Final Report for Period: 06/2011 - 11/2011**Submitted on:** 04/23/2012**Principal Investigator:** Otto, Antonius .**Award ID:** 0614012**Organization:** U of Alaska Fairbanks**Submitted By:**

Otto, Antonius - Principal Investigator

Title:

Plasma Transport at the Magnetospheric Flank Boundary

Project Participants**Senior Personnel****Name:** Otto, Antonius**Worked for more than 160 Hours:** Yes**Contribution to Project:****Name:** Johnson, Jay**Worked for more than 160 Hours:** Yes**Contribution to Project:****Post-doc****Graduate Student****Name:** Adamson, Eric**Worked for more than 160 Hours:** Yes**Contribution to Project:**

model development, simulation runs, and analysis

Name: Stevens, Richard**Worked for more than 160 Hours:** Yes**Contribution to Project:**

model development, simulation runs, and analysis

Name: Ma, Xuanye**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Research on boundary layer physics and development of three-dimensional Hall MHD simulation.

Undergraduate Student**Name:** Macdonald, Jason**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Simple diagnostic tools. Testparticle computations.

Technician, Programmer**Other Participant****Research Experience for Undergraduates**

Organizational Partners

Other Collaborators or Contacts

Prof. Katariina Nykyri (Embry Riddle University) has collaborated on this project by providing observational input using Cluster spacecraft data.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

See attached file.

Findings: (See PDF version submitted by PI at the end of the report)

See attached activities file

Training and Development:

The project provided skill and experience in the numerical modeling and theory of (1) the motion of charged particles in a plasma, (2) Kelvin Helmholtz waves at a magnetic boundary, and (3) plasma transport across the magnetospheric boundary. Results were also used in a new undergraduate course of magnetospheric physics as examples for current research and entered into a graduate class on magnetospheric physics. Several graduate student have been directly involved in the associated research and about 15 other graduate students through the class material.

Outreach Activities:

We have organized the Plasma Entry and Transport Workshop and the International Cambridge Workshop on Magnetic Reconnection in 2009 and are Co-chairs for the GEM focus group on Plasma Entry and Transport. For other activities see the attached file on findings and results. Some material of the research is available in electronic form through undergraduate and graduate class manuscripts.

Journal Publications

Nakamura, T.K.M., M. Fujimoto, and A.Otto, "The structure of an MHD-scale Kelvin-Helmholtz vortex: Two-dimensional two-fluid simulations including finite electron inertial effects", Journal of Geophys. Research, p. 9204, vol. 113, (2008). Published, 10.1029/2007JA012803

Otto, A. and K. Nykyri, "Three-dimensional Kelvin-Helmholtz modes and magnetic reconnection", Annales Geophysicae, p. , vol. , (2009). In preperation,

Otto, A., and F. Hall, "Current sheet thinning and entropy constraints", J. Geophys. Res., p. , vol. , (2009). Submitted,

Johnson, J. R., and S. Wing, "Northward interplanetary magnetic field plasma sheet entropies", J. Geophys. Res., p. , vol. , (2009). Published, 10.1029/2008JA014017

Lin, Y., J. R. Johnson, and X. Y. Wang, "Hybrid simulation of mode conversion at the magnetopause", J. Geophys. Res., p. , vol. , (2010). Published, 10.1029/2009JA014524

Wing, S., and J. R. Johnson, "Substorm entropies", J. Geophys. Res., p. , vol. , (2009). Published, 10.1029/2008JA013989

Adamson, E., Otto, A., Nykyri, K., "3D Mesoscale MHD Simulations of a Cusp-like Magnetic Configuration: Method and First Results", J. Geophys. Res., p. , vol. , (2010). Submitted,

Adamson, E., Otto, A., Nykyri, K., "3D mesoscale mhd simulations of magnetospheric cusp-like magnetic configurations: effects of magnetosheath parameter variations", J. Geophys. Res., p. , vol. , (2010). Submitted,

- Wing, S., and J. R. Johnson, "Introduction to special section on Entropy Properties and Constraints Related to Space Plasma Transport", J. Geophys. Res., p. , vol. , (2010). Published, 10.1029/2009JA014911
2. Adamson, E., A. Otto, and K. Nykyri, "3D mesoscale MHD simulations of a cusp-like magnetic configuration: Method and first results", Ann. Geophys., p. , vol. , (2011). Accepted,
3. Nykyri, K., A. Otto, E. Adamson, and A. Tjulin, "On the Origin of Fluctuations in the Cusp Diamagnetic Cavity", J. Geophys. Res., p. , vol. , (2011). Published, 10.1029/2010JA015888
4. Nykyri, K., A. Otto, E. Adamson, E. Dougel, and J. Mumme, "Cluster Observations of a Cusp Diamagnetic Cavity: Structure, Size and Dynamics", J. Geophys. Res., p. , vol. , (2011). Accepted, 10.1029/2010JA015897
5. Javadi, S., Buechner, J., Otto, A., and Santos, J.-C., "About the relative importance of compressional heating and current dissipation for the formation of coronal X-ray Bright Points", A&A, p. , vol. , (2011). Published, 10.1051/0004-6361/201015614
6. Santos, J.-C., Buechner, J., and A. Otto, "Development of electric currents in a magnetic field configuration containing a magnetic null point", A&A, p. , vol. , (2011). Published, 10.1051/0004-6361/201014758
7. Cassak, P.A. and Otto, A., "Scaling of the Reconnection Rate with Anti-Parallel Symmetric Shear Flow", Geophys. Res. Lett., p. , vol. , (2011). Accepted,
8. Nykyri, K., Otto, A., Adamson, E., Kronberg, E., Daly, P., "Cluster Observations of High-Energy Particle Properties in Cusp Diamagnetic Cavity", JSTP, p. , vol. , (2011). Accepted,

Books or Other One-time Publications

Web/Internet Site

URL(s):

<http://how.gi.alaska.edu/ao/plasma08/index.html>

Description:

This is the web manuscript of the undergraduate plasma class where some of our research results have been used for the class.

Other Specific Products

Contributions

Contributions within Discipline:

We have made major progress in several areas of plasma transport into the magnetosphere:
 Our results contribute to distinguish between cusp reconnection and Flank Kelvin Helmholtz modes as the dominant entry mechanisms
 We have identified a simple three-dimensional mechanism for current sheet thinning during the substorm growth phase.
 We have examined this new process quantitatively.
 We have suggested a new process for current sheet thinning.
 We have examined effects from the boundary perturbation under the condition of entropy conservation for the magnetotail.
 See also the uploaded findings file for details

Contributions to Other Disciplines:

1. The plasma transport across magnetic boundaries is a fundamental plasma physics problem. Therefore our results on plasma entry are relevant to the larger plasma physics community
2. Geomagnetic Substorms are not well understood and have several environmental effects. A critical area is the substorm growth phase for which to date no consistent model existed. Our model is the first that can consistently explain the current sheet thinning and is therefore a major

step to better understand geomagnetic substorms and their environmental impact.

3. There is increased interest in Kelvin Helmholtz waves in the ionospheric and the solar physics community.

Contributions to Human Resource Development:

We employ and train undergraduates and graduate students in the project. The co-author of one submitted publication is a former graduate student and one of the few African Americans in our field. Also one of the former graduate students is native Alaskan.

Contributions to Resources for Research and Education:

The following web sites represent courses including electronic manuscripts for undergraduate and graduate students:

<http://how.gi.alaska.edu/ao/msp/index.html>

<http://how.gi.alaska.edu/ao/plasma/index.html>

<http://how.gi.alaska.edu/ao/sim/index.html>

Feedback indicates that these are also used as resources in our research community

Contributions Beyond Science and Engineering:

As pointed out, geomagnetic substorms can have considerable environmental effects for power grids, high altitude airplanes, and space flight and instrumentation. Therefore, our progress on the substorm growth phases can have societal impacts beyond the field of science and engineering.

Conference Proceedings

Categories for which nothing is reported:

Organizational Partners

Any Book

Any Product

Any Conference

Plasma Transport at the Magnetospheric Flank Boundary

Progress Report for the NSF award 0614012 for the year 2010 - 2011

Principle Investigator: Antonius Otto

Co-Investigator: Jay R. Johnson

Institution: University of Alaska Fairbanks

A. Highlights from the last year of the research project:

1. Entropy change and plasma transport by KH mediated reconnection - mixing and heating of plasma
2. Entropy and plasma transport in the magnetotail - current sheet thinning and tail reconnection
3. Other project related activities - Hall MHD code

B. Summary of the most important results:

1. Entropy change and plasma transport by KH mediated reconnection - mixing and heating of plasma

During the past years we have demonstrated that three-dimensional nonlinear Kelvin Helmholtz modes at the magnetospheric flanks force magnetic reconnection at the northern and southern boundaries of the unstable interaction region for northward IMF conditions. We have examined the properties of this process regarding the growth, mass transport and the effects of density asymmetry of these waves. A critical quantity particularly for comparison with observations is plasma mixing and the nonadiabatic heating of the magnetosheath component during the transport from the magnetosheath side to the magnetospheric side of the boundary.

Figure 1: Sketch of the KH interaction at the magnetospheric flanks (left) and evolution of average entropy of the plasma obtained through integration of entropy and mass along magnetic flux tubes.

During prolonged periods of northward IMF a cold and dense population appears initially close to the flank boundaries and at later times also close to the noon midnight meridian. This cold dense plasma sheet consists of a

mixture of cold and hot populations and observations show a number of interesting properties. Compared to the hot plasma sheet the average density is higher, the average temperature is lower, and the entropy is significantly lower in the cold dense plasma sheet (CDPS) although the entropy is still about an order of magnitude higher than in the magnetosheath.

During the last year we have examined the properties of the mixed plasma in more detail. Since MHD simulation conserve the local entropy this study has been conducted integrating mass and entropy along flux tubes using the assumption that plasma from magnetospheric sections and magnetosheath sections of a newly closed field line mix along this field line. The sketch in Figure 1 illustrates this reconnection process and properties are integrated from one reference plane (as indicated in the figure). By comparison of conjugate foot point locations it is identified whether the field line is closed or open. the location of the foot point determines whether the field line in the southern hemisphere is in the sheath or maps into the magnetosphere. The two color plots next to the sketch show the evolution of the expected average entropy $S = pV^\gamma$ assuming a relaxation of the plasma along the flux tube about a minute apart. The region to the left with high average entropy corresponds to the magnetosphere ($x < 0$). The unit distance in the plots is 600 km. The plots demonstrate that a significant boundary layer develops with a width of about $0.5 R_E$ within one minute of the KH evolution. The average entropy in this boundary layer is significantly reduced and compares well with observations of the CDPS.

These results demonstrate that the plasma transport through KH mediated reconnection at the magnetospheric flanks compares well and is able to explain the basic properties of the boundary layer of the CDPS. However it is important to point out one important piece of the puzzle of the plasma entry that applies to the KH mechanism but even more to the entry by cusp reconnection for northward IMF. While the average properties of the CDPS are nicely consistent, observations show that the cold population in the CDPS is non-adiabatically heated to about 5 times the magnetosheath temperature. While this is still much colder than the hot plasma sheet it is difficult to reconcile this with the plasma entry mechanism for cusp and KH reconnection. It has been argued that magnetic reconnection may be able to provide this heating such that we investigated this possibility too.

In the case of Petschek (slow shock) reconnection the nonadiabatic heating can be determined analytically to

$$\frac{S_o}{S_i} = X^{1-\gamma} \left(1 + \frac{\gamma-1}{\gamma\beta} \right)$$

Figure 2: Density n , entropy p/n^γ , temperature T and pressure p ratio between downstream and upstream regions of slow switch-off shocks.

where X is the plasma compression, β is the plasma β , and the indices o and i indicate down- and upstream regions.

Figure 2 illustrates the pressure, Temperature, entropy, and density ratio between down and upstream regions. Specifically it shows that entropy and temperature increase are of order unity unless the plasma β in the upstream region is much smaller than 1. One could argue that this is only valid for the special case of Petschek reconnection but unfortunately this result can be derived in terms of an inequality in a more general way. Assuming total pressure balance between inflow and outflow regions of reconnection and a guide field we can determine an upper bound for the entropy increase:

$$\frac{S_o}{S_i} = \left(\frac{n_i}{n_o} \right)^\gamma \frac{p_o}{p_i} = \left(\frac{n_i}{n_o} \right)^\gamma \frac{p_{tot} - B_g^2/2\mu_0}{p_i} = \left(\frac{n_i}{n_o} \right)^\gamma \frac{p_i + B_i^2/2\mu_0 - B_g^2/2\mu_0}{p_i} \leq 1 + \frac{1}{\beta_i}$$

such that the entropy increase is always of order unity or smaller unless the $\beta \ll 1$. We have confirmed this result in MHD and Hall MHD simulations which are for Petschek-like conditions in excellent agreement with the

analytic result. Since the captured magnetosheath population is expected to expand along the evolving flux tube (which is necessary to explain the partial density) we would expect this component to cool significantly contrary to observations without an additional heating mechanism. This effect is expected to be stronger for cusp reconnection where a larger fraction of a newly closed flux tube consists of captures magnetosheath plasma.

In conclusion we can summarize that the project has demonstrated that three-dimensional KH modes are largely consistent with observed plasma sheet properties but will require an additional nonadiabatic heating mechanism.

2. Entropy and plasma transport in the magnetotail - current sheet thinning and tail reconnection

A typical property during the growth phase of geomagnetic substorms is the thinning of the near-Earth current sheet, most pronounced in the region between 6 and 15 R_E . We have proposed that the cause for the current sheet thinning is convection from the midnight tail region to the dayside to replenish magnetospheric magnetic flux which is eroded at the dayside as a result of dayside reconnection. Adiabatic convection from the near-Earth tail region toward the dayside must conserve the entropy on magnetic field lines. This constraint prohibits a source of the magnetic flux from a region further out in the magnetotail. Thus the near-Earth tail region is increasingly depleted of magnetic flux (the *Erickson and Wolf* [1980] problem) with entropy matching that of flux tubes that are eroded on the dayside.

In a series of three-dimensional MHD simulations we had examined current sheet thinning based on magnetic flux depletion. The model employs a section of the magnetotail based on a Tsyganenko model which is relaxed into an equilibrium. The condition of sunward azimuthal convection is prescribed at the sunward boundary consistent with a specified reconnection (polar cap) potential. For typical polar cap potentials (40 kV) the magnetic field in the equatorial plane decreases from about 30 nT at 10 R_E to about 1 nT in about 55 minutes. The color plot in Figure 4 presents the initial cross tail current density profile (top) and the current density profile after approximately 1 hour (bottom) for $z > 0$ (note that the system is symmetric with respect to the equatorial plane and distances are in R_E). The plot demonstrates the extreme thinning of the cross-tail current and the evolution of a sharp transition region from a dipolar to the thin and stretched field at about 8 to 9 R_E . The time scale of the current sheet thinning is found to be inversely proportional to the amount of magnetic flux in the near Earth equatorial plane. The increasing depletion leads to a faster increase of the thinning and magnitude of the current density at later times in the process. The process is largely self-similar in the sense that a value of twice the driving potential leads to a current sheet thinning that is twice as fast.

Of particular interest with the current sheet thinning is the onset and evolution of reconnection in the thin tail current sheet. In series of simulations we examined this onset in a first cut as a function of current sheet width and sunward outflow conditions. In all cases reconnection onset was very similar and occurred at or close to the maximum of the current density between 10 and 15 R_E . It is interesting that the subsequent evolution depended on the sunward flow conditions. As long as the sunward flow boundary condition was maintained reconnection remained in the near Earth plasma sheet close to where it originally formed. Only when the sunward outflow was choked off did the X line move away from the near Earth region. In this case reconnected flux accumulated in the near Earth region

Figure 3: Initial cross-tail current density profile (as obtained from the relaxed Tsyganenko model (top) and of the current density profile after sunward azimuthal outflow has been applied for about an hour (bottom).

leading to more dipolarization and pushing the X line tailward. Another interesting aspect is the structure of the reconnection bulge or plasmoid. Although the initial configuration is smooth and continuous the reconnected flux region is highly structured with finger-like intrusions. Figure 4 show the flux tube entropy in the equatorial plane short after onset and about 12 minutes later. Rather small entropy indicates the dipolar magnetic field region. Sharp boundaries in the flux tube entropy indicate different magnetic connection of the respective area in the equatorial plane. For the result shown in Figure 4 the sunward flow was choked off and the initial configuration correspond to the thin current sheet shown in Figure 3. It is seen the the dominant reconnection region has moved to about $x = -24 R_E$.

Figure 4: Flux tube entropy in the equatorial plane immediately after reconnection onset and about 12 minutes later. The unit distance corresponds to $1 R_E$ and x points to ward the sun. The sunward boundary is at $6 R_E$.

We have compared model properties with typical and statistical observations and found excellent agreement between equatorial magnetic field magnitude and current sheet width and strength. In summary the proposed mechanism is able to explain the typical growth time, the location of the current sheet thinning, an accelerated thinning toward the end of the growth phase, and the observed relation between the small equatorial magnetic field and current sheet strength. It also promises to be a highly interesting tool to study onset and evolution of magnetic reconnection in the magnetotail.

3. Other project related activities - Hall MHD code

- We have a completed testing the newly developed Hall MHD code and are using it in a number of 3D KH simulation for a comparison with prior MHD results. It is intended to use the Hall MHD code also for the current sheet thinning and the evolution of reconnection.
- We have obtained further results in the areas of (1) test particle dynamics during reconnection KH vortices at the flank boundaries, (2) mode conversion and kinetic physics associated with KH boundaries (in part illustrated in the list of publications).
- We have organized the focus group on plasma entry and transport in the magnetotail at the 2010 and 2011 GEM workshops and the Co-I has organized a special session on plasma entry at the 2010 Fall AGU in San Francisco.
- We (the PI and the Co-I) had several meetings during the past year to discuss the progress to examine the incorporation of kinetic effects and to consider kinetic Alfvén wave into the KH model.

C. Publications and Presentations:

1. Presentations were given at various international meetings and workshops:

Invited conference presentations and seminars:

- Otto, A., Simulation of Magnetospheric and Ionospheric Physics, University of Alaska Computational Science Symposium, Fairbanks, Alaska, Feb. 2010.
- Otto, A., On the Relation of Localized Parallel Electric Fields, Alfvén Waves, and the Dynamics of Discrete Auroral Arcs, International Workshop on Advances and Perspectives in Auroral Plasma Physics, Beaulieu, France, April 2010.
- Otto, A., The Geomagnetic Cusps: Magnetic Topology and Physical Processes, Geospace Environmental Modeling Workshop, Snowmass, Colorado, June 2010.
- Otto, A., Two invited presentations: (1) Mechanisms of Current Sheet Formation; (2) Entropy Changes Associated with Magnetic Reconnection, International Cambridge Workshop on Magnetic Reconnection, St. Andrews, Scotland, August, 2010.
- Otto, A., Entropy and Magnetospheric Convection and Reconnection, International conference on 'Theory of the Magnetosphere', Santa Fe, New Mexico, 2010.

Other:

- Johnson, J., A. Otto, E. Kim, S. Wing, and Y. Lin, Heavy ion effects on magnetopause transport processes, IAGA, 2009, Sopron, Hungary. Hybrid Simulation of Mode Conversion at the Magnetopause, Y. Lin, J. Johnson, and X. Wang, Fall AGU meeting, 2009, San Francisco.
- Johnson, J., A. Otto, E. Kim, S. Wing, and Y. Lin, Heavy ion effects on magnetopause transport, Fall AGU meeting, 2009, San Francisco.
- Johnson, J., Otto, A., E. Adamson, Ma, X., Several presentations at the GEM workshop, 2010.
- Ma, X., Otto, A., Nykyri, K., 2-D and 3-D Hall MHD Reconnection, AGU 2010
- Otto, A., Ma, X., Entropy Generation Associated with Magnetic Reconnection for Small Plasma Beta, AGU 2010
- Lazerson, S.A., Johnson, J., Delamere, P.A., Otto, A., Lin, Y., Wing, S., Kim, E., How do heavy ions affect plasma entry and transport processes?, AGU 2010

In addition the PI and Co-I are co-chairs for a corresponding GEM focus group and have organized various sessions during the last year at the GEM workshop. The Co-I has organized a special session at the 2010 Fall AGU in San Francisco. PI and Co-I are also members of a successful proposal at the International Space Science Institute (ISSI) and had a first meeting there in April 2011.

2. Student involvement :

- E. Adamson (Ph.D, thesis completion Summer 2010).
- X. Ma (Ph.D, started summer 2009)

3. Publications

1. Wing, S., and J. R. Johnson (2010), Introduction to special section on Entropy Properties and Constraints Related to Space Plasma Transport, *J. Geophys. Res.*, 115, A00D00, doi:10.1029/2009JA014911.
2. Adamson, E., A. Otto, and K. Nykyri, 3D mesoscale MHD simulations of a cusp-like magnetic configuration: Method and first results, *Ann. Geophys.*, accepted for publication, 2010.
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9. Otto, A., and F. Hall, Current sheet thinning and entropy constraints, *Ann. Geophys.*, , submitted, 2011.
10. Otto, A. and K. Nykyri, Three-dimensional Kelvin-Helmholtz modes and magnetic reconnection, to be submitted.

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2. Entropy and plasma transport in the magnetotail - current sheet thinning and tail reconnection

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In a series of three-dimensional MHD simulations we had examined current sheet thinning based on magnetic flux depletion. The model employs a section of the magnetotail based on a Tsyganenko model which is relaxed into an equilibrium. The condition of sunward azimuthal convection is prescribed at the sunward boundary consistent with a specified reconnection (polar cap) potential. For typical polar cap potentials (40 kV) the magnetic field in the equatorial plane decreases from about 30 nT at 10 R_E to about 1 nT in about 55 minutes. The color plot in Figure 4 presents the initial cross tail current density profile (top) and the current density profile after approximately 1 hour (bottom) for $z > 0$ (note that the system is symmetric with respect to the equatorial plane and distances are in R_E). The plot demonstrates the extreme thinning of the cross-tail current and the evolution of a sharp transition region from a dipolar to the thin and stretched field at about 8 to 9 R_E . The time scale of the current sheet thinning is found to be inversely proportional to the amount of magnetic flux in the near Earth equatorial plane. The increasing depletion leads to a faster increase of the thinning and magnitude of the current density at later times in the process. The process is largely self-similar in the sense that a value of twice the driving potential leads to a current sheet thinning that is twice as fast.

Of particular interest with the current sheet thinning is the onset and evolution of reconnection in the thin tail current sheet. In series of simulations we examined this onset in a first cut as a function of current sheet width and sunward outflow conditions. In all cases reconnection onset was very similar and occurred at or close to the maximum of the current density between 10 and 15 R_E . It is interesting that the subsequent evolution depended on the sunward flow conditions. As long as the sunward flow boundary condition was maintained reconnection remained in the near Earth plasma sheet close to where it originally formed. Only when the sunward outflow was choked off did the X line move away from the near Earth region. In this case reconnected flux accumulated in the near Earth region

Figure 3: Initial cross-tail current density profile (as obtained from the relaxed Tsyganenko model (top) and of the current density profile after sunward azimuthal outflow has been applied for about an hour (bottom).

leading to more dipolarization and pushing the X line tailward. Another interesting aspect is the structure of the reconnection bulge or plasmoid. Although the initial configuration is smooth and continuous the reconnected flux region is highly structured with finger-like intrusions. Figure 4 show the flux tube entropy in the equatorial plane short after onset and about 12 minutes later. Rather small entropy indicates the dipolar magnetic field region. Sharp boundaries in the flux tube entropy indicate different magnetic connection of the respective area in the equatorial plane. For the result shown in Figure 4 the sunward flow was choked off and the initial configuration correspond to the thin current sheet shown in Figure 3. It is seen the the dominant reconnection region has moved to about $x = -24 R_E$.

Figure 4: Flux tube entropy in the equatorial plane immediately after reconnection onset and about 12 minutes later. The unit distance corresponds to $1 R_E$ and x points to ward the sun. The sunward boundary is at $6 R_E$.

We have compared model properties with typical and statistical observations and found excellent agreement between equatorial magnetic field magnitude and current sheet width and strength. In summary the proposed mechanism is able to explain the typical growth time, the location of the current sheet thinning, an accelerated thinning toward the end of the growth phase, and the observed relation between the small equatorial magnetic field and current sheet strength. It also promises to be a highly interesting tool to study onset and evolution of magnetic reconnection in the magnetotail.

3. Other project related activities - Hall MHD code

- We have a completed testing the newly developed Hall MHD code and are using it in a number of 3D KH simulation for a comparison with prior MHD results. It is intended to use the Hall MHD code also for the current sheet thinning and the evolution of reconnection.
- We have obtained further results in the areas of (1) test particle dynamics during reconnection KH vortices at the flank boundaries, (2) mode conversion and kinetic physics associated with KH boundaries (in part illustrated in the list of publications).
- We have organized the focus group on plasma entry and transport in the magnetotail at the 2010 and 2011 GEM workshops and the Co-I has organized a special session on plasma entry at the 2010 Fall AGU in San Francisco.
- We (the PI and the Co-I) had several meetings during the past year to discuss the progress to examine the incorporation of kinetic effects and to consider kinetic Alfvén wave into the KH model.

C. Publications and Presentations:

1. Presentations were given at various international meetings and workshops:

Invited conference presentations and seminars:

- Otto, A., Simulation of Magnetospheric and Ionospheric Physics, University of Alaska Computational Science Symposium, Fairbanks, Alaska, Feb. 2010.
- Otto, A., On the Relation of Localized Parallel Electric Fields, Alfvén Waves, and the Dynamics of Discrete Auroral Arcs, International Workshop on Advances and Perspectives in Auroral Plasma Physics, Beaulieu, France, April 2010.
- Otto, A., The Geomagnetic Cusps: Magnetic Topology and Physical Processes, Geospace Environmental Modeling Workshop, Snowmass, Colorado, June 2010.
- Otto, A., Two invited presentations: (1) Mechanisms of Current Sheet Formation; (2) Entropy Changes Associated with Magnetic Reconnection, International Cambridge Workshop on Magnetic Reconnection, St. Andrews, Scotland, August, 2010.
- Otto, A., Entropy and Magnetospheric Convection and Reconnection, International conference on 'Theory of the Magnetosphere', Santa Fe, New Mexico, 2010.

Other:

- Johnson, J., A. Otto, E. Kim, S. Wing, and Y. Lin, Heavy ion effects on magnetopause transport processes, IAGA, 2009, Sopron, Hungary. Hybrid Simulation of Mode Conversion at the Magnetopause, Y. Lin, J. Johnson, and X. Wang, Fall AGU meeting, 2009, San Francisco.
- Johnson, J., A. Otto, E. Kim, S. Wing, and Y. Lin, Heavy ion effects on magnetopause transport, Fall AGU meeting, 2009, San Francisco.
- Johnson, J., Otto, A., E. Adamson, Ma, X., Several presentations at the GEM workshop, 2010.
- Ma, X., Otto, A., Nykyri, K., 2-D and 3-D Hall MHD Reconnection, AGU 2010
- Otto, A., Ma, X., Entropy Generation Associated with Magnetic Reconnection for Small Plasma Beta, AGU 2010
- Lazerson, S.A., Johnson, J., Delamere, P.A., Otto, A., Lin, Y., Wing, S., Kim, E., How do heavy ions affect plasma entry and transport processes?, AGU 2010

In addition the PI and Co-I are co-chairs for a corresponding GEM focus group and have organized various sessions during the last year at the GEM workshop. The Co-I has organized a special session at the 2010 Fall AGU in San Francisco. PI and Co-I are also members of a successful proposal at the International Space Science Institute (ISSI) and had a first meeting there in April 2011.

2. Student involvement :

- E. Adamson (Ph.D, thesis completion Summer 2010).
- X. Ma (Ph.D, started summer 2009)

3. Publications

1. Wing, S., and J. R. Johnson (2010), Introduction to special section on Entropy Properties and Constraints Related to Space Plasma Transport, *J. Geophys. Res.*, 115, A00D00, doi:10.1029/2009JA014911.
2. Adamson, E., A. Otto, and K. Nykyri, 3D mesoscale MHD simulations of a cusp-like magnetic configuration: Method and first results, *Ann. Geophys.*, accepted for publication, 2010.
3. Nykyri, K., A. Otto, E. Adamson, and A. Tjulin, On the Origin of Fluctuations in the Cusp Diamagnetic Cavity, *JGR*, 116, A15, doi 10.1029/2010JA015888, 2011.
4. Nykyri, K., A. Otto, E. Adamson, E. Dougel, and J. Mumme, Cluster Observations of a Cusp Diamagnetic Cavity: Structure, Size and Dynamics, *JGR*, accepted for publ. 10.1029/2010JA015897, 2011.

5. Javadi, S., Buechner, J., Otto, A., and Santos, J.-C., About the relative importance of compressional heating and current dissipation for the formation of coronal X-ray Bright Points, *A&A*, 529, A114, doi 10.1051/0004-6361/201015614, 2011
6. Santos, J.-C., Buechner, J., and A. Otto, Development of electric currents in a magnetic field configuration containing a magnetic null point, *A&A*, 525, p. A3+, doi 10.1051/0004-6361/201014758, 2011.
7. Cassak, P.A. and Otto, A., Scaling of the Reconnection Rate with Anti-Parallel Symmetric Shear Flow, *GRL*, accepted for publ. , 2011.
8. Nykyri, K., Otto, A., Adamson, E., Kronberg, E., Daly, P., Cluster Observations of High-Energy Particle Properties in Cusp Diamagnetic Cavity, *JSTP*, Submitted, June 2011.
9. Otto, A., and F. Hall, Current sheet thinning and entropy constraints, *Ann. Geophys.*, , submitted, 2011.
10. Otto, A. and K. Nykyri, Three-dimensional Kelvin-Helmholtz modes and magnetic reconnection, to be submitted.

Plasma Transport at the Magnetospheric Flank Boundary

Final Report for the NSF award 0614012 for the year 2007 - 2011

Principle Investigator: Antonius Otto

Co-Investigator: Jay R. Johnson

Institution: University of Alaska Fairbanks

A. Research Highlights:

1. Model of magnetic reconnection induced by three-dimensional Kelvin Helmholtz (KH) modes at the magnetospheric flank boundary.
2. Quantitative evaluation of mass transport from the magnetosheath onto closed geomagnetic field for northward IMF.
3. Comparison of mass transfer by cusp reconnection and Flank Kelvin Helmholtz modes.
4. Entropy constraint and plasma transport in the magnetotail - a new mechanism for current sheet thinning.
5. Test particle model for mass transport onto closed geomagnetic field for northward IMF .
6. Influence of density asymmetry and magnetic shear on (a) the linear and nonlinear growth of 3D Kelvin Helmholtz (KH) modes, and (b) three-dimensional KH mediated mass transport.
7. Examination of entropy and plasma transport in the magnetotail.
8. Entropy change and plasma transport by KH mediated reconnection - mixing and heating of plasma.
9. Entropy and plasma transport in the magnetotail - tail reconnection.
10. Wave coupling at the magnetospheric boundary and generation of kinetic Alfvén waves.

B. Summary of the most important results:

1. Model of magnetic reconnection induced by three-dimensional Kelvin Helmholtz (KH) modes at the magnetospheric flank boundary

One of the fundamental unresolved problems of magnetospheric physics is the origin of the plasma sheet material. It is well known that plasma sheet properties correlate with solar wind properties particularly during periods of northward IMF. Some years ago we have demonstrated that nonlinear Kelvin-Helmholtz (KH) waves drive magnetic reconnection even in two dimensions. Subsequent work has shown that this process can provide mass transport into the plasma sheet consistent with the rate required to form the cold dense plasma sheet during northward IMF conditions. Recent work has also shown observational evidence for reconnection driven by magnetic reconnection. Based on initial three-dimensional results we have examined this process more rigorously during the past year.

In the equatorial plane waves growth resembles largely two-dimensional results, however, with more substructure. Specifically we found that the KH waves lead to the formation of multiple strong field aligned current sheets where reconnection is driven when the current density becomes super critical. In these current sheets reconnection occurs in a random manner with large positive and negative values of the parallel electric field and almost random spatial distribution of the reconnection patches.

The most interesting result of these studies is that plasma transport is not determined by this 2D type of reconnection. Magnetic line tying requires reconnection to occur in a systematic manner or else the interchange motion of the KH waves would be reversed (which is not physical). The shear introduced by the interchange motion in combination with the line tying leads to very large currents with a systematic direction at the northern and southern boundaries of the interaction region. Thus the formation of these strong current sheets as illustrated in Figure 1 leads to systematic parallel and anti-parallel electric fields in these regions which have exactly the sign required to allow for the decoupling of the magnetic field in the manner required by the KH interchange motion.

Figure 1: Sketch of the KH motion at the magnetospheric flanks and integrated parallel electric field and current density.

2. Quantitative evaluation of mass transport from the magnetosheath onto closed geomagnetic field for northward IMF.

To evaluate the mass transport from the magnetosheath side onto closed magnetospheric flux is not a trivial issue because of the turbulent nature of the three-dimensional dynamics. However, we can integrate any physical quantity along magnetic force lines and map these integrals to the northern or southern boundaries of the simulation box. At the boundary the line tying condition enables us to distinguish between ‘geomagnetic’ and ‘magnetosheath’ region.

Figure 2 shows a result where we have integrated the flux tube mass and parallel electric field to the southern boundary of the simulation after 2 min and 2 1/2 min of the evolution. Here $x < 0$ correspond to the magnetospheric region. Comparison of the two plots with flux tube mass illustrates that mass has significantly increased on the magnetospheric side. It is worth noting that the closed (stretched) contours show open field in all three plots which demonstrates that most of the mass transport occurs onto closed magnetospheric field for this case.

Figure 2: Flux tube mass at 2 min (left) and 2.5 min (middle) and field-aligned potential (at 2.5 min) into the simulation.

Evaluating this mass transport quantitatively yields a mass diffusion coefficient of 2 to $4 \cdot 10^9 \text{ m}^2/\text{s}$ - well sufficient to explain the density observed in the cold dense plasma sheet. The maximum field-aligned potential drop (or three-dimensional reconnection rate) is about 20 to 30 keV. Although reconnection occurs in similar regions north and south of the interaction region it does not occur simultaneously on the same field lines. This asymmetry creates open flux and is stronger for stronger asymmetric situations thus creating more open flux in the low latitude boundary layer.

3. Comparison of mass transfer by cusp reconnection and Flank Kelvin Helmholtz modes.

Magnetic reconnection within 3D KH vortices is not entirely unlike cusp reconnection but it occurs in different locations and reconnects a shorter segment of a magnetic field line than in the case of cusp reconnection. In reality both processes are likely to operate but there has been no straightforward diagnostic to distinguish their relative contributions to the mass transport. Using the potential Φ_c associated with transferring mass from the magnetosheath to the magnetosphere the number density of magnetosheath particles n_{msh} on a reconnected flux tube, and the magnetosheath magnetic field B_{msh} we have established a relation between the potential and the change of the average plasma sheet number density n_{ps} as

$$\Phi \approx B_{msh} \frac{V_{ps}}{n_{msh} L_{ft}} \frac{dn_{ps}}{dt}$$

where V_{ps} is the plasma sheet volume and L_{ft} the length of the corresponding flux tube. For typical parameters ($B_{msh} = 30nT$, $n_{msh} = 10cm^{-3}$, $V_{ps} = 6 \cdot 10^{25}m^3$, and $dn_{ps}/dt = 0.5cm^{-1}s^{-1}$) the required total potentials are about 20 kV for cusp reconnection ($L_{ft} = 25R_E$) and about 80 kV ($L_{ft} = 6R_E$) for KH driven reconnection. Our simulations indicate a potential of 20kV for a single KH vortex implying that about 4 vortices have to operate at any given time. It is important to note that the associated potential is not the total reconnection potential but only the contribution that generates closed magnetic flux.

4. Entropy constraint and plasma transport in the magnetotail - a new mechanism for current sheet thinning

We have tested a hypothesis that entropy conservation in combination with dayside reconnection can cause the current sheet thinning that is observed during the growth phase of substorms. The reconnected dayside magnetic flux will cause sunward convection to replace this flux as evident from the ionospheric convection pattern. Adiabatic convection from the near-Earth tail region toward the dayside must conserve the entropy on magnetic field lines. This constraint prohibits a source of the magnetic flux from a region further out in the magnetotail. Thus the near-Earth tail region should be increasingly depleted of magnetic flux with entropy matching that of flux tubes that are eroded on the dayside. We have conducted three-dimensional meso-scale simulations of a section of the magnetotail extending from -6 to -46 R_E . Here the convection toward the dayside is prescribe as a boundary condition on the sunward boundary as Sketched in Figure 3.

Figure 3: Sketch of the simulation domain and the sunward flow (red lines) and snapshots of the cross tail current density in the noon midnight meridian at time $t = 0$ min and 50 min. Distances are in R_E .

The simulation results are in nice agreement with typical growth phase properties of current sheet thinning (temporal evolution, location, B_z , and current sheet width). Figure 3 presents a snapshot of the crosstail current density at the beginning of the simulation (start of the growth phase) and after about 50 minutes. At the end of the simulation

the current sheet half-width is close to 1000 km. This result provides for the first time a relatively simple and consistent explanation for the current sheet thinning during the growth phase. It also is an impressive demonstration of the importance of entropy as an organizing agent for magnetotail convection and dynamics.

5. Test particle simulations for mass transport onto closed geomagnetic field for northward IMF

Comparing the entropy p/n^γ for the magnetosheath, low latitude boundary layer, and the plasma sheet (including the cold dense plasma sheet) demonstrates that the plasma sheet entropy is one to two order of magnitude higher than in the magnetosheath. This is not easily explained, particularly in view that entropy should be well conserved in MHD. We have demonstrated that - although entropy can change in shocks - an increase by an order of magnitude is unrealistic in a plasma with a plasma β or order unity and can occur only in a large Mach number fast shock which is not present at the magnetospheric boundary. We have therefore started to conduct test particle simulations in the MHD fields of three-dimensional KH waves to examine kinetic effects on entropy changes. Noteworthy initial results demonstrate that particles can in fact be trapped in the KH vortices. While the trapping is not particularly efficient it can lead to some heating of the trapped populations. Note that some non-adiabaticity is introduced by the rather thin boundaries that develop in the nonlinear KH wave. The results also demonstrate an efficient transport of particles across the magnetospheric boundary that is in part due to the reconnection processes and in part cause by particle drifts. Specifically the results illustrate that particles cross the boundary frequently back and forth before they may actually enter sufficiently deep into the magnetosphere or being lost in the magnetosheath.

6. Influence of density asymmetry and magnetic shear on 3D KH modes

We have conducted a systematic study of the effects of density asymmetry and magnetic shear. Considering the analytic dispersion relation it is expected that lower density asymmetry has a destabilizing effect on the KH mode. Such a lower asymmetry would be the case in the presence of heavy ions on the magnetospheric side of the boundary. The simulation indeed show this behavior for large magnetic shear for the case of low (1:3 solid) and higher (1:7 dashed) density asymmetry. It is however also noted that for the cases of lower magnetic shear (50° or less) the growth of the instability occurs almost with the same rate for different density asymmetries. Therefore effects of density asymmetry are only important in cases which are marginal for the development of nonlinear vortices.

We have examined the associated net transport for different magnetic field and density asymmetries and have assumed the the local geomagnetic field in the equatorial plane points northward. For a fixed density asymmetry we have examined the amount of mass transported onto closed field lines and the associated magnetic flux transport and reconnection rates. The results demonstrate that smaller magnetic shear (i.e., a more symmetric situation) leads to the most symmetric reconnection processes with a large net mass transport into the magnetosphere. The initial drop of magnetospheric mass/flux occurs because all asymmetric cases have the generation of some open flux such that the net closed magnetospheric flux and mass first decreases. This decrease is significantly more pronounced in the presence of larger magnetic shear. For large magnetic shear of 70° almost all reconnection contributes to the generation of open magnetic flux. It is worth emphasizing the combination of density and magnetic asymmetry. If there were no magnetic shear (i.e., purely northward IMF) reconnection rates in the northern and southern hemisphere should be identical independent of the density asymmetry. However, in the presence of magnetic shear, larger density asymmetry leads to less mass transport.

7. Entropy and plasma transport in the magnetotail

A currently unresolved problem during periods of northward IMF is the transport of colder material from the flanks toward the noon midnight meridian. The time scale for this transport is of the order of 10 to 20 hours which translates into an average transport velocity of about 1.5 km/s. It is not clear whether there exists such slow orderly convection or whether this transport is generated by turbulent eddy diffusion. Such turbulence is observed and the

eddy diffusion coefficient is estimated to about $2.6 \cdot 10^{11} m^2 s^{-1}$ in good agreement with the observed transport time scale.

We have examined if entropy change associated with KH induced reconnection at the flank boundary can potentially be a cause for turbulent motion. Our three-dimensional simulation use a section of the the magnetotail where we applied different types of perturbations that can be associated with KH dynamics. Specifically we used velocity and pressure (entropy) perturbations. Several basic results from these still very young studies are illustrated in Figure 4 which shows a section of the equatorial plane with x pointing sunward and the right boundary about $7 R_E$ tailward of Earth. In the case of initial velocity perturbation these perturbations decay relatively fast and appear to remain more localized to the boundary of the system. In contrast the pressure perturbations decay somewhat slower and more importantly they show a strong tendency of developing azimuthal channels that connect the boundary with the noon-midnight meridian. Such 'fingers' have also been seen in some global simulations.

Localized entropy perturbations have been shown to lead to so-called plasma bubbles or blobs which travel earth- or tailward depending on a local increase or decrease of field line entropy. However, while our perturbation develop some radial motion their main propagation appears azimuthal. The reason for this may be that for the quasi-periodicity earth and tailward motion are somewhat balanced such that the main process to equilibriate flux tube entropy becomes the azimuthal propagation.

The entropy perturbations naturally also develop density perturbation. These perturbations appear to remain fairly stable and localized. They also propagate at a very small velocity. This is interesting because such plasma blobs with enhanced density are indeed observed deep into the plasma sheet.

Figure 4: Velocity in the equatorial plane 10 minutes after a quasi-periodic velocity (top) or a pressure/entropy perturbation (middle) were applied at the boundary at ($y = -15 R_E$). The bottom plot shows the initial pressure perturbation.

8. Entropy change and plasma transport by KH mediated reconnection - mixing and heating of plasma

A critical quantity of plasma entry for comparison with observations is plasma mixing and the nonadiabatic heating of the magnetosheath component during the transport from the magnetosheath side to the magnetospheric side of the boundary. During northward IMF the plasma sheet consists of a mixture of cold and hot populations and observations show a number of interesting properties. Compared to the hot plasma sheet the average density is higher, the average temperature is lower, and the entropy is significantly lower in the cold dense plasma sheet (CDPS) although the entropy is still about an order of magnitude higher than in the magnetosheath.

We have examined the properties of the mixed plasma in more detail. Since MHD simulation conserve the local entropy this study has been conducted integrating mass and entropy along flux tubes using the assumption that plasma from magnetospheric sections and magnetosheath sections of a newly closed field line mix along this field line. The results demonstrate that a significant boundary layer develops with a width of about $0.5 R_E$ within one

minute of the KH evolution. The average entropy in this boundary layer is significantly reduced and compares well with observations of the CDPS. However, while the average properties of the CDPS are nicely consistent, observations show that the cold population in the CDPS is non-adiabatically heated to about 5 times the magnetosheath temperature. Although this is still much colder than the hot plasma sheet it is difficult to reconcile this observation with the plasma entry mechanism for cusp and KH reconnection.

It has been argued that magnetic reconnection may be able to provide this heating such that we investigated this possibility with MHD and Hall MHD simulations. The results demonstrate that significant nonadiabatic heating can only be achieved in reconnection for very low plasma β . This can be directly shown for Petschek reconnection and we have derived this result in terms of an inequality in a more general way. Assuming total pressure balance between inflow and outflow regions of reconnection and a guide field we can determine an upper bound for the entropy increase:

$$\frac{S_o}{S_i} = \left(\frac{n_i}{n_o}\right)^\gamma \frac{p_o}{p_i} = \left(\frac{n_i}{n_o}\right)^\gamma \frac{p_{tot} - B_g^2/2\mu_0}{p_i} = \left(\frac{n_i}{n_o}\right)^\gamma \frac{p_i + B_i^2/2\mu_0 - B_g^2/2\mu_0}{p_i} \leq 1 + \frac{1}{\beta_i}$$

such that the entropy increase is always of order unity or smaller unless the $\beta \ll 1$. We have confirmed this result in MHD and Hall MHD simulations which are for Petschek-like conditions in excellent agreement with the analytic result. Since the captured magnetosheath population is expanding along the evolving flux tube (which is necessary to explain the partial density) we expect this component to cool significantly contrary to observations without an additional heating mechanism. This effect is expected to be stronger for cusp reconnection where a larger fraction of a newly closed flux tube consists of captures magnetosheath plasma.

Figure 5: Flux tube entropy in the equatorial plane immediately after reconnection onset and about 12 minutes later. The unit distance corresponds to $1 R_E$ and x points to ward the sun. The sunward boundary is at $6 R_E$.

9. Entropy and plasma transport in the magnetotail - current sheet thinning and tail reconnection

In a series of three-dimensional MHD simulations we had examined current sheet thinning based on magnetic flux depletion. Of particular interest with the current sheet thinning is the onset and evolution of reconnection in the thin tail current sheet. In series of simulations we examined this onset in a first cut as a function of current sheet width and sunward outflow conditions. In all cases reconnection onset was very similar and occurred at or close to the maximum of the current density between 10 and $15 R_E$. It is interesting that the subsequent evolution depended on the sunward flow conditions. As long as the sunward flow boundary condition was maintained reconnection remained in the near Earth plasma sheet close to where it originally formed. Only when the sunward outflow was choked off did the X line move away from the near Earth region. In this case reconnected flux accumulated in the near Earth region leading to more dipolarization and pushing the X line tailward. Another interesting aspect is the structure of the reconnection bulge or plasmoid. Although the initial configuration is smooth and continuous the reconnected flux region is highly structured with finger-like intrusions. Figure 5 show the flux tube entropy in the equatorial plane short after onset and about 12 minutes later. Rather small entropy indicates the dipolar magnetic

field region. Sharp boundaries in the flux tube entropy indicate different magnetic connection of the respective area in the equatorial plane.

We have compared model properties with typical and statistical observations and found excellent agreement between equatorial magnetic field magnitude and current sheet width and strength. In summary the proposed current sheet thinning mechanism is able to explain the typical growth phase properties. It also promises to be a highly interesting tool to study onset and evolution of magnetic reconnection in the magnetotail.

10. Wave coupling at the magnetospheric boundary and generation of kinetic Alfvén waves.

Wave-particle diffusive processes are believed to provide an effective mechanism for plasma entry at the Earth's magnetopause, particularly for periods of northward interplanetary magnetic field. Recent THEMIS spacecraft observations show direct evidence of a turbulent spectrum of kinetic Alfvén waves at the magnetopause, and estimates of transport based on the wave observations is consistent with entry rates required to populate the low-latitude boundary layer and cold-dense plasma sheet populations. However, a key assumption in estimating the cross-field transport is that the fluctuations have short-wavelengths in the azimuthal direction. Although the kinetic Alfvén waves are believed to result from mode conversion of compressional waves, the linear theory of mode conversion predicts that the kinetic Alfvén waves would have small-scale radial wavelengths (rather than short-scale azimuthal wavelength) significantly reducing estimates of transport.

To understand how short-scale azimuthal modes could develop, we performed three-dimensional simulations of the mode conversion process in collaboration with Yu Lin (Auburn University). We found that following a linear stage of growth of the mode converted kinetic Alfvén wave, that the short radial wavelength mode converted wave decays into counter propagating short azimuthal wavelength (gyroradius scale) modes of comparable amplitude. These modes are particularly effective for radial transport of plasma across the magnetopause and constitutes a breakthrough in understanding of wave processes at the magnetopause. The three-dimensional nature of these simulations is critical because these short-wavelength azimuthal modes did not develop in two-dimensional simulations as explained by our analytical analysis.

C. Publications and Presentations:

1. Presentations were given at various international meetings and workshops:

Invited conference presentations and seminars:

- Otto, A., Plasma Transport and Entropy Considerations at the Magnetospheric Flanks, tutorial review, GEM workshop, Zermatt, Utah, June 2007.
- Otto, A., Two invited tutorials (End-to-End View of Solar Terrestrial Physics; The Magnetosphere), PARS Summer School, Fairbanks, Alaska, August 2007.
- Otto, A., Plasma transport through KH modes, International Workshop on Magnetic Reconnection, St. Michaels, MD, September 2007.
- Otto, A., Kelvin Helmholtz Modes and Magnetic Reconnection, Univ. Massachusetts Lowell, September 2007.
- Otto, A., Kelvin Helmholtz Modes and Magnetic Reconnection: Plasma Transport Across Magnetic Boundaries, Physics Colloquium, Univ. Colorado, Boulder, November 2007.
- Otto, A., Cusp diamagnetic cavities and particle acceleration, Physics Colloquium, Univ. Colorado, Boulder, November 2007.
- Otto, A., Plasma Entry and Kelvin-Helmholtz Modes at the Flanks of the Magnetosphere, American Geophysical Union Fall Meeting, San Francisco, Ca, December 2007
- Otto, A., Particle acceleration in diamagnetic cavities, Max Planck Institute for Aeronomy, Lindau, Germany, January 2008.

- Otto, A., Cusp Diamagnetic Cavities and Particle Dynamics, American Geophysical Joint Assembly, Fort Lauderdale, FL, May 2008.
- Otto, A., Magnetosphere-Ionosphere Coupling (invited tutorial), PARS Summer School, Fairbanks, Alaska, July 2008.
- Otto, A., Two invited presentations: (1) Cusp Type Configurations and Particle Energization, (2) Three-Dimensional reconnection in Kelvin-Helmholtz Modes - Plasma Transport, International Cambridge workshop on magnetic reconnection, Bad Honnef, Germany, August 2008.
- Otto, A., Plasma transport and Mixing by Magnetic Reconnection in Three-Dimensional Kelvin-Helmholtz Modes, Huntsville workshop on 'The Physical Processes for Energy and Plasma Transport across Magnetic Boundaries', Huntsville, Alabama, Oct. 2008.
- Otto, A., Solar Wind Entry into the Earth's Plasma Sheet, International workshop on the nonlinear magnetosphere, Vina del Mar, Chile, Jan. 2009.
- Otto, A., Plasma Transport and Mixing by Magnetic Reconnection in Three-Dimensional Kelvin-Helmholtz Modes, Fairbanks workshop on Plasma Entry and Transport into the magnetosphere, Fairbanks, Alaska, March 2009.
- Otto, A., Reconnection trigger and current sheet formation, International Cambridge Workshop on Magnetic Reconnection, Fairbanks, August 2009
- Otto, A., Magnetic reconnection in asymmetric current sheets, International Cambridge Workshop on Magnetic Reconnection, Fairbanks, August 2009
- Otto, A., Solar wind plasma entry into the Earth's plasma sheet for northward IMF, IAGA, Sopron, Hungary, September 2009
- Otto, A., Thin Current Sheet Formation through KH Modes at the Magnetospheric Flank, Yellowstone Workshop on Thin Current Sheets, Yellowstone, September 2009
- Johnson, J., A. Otto, E. Kim, S. Wing, Y. Lin, How do heavy ions affect magnetopause transport?, International Space Physics Symposium, 2010, Tainan.
- Johnson, J., E. Kim, Y. Lin, E. Valeo, S. Wing, D Lee, Transport Resulting from Mode Conversion of Compressional Waves near the Alfvén and Ion-Ion Hybrid Resonances at the Magnetopause and within the Magnetosphere, Western Pacific Geophysics Meeting, 2010, Taipei.
- Otto, A., The geomagnetic cusps: Magnetic topology and physical processes, GEM 2010
- Otto, A., Simulation of Magnetospheric and Ionospheric Physics, University of Alaska Computational Science Symposium, Fairbanks, Alaska, Feb. 2010.
- Otto, A., On the Relation of Localized Parallel Electric Fields, Alfvén Waves, and the Dynamics of Discrete Auroral Arcs, International Workshop on Advances and Perspectives in Auroral Plasma Physics, Beaulieu, France, April 2010.
- Otto, A., The Geomagnetic Cusps: Magnetic Topology and Physical Processes, Geospace Environmental Modeling Workshop, Snowmass, Colorado, June 2010.
- Otto, A., Two invited presentations: (1) Mechanisms of Current Sheet Formation; (2) Entropy Changes Associated with Magnetic Reconnection, International Cambridge Workshop on Magnetic Reconnection, St. Andrews, Scotland, August, 2010.
- Johnson, J., How do Heavy Ions Affect Plasma Entry and Transport Processes, Theory of the Magnetosphere (Invited talk), Santa Fe, NM, October, 2010.
- Otto, A., Entropy and Magnetospheric Convection and Reconnection, International conference on 'Theory of the Magnetosphere', Santa Fe, New Mexico, 2010.
- Otto, A., Current Sheet Thinning and Entropy Constraints During the Substorm Growth Phase, IAGA, Melbourne, Australia, June/July, 2011.

- Otto, A., Entropy Changes and Plasma Entry into the Magnetosphere for Northward IMF Orientation, IAGA, Melbourne, Australia, June/July, 2011.
- Otto, A., Current sheet thinning and magnetic reconnection during the substorm growth and expansion phase, 2011 International Conference on Storms, Substorms, and Space Weather (ICSSSW2011), Hangzhou, China, Sept., 2011.
- Otto, A., Magnetic flux transfer events patchy reconnection dynamics, 2011 International Conference on Storms, Substorms, and Space Weather (ICSSSW2011), Hangzhou, China, Sept., 2011.
- J. R. Johnson, P. A. Delamere, A. Otto, Eun-Hwa Kim, and Simon Wing, The effect of heavy ions on magnetopause transport processes, EPS/ICPP Conference on Plasma Physics, Stockholm, July, 2012.

Other presentations:

- Otto, A., Mass Transport at the Magnetospheric Flanks Associated with Three-Dimensional Kelvin- Helmholtz Modes, AGU Fall meeting, 2007.
- Otto, A. and E. Adamson, Several presentations at the GEM workshop, 2007
- Nykyri, K. and Otto, A., Kelvin-Helmholtz instability at the magnetospheric flanks, 37th COSPAR Scientific Assembly, 37, pp. 2255, 2008.
- Otto, A. and E. Adamson, Several presentations at the GEM workshop, 2008.
- Johnson, J., A. Otto, E. Kim, S. Wing, and Y. Lin, Heavy ion effects on magnetopause transport processes, IAGA, 2009, Sopron, Hungary. Hybrid Simulation of Mode Conversion at the Magnetopause, Y. Lin, J. Johnson, and X. Wang, Fall AGU meeting, 2009, San Francisco.
- Johnson, J., A. Otto, E. Kim, S. Wing, and Y. Lin, Heavy ion effects on magnetopause transport, Fall AGU meeting, 2009, San Francisco.
- Johnson, J., Otto, A., E. Adamson, Ma, X., Several presentations at the GEM workshop, 2010.
- Ma, X., Otto, A., Nykyri, K., 2-D and 3-D Hall MHD Reconnection, AGU 2010
- Otto, A., Ma, X., Entropy Generation Associated with Magnetic Reconnection for Small Plasma Beta, AGU 2010
- Lazerson, S.A., Johnson, J., Delamere, P.A. , Otto, A., Lin, Y., Wing, S., Kim, E., How do heavy ions affect plasma entry and transport processes?, AGU 2010.
- Jay R. Johnson, S. Wing, and Y. Lin, Entropy constraints on the origin of plasma sheet populations and mechanisms of plasma entry, AGU Fall meeting, 2011.
- Jay R. Johnson, P. A. Delamere, A. Otto, Y. Lin, S. Wing, E-H Kim, The role of heavy ions in plasma entry and transport processes, and IUGG meeting, Melbourne, July 2011.
- Jay R. Johnson, P. Damiano, Yu Lin, X. Wang, Kinetic Simulations of Mode Conversion at the Magnetopause, IUGG meeting, Melbourne, July, 2011.

2. Organisation of meetings and workshops:

In addition the PI and Co-I were co-chairs for a corresponding GEM focus group and have organized various sessions at the GEM workshops and AGU Fall meetings from 2007-2011. The working group has included a breakout session each year on plasma entry and plasma sheet transport, which has helped to advance understanding in this area and brought attention to the importance of entropy as an organizing principle in the magnetosphere.

The PI was also Co-organiser for the International Workshop on Magnetic Reconnection, St. Michaels, MD, September 2007.

The PI and Co-Pi were also organizers for 2009 Fairbanks PET09 workshop (summary listed as item 4).

The PI was also organizer of the 2009 Cambridge Workshop on Magnetic Reconnection in Fairbanks, Alaska on August 7-12, 2010

The Co-I has organized a special session at the 2010 Fall AGU in San Francisco. PI and Co-I are also members of a successful proposal at the International Space Science Institute (ISSI) and had two meetings there in 2011.

3. Student involvement :

- S. Walker (undergrad. student assistant, 2008)
- R.J. Stevens (M.S., completion expected in 2012)
- E. Adamson (Ph.D, thesis spring 2012).
- X. Ma (Ph.D, started summer 2009, thesis defense expected 2012)

4. Publications

1. T.K.M. Nakamura, M. Fujimoto, and A.Otto, The structure of an MHD-scale Kelvin-Helmholtz vortex: Two-dimensional two-fluid simulations including finite electron inertial effects, *J. Geophys. Res.*, *113*, p.9204, doi 10.1029/2007JA012803, 2008.
2. Johnson, J. R., and S. Wing, Northward interplanetary magnetic field plasma sheet entropies, *J. Geophys. Res.*, *114*, A00D08, doi:10.1029/2008JA014017, 2009.
3. Wing, S., and J. R. Johnson, Substorm entropies, *J. Geophys. Res.*, *114*, A00D07, doi:10.1029/2008JA013989, 2009.
4. Lin, Y., J. R. Johnson, and X. Y. Wang, Hybrid simulation of mode conversion at the magnetopause, *J. Geophys. Res.*, *115*, A04208, doi:10.1029/2009JA014524, 2010.
5. Wing, S., and J. R. Johnson, Introduction to special section on Entropy Properties and Constraints Related to Space Plasma Transport, *J. Geophys. Res.*, *115*, A00D00, doi:10.1029/2009JA014911, 2010.
6. Wing, S., and J. R. Johnson, Introduction to special section on Entropy Properties and Constraints Related to Space Plasma Transport, *J. Geophys. Res.*, *115*, A00D00, doi:10.1029/2009JA014911, 2010.
7. Adamson, E., A. Otto, and K. Nykyri, 3D mesoscale MHD simulations of a cusp-like magnetic configuration: Method and first results, *Ann. Geophys.*, *29*, doi:10.5194/angeo-29-759-2011, 2011.
8. Cassak, P.A. and Otto, A., Scaling of the Reconnection Rate with Anti-Parallel Symmetric Shear Flow, *Physics of Plasmas*, doi: 10.1063/1.3609771, 2011.
9. Javadi, S., Buechner, J., Otto, A., and Santos, J.-C., About the relative importance of compressional heating and current dissipation for the formation of coronal X-ray Bright Points, *A&A*, *529*, A114, doi 10.1051/0004-6361/201015614, 2011.
10. Nykyri, K., A. Otto, E. Adamson, and A. Tjulin, On the Origin of Fluctuations in the Cusp Diamagnetic Cavity, *JGR*, *116*, A15, doi 10.1029/2010JA015888, 2011.
11. Nykyri, K., A. Otto, E. Adamson, E. Dougel, and J. Mumme, Cluster Observations of a Cusp Diamagnetic Cavity: Structure, Size and Dynamics, *JGR*, doi: 10.1029/2010JA015897, 2011.
12. Santos, J.-C., Buechner, J., and A. Otto, Development of electric currents in a magnetic field configuration containing a magnetic null point, *A&A*, *525*, p. A3+, doi 10.1051/0004-6361/201014758, 2011.
13. Adamson, E., A. Otto, and K. Nykyri, 3D mesoscale MHD simulations of a cusp-like magnetic configuration: Method and first results, *Ann. Geophys.*, *29*, doi:10.5194/angeo-30-1-2012, 2012
14. Nykyri, K., Otto, A., Adamson, E., Kronberg, E., Daly, P., Cluster Observations of High-Energy Particle Properties in Cusp Diamagnetic Cavity, *JSTP*, Submitted, June 2011.
15. Otto, A., and F. Hall, Current sheet thinning and entropy constraints, *Ann. Geophys.*, submitted, 2011.
16. Lin, Yu and J. R. Johnson, and X. Wang, Three-dimensional mode conversion associated with kinetic Alfvén waves, submitted to *Phys. Rev. Lett.*, 2012.