? What is the role of magnetic flux pileup in collisionless reconnection?*)

Q2.3: What determines the aspect ratio of the electron diffusion region in open boundary condition PIC simulations? (*Are macroscopic current sheets possible in collisionless reconnection? What determines the length of the electron diffusion region in collisionless reconnection? What is the role of secondary island formation in the determination of the length of the electron diffusion region? What impact does secondary island formation have on the reconnection rate?*)

Q2.4: Is the Hall effect necessary to produce fast collisionless reconnection? (*How does fast reconnection work in electron-positron plasmas? Is fast reconnection possible in so-called "Hall-less" hybrid codes?*)

Q2.5: What is the role of dispersive waves in the physics of fast collisionless reconnection?

Q3: Can we extend global resistive MHD to include microscale physics, which is needed to accurately model reconnection?

Q3.1: What is the status of global Hall MHD modeling? (*What are the most robust numerical approaches? Should we go fully implicit? Semi-implicit? What about Godunov approaches? How do we handle Adaptive Mesh Refinement (AMR)?*)

Q3.2: What is the status of global hybrid codes? (*What is the role of the Hall effect in a* *global 3D context? How does the reconnection rate in global hybrid codes depend on the resistivity model?*)

Q3.3: What is the status of “embedding” approaches, in which kinetic physics is added locally to an MHD code (either via code coupling or via local modification of the equations)? (*What are the most important code coupling issues? Is it even possible to couple an MHD code with a PIC code? Is the region of MHD breakdown in a global MHD code sufficiently localized to make embedding computationally feasible?*)

The three broad questions **Q1-Q3** are motivated by a popular approach to GGCM development known as the *MHD spine* approach. In the MHD spine approach, a global MHD model is used as the underlying computational "spine" of the GGCM, with non-MHD physics added (e.g., via coupling with another code) in regions of the simulation domain where the MHD approximation breaks down. While this approach seems to be yielding improvements in modeling of the inner magnetosphere (e.g., several kinetic models of the ring current are being successfully coupled to global MHD codes), the important problem of collisionless reconnection—likely the ultimate driver of much of the activity in the magnetosphere—has received comparatively little attention in the context of GGCM development.

3. Activity

The Modules and Methods group met between 2005 and 2010 at Fall AGU meetings in San Francisco and at the GEM summer workshops in Santa Fe, NM; Midway, UT; and Snowmass, CO. The following section presents highlights of from the sessions.

Q1: Can global resistive magnetohydrodynamics (MHD) codes accurately model magnetospheric reconnection?

GEM Workshop 2008

Christopher Russell presented an interesting statistical analysis of “reconnection efficiency” — as measured by the ratio of the variation in geomagnetic activity to the variation in the z component of the Interplanetary Magnetic Field (IMF) — at Earth’s dayside magnetopause. Two results of this study were relevant to question Q1.3: How does dayside magnetopause reconnection work in global MHD codes? First, the dependence of reconnection efficiency on IMF clock angle is not as abrupt as one would expect from a simple “half-wave” rectifier model. Russell interpreted this result to mean that reconnection at a particular location on the magnetopause may depend sensitively on the local magnetic shear across the magnetopause; nevertheless, reconnection occurs simultaneously at multiple locations on the magnetopause, so that the integrated effect on geomagnetic activity may show a more gradual dependence on the IMF clock angle. Secondly, there was a dependence of reconnection efficiency on solar wind Mach number, suggesting that the solar wind exerts some degree of control over the reconnection rate.

Paul Cassak presented his latest results on asymmetric reconnection, extending previous resistive MHD work to the collisionless regime. Using conservation laws, Cassak derived an analytic expression for the reconnection electric field in a two-dimensional, steady state, asymmetric, i.e., different densities and magnetic field strengths on either side of the current sheet (see Figure 1). The resulting expression predicts that the reconnection electric field depends only on the upstream and downstream plasma mass densities and magnetic field strengths:

$$E \sim \left(\frac{B_1 B_2}{B_1 + B_2}\right) \frac{v_{out}}{c} \frac{2\delta}{L}$$

$$\rho_{out} \sim \frac{\rho_1 B_2 + \rho_2 B_1}{B_1 + B_2}$$

$$v_{out}^2 \sim \frac{B_1 B_2}{4\pi \rho_{out}}$$

Thus the reconnection electric field is proportional to a “reduced” upstream magnetic field strength, and the outflow speed is pre-

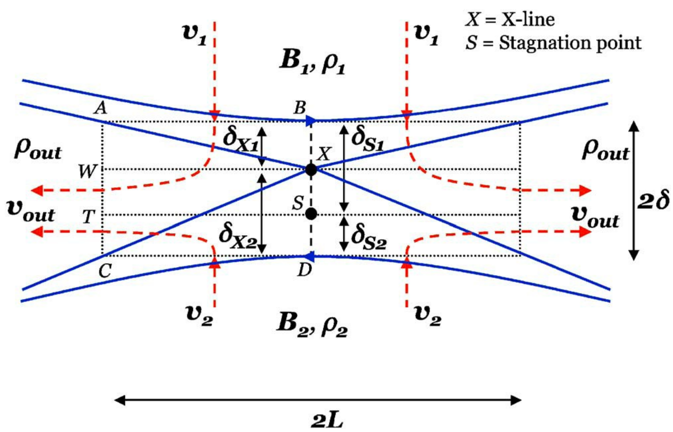

Figure 1. (From P. A. Cassak and M. A. Shay. Scaling of asymmetric magnetic reconnection: General theory and collisional simulations. Physics of Plasmas, 14:102114, 2007.) Schematic diagram of the dissipation region during asymmetric reconnection. Quantities above and below the dissipation region have a subscript of "1" and "2," respectively. Quantities describing the outflow have "out" subscripts. The magnetic field lines are the blue solid lines, the velocity flow is the red dashed lines. The points *X* and *S* mark the X-line and the stagnation point, which are not colocated. The edges of the dissipation region and lines through the X-line and stagnation point are marked by dotted lines.

dicted to go like the Alfvén speed based on the downstream density and the geometric mean of the upstream fields.

The Cassak-Shay formulas also predict that when the plasma resistivity is constant, the reconnection electric field scales like the square root of the resistivity. Thus, the Cassak-Shay formulas provide a potential answer to questions Q1.2 and Q1.3.

Joachim Birn -- Joachim Birn substituted for *Joe Borovsky*, who could not attend the meeting. Borovsky addressed question Q1.3: How does dayside magnetopause reconnection work in global MHD codes? Essentially, Borovsky argued that under pure southward IMF conditions in the BATSRUS code, the subsolar magnetopause reconnection electric field is well predicted by the Cassak-Shay formula. Borovsky went on to derive a solar wind-magnetosphere coupling function, using the Cassak-Shay formula as a starting point. Borovsky further argued, based on the agreement between the Cassak-Shay prediction with the simulated reconnection electric field, that reconnection is controlled by local plasma parameters and not "driven by" (which, for Borovsky, means "matched to") the solar wind electric field. Borovsky presented three pieces of evidence for this (from BATSRUS simulations): 1) reconnection rate didn't "match" the solar wind electric field (it's more consistent with the Cassak-Shay formula), 2) magnetic flux pileup didn't depend on the IMF clock angle, 3) a "plasmasphere" effect was observed, in which the reconnection electric field was observed to drop as a plasmaspheric density plume arrived at the dayside magnetopause.

John Dorelli presented a critique of the application, by Joe Borovsky, of the Cassak-Shay formula to the dayside magnetopause. In this talk, Dorelli addressed questions Q1.2 and Q1.3, arguing that: 1) magnetopause reconnection is "driven by" the solar wind in the usual sense: the solar wind electric field imposes a constraint on the local reconnection electric field such that local conditions adjust to accommodate the imposed external electric field. In 2D, this implies a matching of the solar wind electric field to the magnetopause electric field. In 3D, however, imposing zero curl on the electric field (consistent with steady-state) does not imply such an exact matching; therefore, Borovsky's observation that the BATSRUS magnetopause reconnection electric field does not "match" the solar wind electric field does not imply that reconnection is controlled by local plasma parameters, as Borovsky argues. 2) When the plasma resistivity is constant and uniform, reconnection occurs via a flux pileup mechanism such that a) the amount of magnetic energy pileup is independent of the IMF clock angle (consistent with Borovsky's BATSRUS observations), and b) the reconnection electric field scales like the fourth root of the plasma resistivity (which contradicts the Cassak-Shay formula). Dorelli concluded by deriving an analytic expression (based on the Sonnerup-Priest 3D stagnation flow equations) for the flux pileup reconnection electric field at the dayside magnetopause. Dorelli further suggested that a simple way to test Cassak-Shay vs. the Sonnerup-Priest electric fields would be to look at the dependence of the reconnection electric field on the plasma resistivity: Cassak-Shay predicts a square root dependence; Sonnerup-Priest predicts a fourth root dependence.

Brian Sullivan presented results from 3D resistive Hall MHD simulations of driven reconnection. Starting from a 1D double Harris sheet equilibrium, reconnection was driven by a three-dimensionally localized inflow. This driving produced a three-dimensional stagnation point flow, making this study relevant to Earth's dayside magnetopause. Thus, this study addressed questions Q1.3 (How does dayside magnetopause reconnection work in global MHD codes?). An attempt was made to define and identify a three-dimensional "magnetic island" and determine the dependence of the reconnection rate on the aspect ratio of the dissipation region. Interestingly, the three-dimensional nature of the forcing function resulted in the addition of a "geometrical factor" of ½ (resulting from the fact that plasma flows out in all directions downstream of the reconnection current sheet) to the familiar two-dimensional expression.

GEM 2009 Workshop

Masha Kuznetsova presented results on 3D dayside reconnection in global MHD simulations (Q1.3), with the following conclusions: 1) Flux ropes are not necessary tilted quasi-2D structures; 2) Flux ropes have bends and elbows; and 3) Flux ropes internal structure and core magnetic field strength are changing on a spatial scale of the order of 1-2 Earth radii.

GEM 2010 Workshop

Ray Fermo presented a statistical model of magnetic islands with results from Hall MHD simulations and comparisons to Cluster observations of flux transfer events (FTEs), addressing question Q1.3. The idea behind the statistical model is that it may allow quantitative characterization of systems larger than those we can afford to simulate. The model describes the formation, growth, convection and coalescence of magnetic islands. Fermo *et al.* derived an integro-differential equation to describe a distribution function for islands characterized by two parameters: their cross sectional area, and the flux they contain. Benchmarking of this model with Hall MHD simulations produced results that compare well with 1,098 Cluster observations of FTEs from between 2001 and 2003.

Joachim Birn presented results on the effects of compressibility on asymmetric reconnection with corrections to the original Cassak-Shay asymmetric reconnection scaling predictions. These corrections involve an assumption of force balance and the inclusion of finite enthalpy and Poynting flux through the reconnection region. This additional physics leads to some interesting new features. One is a plasma β dependent factor in the reconnection rate, with the outflow density increasing as $\beta \to 0$.

Another feature is an even partitioning of Poynting flux into bulk kinetic energy and enthalpy flux. This even partitioning appears to be independent of the ratio of the two upstream B-field strengths in the asymmetric reconnection, and also independent of the plasma β.

Michael Shay presented results on asymmetric reconnection in turbulent plasma, motivated by Cluster observations of turbulence with reconnection downstream of the bow shock. This investigation primarily asked the question: "Are current sheets & reconnection key to understand dissipation in turbulence?" This work addresses question Q1.

Reconnection in the turbulent simulations was found to be asymmetric in general, and significantly, current sheets with some amount of extension yielded more reconnection than cusp like x-points. Islands that moved toward each other relatively slowly for an extended period of time to form a current sheet were the most effective generators of reconnection in the turbulence. The simulated system self generated such current sheets. However, Shay found that if the Fourier components of the magnetic field were rearranged with randomized phases, the resulting field exhibited many fewer extended current sheets resulting in less reconnection overall. This is a further demonstration of the systems self-organization into a state that optimizes reconnection in order to dissipate energy from the turbulent flow.

John Lyon presented work done primarily by *Jeremy Ouellette* at Dartmouth, regarding scaling of reconnection at the dayside magnetopause (addressing question Q1.3). Simulations employed a numerical resistivity that engages at the grid scale. The simulation results indicated that the reconnection rate was controlled by solar wind conditions with the reconnection electric field scaling as 0.53 times the solar wind electric field. This multiplicative factor is explained as relating to the fraction of the incoming flux that reconnects vs. being deflected around the flanks of the magnetosphere. This is similar to the geometric factor described above by Sullivan in the context of forced two-fluid reconnection simulations. Ouellette et al. found reconnection electric fields that exceed that predicted by the Cassak-Shay formula by a factor of three or more, and measured outflow velocities smaller than those predicted by the Cassak-Shay formulation (although it was noted that higher grid resolution might yield better agreement). This lower outflow could make steady state reconnection less likely, leading to a larger number of FTEs. Two sources of outflow were identified: outflow due to reconnection, and outflow due to conservation of momentum at the bow shock. With the bow shock flow removed, the reconnection outflow speed scales closely with the reconnection current density.

Brian Sullivan presented results from simulations conducted using BATSRUS at CCMC, addressing question Q1.2, and Q1.3. Each simulation presented included a constant uniform resistivity in the model, with values of that resistivity varying by a decade. These simulations employed a resolution of 1/32 R_e in the region around the dayside magnetopause. This high resolution allowed the use of small uniform resistivities, while still keeping the uniform resistivity much larger than the usual dissipation provided by the upwinding techniques employed in the code. The scalings of the time averaged sub-solar current sheet width and the sub-solar reconnection electric field showed excellent agreement with the predictions of Sweet-Parker analysis of the system, despite the presence of the complex, three dimensional stagnation point in the flow. The square root dependence of the reconnection electric field on the plasma resistivity in this study is in agreement with Cassak Shay predictions, as opposed to the fourth-root dependence predicted by the Sonnerup-Priest model. In contrast to earlier resistive runs performed earlier by John Dorelli using OpenGGCM, the runs presented showed very little flux pile up. Sullivan believed that this difference likely stems from the solar wind Mach number in his simulations being five times smaller than that employed in the earlier study. Further runs will be conducted to investigate whether the flux pile up returns at more realistic solar wind Mach number.

Kittipat Malakit presented a comprehensive test of the asymmetric reconnection scaling theory proposed by Cassak and Shay in 2007 (addressing questions Q1.2 and Q1.3). This test employed fully electromagnetic particle-in-cell simulations of antiparallel, asymmetric magnetic reconnection. A controlled study of the asymmetric upstream densities and magnetic fields revealed reconnection rates, outflow speeds, and outflow densities consistent with the aforementioned scaling theory. This result indicates that kinetic electron and proton physics beyond the Hall term appear not to dramatically alter the basic properties of the asymmetric diffusion region as understood in Cassak-Shay (2007). These results confirmed the validity of the assumption of mixing of particles on recently reconnected flux tubes, which is of key importance for accurately predicting the location of the stagnation point of the flow through the diffusion region.

Dmitri Uzdensky presented theoretical predictions regarding plasmoid dominated resistive reconnection in the high Lundquist number regime, (potentially addressing questions Q1.3, Q1.4 and Q2.4). Even in simple, resistive MHD, reconnection may be much faster than had been previously thought. Until recently, resistive MHD studies of magnetic reconnection have been confined to Lundquist numbers lower than S=10,000. However, the latest simulations of reconnection at higher S have revealed that the long, thin current sheets predicted by Sweet-Parker analysis to occur in steady state do not in fact occur, because of the presence of a rapid plasmoid instability leading to the breakup of the current sheet into many islands or plasmoids. This instability was first suggested analytically by Bulanov in 1978, and had been observed numerically by Biskamp 1986; Jin & Ip 1991; Lee & Fu 1986; and Loureiro et al. 2005. The past three years have produced a surge of numerical and analytic studies of this phenomenon, which have also been observed in kinetic PIC simulations of reconnection, e.g., Drake et al. 2006 Daughton et al. 2009, and Daughton et al. 2009 (see figure 2). These ubiquitous plasmoids seem to indicate that weakly collisional reconnection may be inherently bursty, requiring a statistical description.

Q2: How does the physics of collisionless reconnection observed in Particle-In-Cell (PIC) simulations scale up to reality?

GEM 2008 Workshop

Michael Hesse addressed question Q2.3: What determines the aspect ratio of the electron diffusion region in open BC PIC simulations? In previous studies, the electron diffusion region was identified as the region where the electron frozen flux condition is violated. That is, the electron diffusion region was identified as the region where there are significant corrections to the UxB and Hall electric fields. Such an identification seems to imply that the aspect ratio of the electron diffusion region is larger than that found in earlier PIC simulations (which used periodic boundary conditions). Hesse pointed out, however, that particles are actually losing energy to the electromagnetic fields (with the electron fluid simply drifting diamagnetically) throughout most of this large diffusion region. If one *defines* the electron diffusion region to be that region where particles gain energy from the fields (i.e., the dot product of current density and electric field is positive), then the electron diffusion region is much smaller.

Kittipat Malakit addressed question Q2.4: Is the Hall effect necessary to produce fast reconnection? Malakit's work was motivated by recent so-called “Hall-less” hybrid simulations (in which the Hall term in Ohm's law is turned off), carried out by Homa Karimabadi, which seemed to demonstrate that fast reconnection was possible even in the absence of the Hall electric field. In his talk, Malakit provided a counterexample, demonstrating that in the case of reconnection of a double tearing mode, turning off the Hall term effectively turns off fast reconnection (producing long Sweet-Parker-like current sheets).

Vadim Roytershteyn presented new large-scale PIC simulations in collaboration with Bill Daughton & Homa Karimabadi (addressing question Q2). The main points of the presentation were:

1. These PIC simulations were NOT with open boundary conditions - but rather with two standard periodic test problems (1) single Harris and (2) double Harris sheet. We realize that the open boundary model is somewhat complicated and controversial, so our approach in this study was to fall back to very simple boundary conditions and use brute force to make the system size large enough to give the layer a chance to develop over longer time scales.
2. Both of these periodic test problems were worked with two completely different PIC codes (NPIC vs VPIC) that use very different numerical methods. However, the results from these two codes are in excellent agreement on the question of electron sheet elongation + secondary island formation.

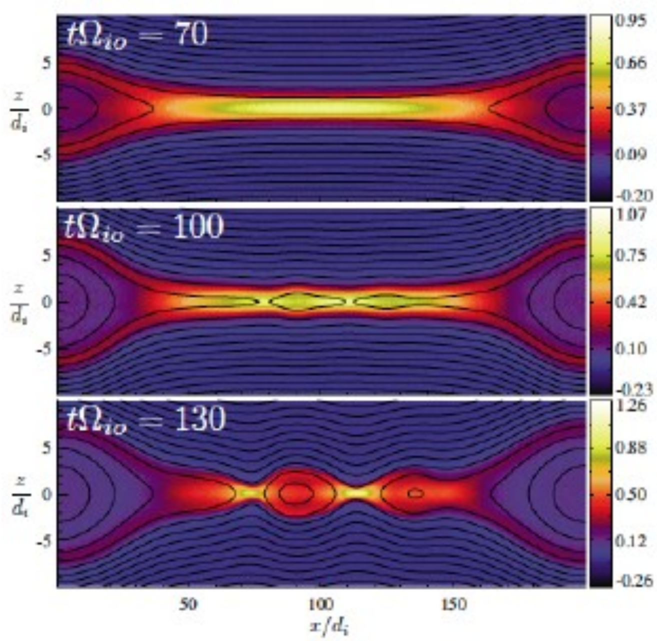

Figure 2 (From Daughton et al., Phys. Plasmas 2009). Time evolution of the current density *Jy* for the *Lx* = 200*di* simulation with initial resistivity $\eta_{\perp 0} = 0.1$. The transition away from SP (top panel) involves the formation of magnetic islands in the resistive layer. The black lines are the magnetic flux surfaces and the current density is normalized to the initial peak value J_0 .

3. We furthermore used both of our PIC codes to work exactly the same double Harris sheet problems as the recent PRL by Shay et al. Both of our PIC codes show multiple secondary island formation (even at late time) in clear contradiction to the results obtained by Shay et al. Furthermore, the reconnection rate in our PIC simulations is modulated in time with the length of the electron layer, while the results from Shay are "steady". This is not a matter of a "different interpretation". The simulation results are clearly different. We welcome further comparisons from anyone in the community who is interested in resolving this discrepancy. It would seem crucial to understand these very real code differences, in order to move forward on the "role" of secondary islands.

4. Secondary-island formation cannot be the whole story - but we believe it clearly offers one mechanism to control the length of the electron layer. The fact that reconnection rates are similar to Hall MHD does not prove the physics is the same - especially when the time-dependence and macroscopic structure are quite different. Kinetic simulations of pair plasma ($m_i = m_e$) give precisely this rate, even in small systems where there are no plasmoids and no Weibel instability. Two-fluid simulations of pair plasma have also demonstrated this same rate without plasmoids or Weibel [Chacón, PRL, 2008].

Mikhail Sitnov, using an open boundary condition version of the P3D code [Zeiler et al., 2002] that was modified by Divin et al. [GRL, 34, L09109, 2007], addressed the possible role of the ion tearing mode in producing the secondary magnetic islands observed in open BC PIC simulations (thus potentially addressing questions Q2.1-Q2.5). Sitnov noted that the code differs from Bill Daughton's both in way it handles particles (maintaining continuity of only the two first moments at the boundary) and in the way it handles fields (eliminating any Bz change at the x-boundaries, mimicking magnetopause reconnection). Sitnov argued that in periodic BC PIC simulations, there are no "passing" electron orbits (i.e., electrons which leave the system, a population which is essential to the development of the ion tearing mode). Sitnov argued that open boundary condition simulations allow for the existence of such passing orbits and, thus, the ion tearing mode may be responsible for secondary island generation in open boundary condition PIC simulations. The effect of passing electrons suggests that the reconnection onset conditions in the magnetotail may be essentially nonlocal. Specifically, to be tearing-or reconnection-unstable, the tail current sheet not only must be thin enough (of the order of the ion gyro-radius, to provide ion dissipation), but must also be sufficiently long to provide a sufficient number of passing electrons. There was some debate among focus group participant about the relevance of ion tearing in the secondary island generation process.

2009 GEM Workshop

Joachim Birn presented work on the question, "What limits aspect ratio of the dissipation region? (Q2.3)" One answer is the shape of a localized resistive spot:

- A longer resistive spot limits the reconnection rate
- The aspect ratio of the diffusion region is not strongly influenced by a localized *viscous* spot
- Electron viscosity does not appear to slow reconnection in a 2 fluid model

Joe Borovsky presented results on the question, "How does reconnection rate scale with disspation region parameters? (Q2)" The Cassak-Shay formula for asymmetric reconnection appears to accurately predict the reconnection rate at the dayside magnetopause in BATSRUS simulations. There should perhaps be some further explanation though. Namely, the Cassak-Shay formula does successfully extend Sweet Parker type scaling arguments to the case of asymmetric reconnection. However, as with previous theoretic approaches, the length of the dissipation region is not predicted by the Cassak-Shay formula. Once the aspect ratio of the dissipation region has been measured, the Cassak-Shay formula does appear to accurately model asymmetric reconnection.

With regard to the Axford conjecture, Borovsky says that the Cassak-Shay formula appears to take precedence; driving can change the reconnection rate only by changing the local plasma parameters. (The Axford Conjecture posits that global driving alone controls the reconnection rate with no role being played by the diffusion region.)

The above results were presented as indicating that the reconnection rate at the dayside magnetopause is essentially controlled by the local parameters. The external driving appears to influence the dayside reconnection rate to the extent that it changes the local parameters, which themselves determine the reconnection rate.

Q3: Can we extend global resistive MHD to include microscale physics, which is needed to accurately model reconnection?

2008 Summer Workshop

Masha Kuznetsova presented results, which addressed the effects of collisionless physics on magnetotail dynamics (specifically, substorm onset and expansion), thus addressing questions Q1.4 (How does magnetotail reconnection work?) and Q3.3 (What is the status of "embedding approaches," in which kinetic physics is added locally to an MHD code (either via code coupling or via local modification of the equations)). Kuznetsova used analytic expressions for the nongyrotropic corrections to the electron pressure tensor to locally modify the resistive MHD Ohm's law in the BATSRUS code. These modifications result in a collapse of the Sweet-Parker current sheet to microscopic size (of the order of the ion gyroradius) as well as a dramatic increase in the reconnection rate (consistent with fast reconnection observed in PIC simulations).

2009 Summer Workshop

Yuri Shprits presented results in 2009 from the Versatile Electron Radiation Belt (VERB) code. This radiation belt module for GGCM accounts for the dominant physical processes identified during Inner Magnetosphere, Storms Campaign. The module has been made available to the community: http://www.atmos.ucla.edu/~yshprits/ VERB_code

2010 Summer Workshop

John Meyer presented results on 3D x-line growth in three-dimensional, two-fluid simulations of magnetic reconnection, relevant to questions Q1.4 and Q3.2. The simulations employed an initially 1D current sheet with parameters chosen match those in the near-earth magnetotail. The physics of 3D x-line growth may be important to understanding the structure of busty bulk flows, such as those observed, by e.g., Angelopoulos 1996. Electrons play the dominant role in carrying the current, and, being frozen-in to smaller scales than the ions, the electrons tend to drag magnetic flux with them. Variations in the current sheet width and strength thus lead to variations in the structure of the field in the direction downstream with respect to the electron flow, as the localized 3D x-lines expand and propagate.

Brian Sullivan presented a report on behalf of *Kai Germaschewski* regarding the porting OpenGGCM to run on the Cell Broadband Engine Architecture, which is the processor used in Playstation 3 (PS3) gaming machines. This work addresses question Q3, and its subquestions. In runs executed on a cluster of PS3's, Germaschewski has achieved a speed up in execution time on the order of 50 with respect to simulations preformed using a traditional CPU based Beowulf cluster. A code generator, created by Germaschewski, facilitates this remarkable speed-up. The code generator, which works well for stencil-based finite difference approaches, separates the description of the problem from the implementation by providing the user with a front end in which high level code can be written, and a back end which generates efficient machine level instructions for the particular architecture being employed, in this case, the Cell. The presentation ended with some preliminary results, which included the Hall term in the OpenGGCM solver.

4. Summary

In conclusion, the focus group has made good progress in the understanding of reconnection processes in large, collisionless and weakly collisional systems, although many questions remain open. Two major accomplishments over the last five years have been progress in the understanding of asymmetric reconnection, and the realization that very long Sweet-Parker sheets are subject to a super-Alfvénic plasmoid instability.

Reconnection in our system of interest is generally asymmetric, especially in the case of the dayside magnetopause. The Cassak-Shay formulas for asymmetric reconnection represent one major step toward a more complete understanding of reconnection in non-ideal, real world geometries. Others have refined these formulas to include more physics (e.g. pressure gradients, enthalpy flux). This work provides a good description of the dissipation region, and predictions of the outflow speeds and reconnection electric fields in 2D simulations with idealized geometries. In some global MHD simulations (such as the BATSRUS runs presented by Borovsky) the Cassak-Shay formula performs well. In the LFM runs presented by Lyon in 2010, however, outflow due to bow shock physics led to some disagreement between simulation results and the Cassak-Shay predictions. The component of outflow due to the bow shock in those simulations dominated that due to reconnection. However, after subtracting off that bow shock component of outflow, the outflow predictions matched fairly well with the Cassak-Shay predictions. Three-dimensional effects have been observed to result in a reduction of the sub-solar reconnection electric field by a factor of about two in the case of pure southward IMF. This is due to the fact that in 3D some flux can divert around the reconnection region rather than reconnecting.

The recognition of the importance of secondary tearing, or "plasmoid" instabilities in high-Lundquist-number plasmas represents an additional area of progress made by the members of this focus group (including Bhattacharjee, Uzdensky, and others). Plasmoids also appear to be a general feature in PIC simulations of reconnection in sufficiently large systems, as seen in work by Daughton *et al.* The plasmoid instability hastens reconnection in two different ways. First it drastically raises the reconnection rate in resistive MHD itself by breaking up what would become a long, thin Sweet-Parker type current sheet. Secondly, the plasmoid instability may trigger a cascade toward kinetic scale current sheets, leading to the onset of Hall, and other non-MHD physics. Depending on system parameters, the plasmoid instability may either simply hasten the onset of fast (potentially dissipation independent) reconnection, or it may even enable it in systems, which would not otherwise be expected to exhibit such fast reconnection. Plasmoid dominated reconnection is much more of a stochastic process than the stable, smooth current sheets generally considered in the past. Reconnection in this regime requires a statistical treatment, and good progress has been made on that front, including work by Fermo *et al.* and by Uzdensky *et al.* We have yet to see much in the way of detailed three-dimensional studies of this plasmoid instability. Hopefully future work will make connections between the complex kinked flux tubes associated with FTEs and the many plasmoids observed in weakly collisional fluid and collisionless PIC simulations of reconnection.

The following are some of the outstanding questions, which still require further attention in the future:

- What is the status of embedded, non-MHD approaches to global magnetospheric modeling (e.g. embedded Hall MHD regions, hybrid models, embedded PIC regions, etc.)?
- Are the regions of MHD breakdown in the global system sufficiently localized to make embedding a PIC or extended MHD module within a global MHD code computationally feasible?
- What is the role of secondary magnetic islands in reconnection in the magnetosphere? Are the flux ropes associated with FTEs the 3D analog of the plasmoids observed in localized simulations?

Progress is underway and ongoing on these questions, and we look forward to seeing the answers to them in continued work in the GEM reconnection physics and modeling community. Many individuals with a variety of viewpoints came together to contribute to the lively discussions at our sessions, and we would like to thank all of them for their participation in the Modules and Methods focus group.

References

A non-exhaustive list of published papers related to the Focus Group presentations:

Axford, W. I., Magnetic reconnection, in Magnetic Reconnection in Space and Laboratory Plasmas, *Geophys. Monogr. Ser.,* **vol. 30**, edited by J. E. W. Hones, pp. 1–8, AGU, Washington, D.C. (1984).

Bhattacharjee, A, Y. M. Huang, H. Yang, and B. N. Rogers. Fast reconnection in high-Lundquist-number plasmas due to the plasmoid Instability. *Phys. Plasmas*, **16**, 112102 (2009). doi:10.1063/1.3264103

Birn, J., et al. (2001), GEM magnetic reconnection challenge, J. Geophys. Res., 106(A3), 3715, doi:10.1029/ 1999JA900449.

Birn, J., M. Hesse, and J. E. Borovsky, Properties of asymmetric reconnection, *Phys. Plasmas*, **15,** 032101, doi: 10.1063/ 1.2888491, 2008.

Birn, J., J. E. Borovsky, M. Hesse, and K. Schindler (2010), Scaling of asymmetric reconnection in compressible plasmas, *Phys. Plasmas*, 17, 052108.

Biskamp, D., Magnetic reconnection via current sheets, *Phys. Fluids* 1520 **29** (1986).

Borovsky, J. E. , The rudiments of a theory of solar wind/ magnetosphere coupling derived from first principles, *J. Geophys. Res.,* 113, A08228, doi:10.1029/ 2007JA012646. (2008).

Borovsky, J. E., and M. Hesse, The reconnection of magnetic fields between plasmas with different densities: Scaling relations, *Phys. Plasmas,* **14**, 102309. (2007)

Borovsky, J. E., M. Hesse, J. Birn, and M. M. Kuznetsova, What determines the reconnection rate at the dayside magnetosphere? *J. Geophys. Res.*, 113, A07210, doi:10.1029/2007JA012645, 2008.

S. V. Bulanov and P. V. Sarasov*, Fiz. Plazmy* **4,** 746 (1978). [Sov. J. Plasma Phys. 4, 418 (1978)].

Cassak, P. A. , M. A. Shay, and J. F. Drake. Catastrophe Model for Fast Magnetic Reconnection Onset. Phys. Rev. Lett. **95** 235002 (2005).DOI:10.1103/PhysRevLett. 95.235002

Cassak, P. A. and M. A. Shay. Scaling of asymmetric magnetic reconnection: General theory and collisional simulations. Physics of Plasmas, **14** 102114, (2007). DOI: 10.1063/1.2795630

Cassak, P. A. and M. A. Shay, The scaling of asymmetric Hall reconnection, *Geophys. Res. Lett.*, **35**, L19102, (2008).

Cassak, P. A. and M. A. Shay, Structure of the dissipation region in fluid Simulations of asymmetric magnetic reconnection, *Phys. Plasmas*, **16**, 055704, (2009).

Cassak, P. A. M. A. Shay, and J. F. Drake. Scaling of Sweet–Parker reconnection with secondary islands. *Phys. Plasmas*, **16**, 120702(2009). doi:10.1063/1.3274462

Daughton, W. V. Roytershteyn, B. J. Albright, H. Karimabadi, L. Yin, and Kevin J. Bowers *Phys. Plasmas* **16**, 072117 (2009). DOI: 10.1063/1.3191718

Dai, L., Collisionless Magnetic Reconnection via Alfvén Eigenmodes. Phys. Rev. Lett. 102, 245003 (2009). doi: 10.1103/ PhysRevLett.102.245003

Divin, A. V., M. I. Sitnov, M. Swisdak, J. F. Drake. Reconnection onset in the magnetotail: Particle simulations with open boundary conditions. *Geophys. Res. Lett.* **34**, L09109, 2007. doi:10.1029/2007GL029292

Drake, J. F., M. Swisdak, K. M. Schoeffler, B. N. Rogers, and S. Kobayashi, Formation of secondary islands during magnetic reconnection, *Geophys. Res. Lett.,* **33**, L13105, doi:10.1029/2006GL025957, 2006.

Dorelli J. C., and A. Bhattacharjee, Defining and identifying three-dimensional magnetic reconnection in resistive magnetohydrodynamic simulations of Earth's magnetosphere, *Phys. Plasmas* 15, 056504; DOI:10.1063/1.2913548, 2008.

Dorelli J. C., and A. Bhattacharjee, On the generation and topology of flux transfer events, *J.Geophys. Res., 114*, A06213, doi:10.1029/2008JA013410, 2009.

Dorelli, J. C., A. Bhattacharjee, J. Raeder, Separator reconnection at Earth's dayside magnetopause under generic northward interplanetary magnetic field conditions, *J. Geophys. Res.*, 112, A02202, doi:10.1029/2006JA011877, 2007.

Fermo, R. L. , J. F. Drake, and M. Swisdak. A statistical model of magnetic islands in a current layer. *Phys. Plasmas* **17**, 010702 (2010). doi:10.1063/1.3286437

Huang, Y. M, and A. Bhattacharjee. Scaling laws of resistive magnetohydrodynamic reconnection in the high-Lundquist-number, plasmoid-unstable regime. *Phys. Plasmas* **17**, 062104 (2010).

Jin, S.P. and W.H. Ip, Two-dimensional compressible magnetohydrodynamic simulation of the driven reconnection process, *Phys. Fluids* **8** 1927–1936 (1991).

Karimabadi, H, W. Daughton, and K. B. Quest, Physics of saturation of collisionless tearing mode as a function of guide field, *J. Geophys. Res.*, *110*, A03213, doi:10.1029/2004JA010750, 2005a.

Le A., J. Egedal, W. Fox, N. Katz, A. Vrublevskis, W. Daughton, J.F. Drake, Equations of state in collisionless magnetic reconnection *Phys. Plasmas* **17,** 055703 (2010).

Malakit, K., M. A. Shay, P. A. Cassak, and C. Bard. Scaling of asymmetric magnetic reconnection: Kinetic particle-in-cell simulations. *J. Geophys. Res.*, 115, A10223, (2010). doi:10.1029/2010JA015452.

Ni, L., K. Germaschewski, Y.M. Huang, B. P. Sullivan, H. Yang, and A. Bhattacharjee. Linear plasmoid instability of thin current sheets with shear flow. Phys. Plasmas **17**, 052109 (2010). doi:10.1063/1.3428553

Ouellette, J. E., B. N. Rogers, M. Wiltberger, and J. G. Lyon. Magnetic reconnection at the dayside magnetopause in global Lyon-Fedder-Mobarry simulations. *J. Geophys. Res.*, **115**, A08222, (2010). doi:10.1029/2009JA014886

Pritchett, P. (2008), Collisionless magnetic reconnection in an asymmetric current sheet, *J. Geophys. Res.*, **113**, A06210, doi:10.1029/2007JA012930.

Pritchett, P. L., and F. S. Mozer (2009), Asymmetric magnetic reconnection in the presence of a guide field, *J. Geophys. Res.,* **114**, A11210, doi:10.1029/ 2009JA014343.

Roytershteyn V., W. Daughton, S. Dorfman, Y. Ren, H. Ji, M. Yamada, H. Karimabadi, L. Yin, B. J. Albright, K. J. Bowers, Driven magnetic reconnection near the Dreicer limit. *Phys. Plasmas* **17,** 055706 (2010).

Servidio, S., W. H. Matthaeus, M. A. Shay, P. A. Cassak, and P. Dmitruk (2009), Magnetic reconnection in two-dimensional magnetohydrodynamic turbulence, *Phys. Rev. Lett.,* **102**, 115003.

Shprits, Y. Y., D. Subbotin, and B. Ni (2009), Evolution of electron fluxes in the outer radiation belt computed with the VERB code, *J. Geophys. Res.,* **114**, A11209, doi:10.1029/2008JA013784.

Sullivan, B. P. and B. N. Rogers. The Scaling of Forced Collisionless Reconnection. *Phys. Plasmas* **15**, 102106 (2008). doi:10.1063/1.2992136

Sullivan, B. P., A. Bhattacharjee, and Yi-Min Huang. Extension of the electron dissipation region in collisionless Hall magnetohydrodynamic reconnection. *Phys. Plasmas* 16, 102111 (2009). doi:10.1063/1.3251423

Sullivan, B. P. , A. Bhattacharjee, and Y. M. Huang. On the question of Hysteresis in Hall magnetohydrodynamic reconnection. *Phys. Plasmas* 17, 114507 (2010). doi:10.1063/1.3518752

Winglee, R. M., E. Harnett, A. Stickle and J. Porter, Multi-scale/multi-fluid simulations of flux ropes at the magnetopause, *J. Geophys. Res.,* **113**, A02209:10.1029/ 2007 JA012653, 2008.

Zeiler, A., D. Biskamp, J. F. Drake, B. N. Rogers, M. A. Shay, M. Scholer. Three-dimensional particle simulations of collisionless magnetic reconnection. *J. Geophys. Res.* **107** 1230 (2002). doi:10.1029/2001JA000287