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Focus Group Final Reports

Table of Contents

Tail-Inner Magnetosphere Interactions (TIMI) Focus Group (2012-2016): Final Report 3

Vassilis Angelopolous, Pontus Brandt, John Lyon, and Frank Toffoletto

Magnetic Reconnection in the Magnetosphere Focus Group (2013-2017): Final Report 4

Paul Cassak, Andrei Runov, Homa Karimabadi, Brian Walsh, and Yi-Hsin Liu

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Tail-Inner Magnetosphere Interactions (TIMI) Focus Group 2012-2016: Final Report

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This report serves as a brief summary of the overall activities of the TIMI focus group, detailed reports on the activities over the 4 years for the focus group can be found in the GEMstone.

2012: The first year of the focus group was used to review the state of our understanding of the interactions between the tail and the inner magnetosphere, with presentations that looked at both observational and theoretical properties of the physics of bubbles/BBFs. There were two tutorials related to focus group concerns: Harry Warren who discussed supra-arcade down flows and comparative solar/geospace systems (http://www-ssc.igpp.ucla.edu/gem/tutorial/2012/WarrenGEM.pdf), and Dick Wolf on the physics of bubbles and BBFs (http://www-ssc.igpp.ucla.edu/gem/tutorial/2012/Wolf/Wolf_GemTutorial2012.pdf).

2013 workshop discussion and presentations concentrated on 4 topic areas: (1) The origin and evolution of BBFs and related phenomena; (2) The impact of BBFs and other phenomena on transport during different levels of activity (e.g., quiet times, SMCs, substorms, storm main phases); (3) The impact of BBFs et al on the inner magnetosphere; (4) Auroral streamers and other ionospheric signatures of BBFs. Andrei Runov gave a tutorial on magnetotail transients. (http://www-ssc.igpp.ucla.edu/gem/tutorial/2013/Runov-2013-Tutorial.pdf)

2014: The focus group had sessions on a variety of topics related to the specific questions related to dipolarization fronts. Specifically speakers we asked to address 2 questions: (1) How is the formation of the substorm current wedge related to BBFs/dipolarization fronts? (2) What is the physics of the oscillations in the field and plasma seen ahead of the front? In addition to the 3 sessions reported here there was also a joint session with the reconnection focus group, the report for which can be found in the reconnection focus group report. Drew Turner gave the tutorial on recent insights on the nature of the inner magnetosphere (http://www-ssc.igpp.ucla.edu/gem/tutorial/2014/Turner-2014-Probing-tempest.pptx).

2015: The TIMI focus group had 4 breakout sessions during the 2015 workshop. 2 sessions were joint with other focus groups. The first session was joint with the Magnetic Reconnection in the Magnetosphere focus group. The second session was also joint with the Storm-Time Inner Magnetosphere-Ionosphere Convection (SMIC) focus group. Toshi Nishmura gave a tutorial on fast flow channels (http://www-ssc.igpp.ucla.edu/gem/tutorial/2015/Nishimura-2015-Fast-flow-channels.pdf)

2016: A session was held that summarized some of the work that was done over the 4 years and discussed plans for the future.

While there has been significant progress in our understanding of the relationship between the tail and the inner magnetosphere, much work needs to be done. We are happy to report that a new follow-on focus group on "Magnetotail Dipolarization and Its Effects on the Inner Magnetosphere" started in 2017 headed by Christine Gabrielse, Matina Gkioulidou, Slava Merkin, Drew Turner, and David Malaspina. We look forward to having more exciting sessions at GEM on this important topic.

Focus Group summary
Magnetic Reconnection in the Magnetosphere

Paul Cassak (West Virginia University, 2013-2017), Andrei Runov (UCLA, 2013-2017), Homa Karimabadi (UCSD, 2013-2014), Brian Walsh (Boston University, 2015-2017), and Yi-Hsin Liu (Dartmouth College, 2015-2017)

This is a summary of activities and accomplishments of the "Magnetic Reconnection in the Magnetosphere" focus group that was in place from 2013-2017. Magnetic reconnection is the process for which a change in magnetic topology allows conversion of magnetic energy into other forms of energy. It perpetually happens at the dayside magnetopause, allowing solar wind mass, energy, and momentum to couple to Earth's magnetosphere, generating the Dungey cycle of magnetospheric convection. It also episodically occurs in Earth's magnetotail, releasing stored energy to the inner magnetosphere. It is observed by spacecraft including Cluster, THEMIS, and MMS and its impacts on the rest of the magnetosphere can be seen anywhere from the Van Allen Probes to SuperDARN. Local and global numerical simulations also play a crucial role for studying the reconnection process.

The group convened four sessions at every summer workshop, except for 2017 which had five. Given the relevance of reconnection to many research areas within the GEM community, it easily lends itself to inter-group discussion. Of the 21 sessions we convened at summer workshops, a majority (12) were held jointly with other focus groups.

Session attendance at each session ranged from 30 to 100, with typical attendance in the 40-60 range. We carried out a number of activities to preserve the GEM workshop-style approach, including scene-setting talks, debates between community members that disagreed on a topic, and community-led discussions on open questions and future directions of research.

There were five main topics proposed to guide the discussion for the focus group. While we did not restrict the discussion to these topics to allow for new discoveries and directions to guide our trajectory, significant progress was made on each of the proposed topics. As expected, the new observations from MMS have played a significant role in the discussions held in this focus group. Brief discussions of advances follow; the five topics proposed in the original focus group proposal are included verbatim followed by a discussion.

Topic 1 **-** *What is the physics of reconnection at the kinetic scale and how does it couple to the magnetosphere at macro-scales? Particular topics include the role of the extended electron diffusion region, pressure anisotropies, normal magnetic fields for magnetotail applications, asymmetries in density and magnetic field, and whether or how the microphysics of reconnection can be incorporated into fluid models in geospace general circulation models (GGCMs). Examples of deliverables for simulation and modeling work include answers to the following questions - What sets the scale of the extended electron diffusion region and what is its effect on reconnection? (This will be important both before and after the launch of MMS for locating and analyzing reconnection events.) How do asymmetries effect the kinetic signatures of reconnection? Under what conditions do pressure anisotropies arise? Observational deliverables include THEMIS/ARTEMIS and MMS results, which will be compared to numerical simulations.*

Brief Summary
It is an understatement to say that MMS has revolutionized our understanding of the kinetic scale of reconnection. At least 12 dayside events close to electron diffusion regions were measured in Phase 1a of the mission, with more in Phase 1b. It has observed electric

fields much stronger than predicted by simulations and now routinely measures crescent-shaped distribution functions that are a characteristic of asymmetric dayside reconnection. Our focus group served as a natural conduit for MMS research to the GEM community and guided discussion of kinetic scale physics of reconnection, especially for asymmetric reconnection at the dayside.

Kinetic physics in the magnetotail also was a common topic of discussion, especially related to matters of onset. The need for 3D kinetic simulations to address tail onset was a key result of the focus group discussion. Tracing particles in simulations to understand where they are accelerated was a common approach for this group.

We also point out the expansion of global magnetospheric modeling that incorporates kinetic effects, for the ions and even also for electrons. At the beginning of the focus group, the research thrust was to determine how to incorporate kinetic physics within the fluid model, but the community has progressed far beyond this with the direct incorporation of kinetic physics in global codes. This trend will surely continue and will likely become the norm.

Details

A number of properties of asymmetric reconnection and reconnection with external (sheath) flow were studied. Crescent distributions were discovered observationally by MMS (Dorelli); effort has been made to explain these theoretically (Egedal, Shay). The dissipation mechanism is different in symmetric and asymmetric reconnection (Hesse), and a guide field can alter the diffusion region structure (Hesse). A new signature of asymmetric reconnection at the dayside, called the Larmor electric field, was introduced (Malakit). A catalog of distribution functions near asymmetric reconnection sites was presented, with non-gyrotropic distributions being a potential observable to identify electron diffusion regions (Shuster). There are differences in diamagnetic effects in asymmetric reconnection when caused by temperature vs. density gradients (Liu). Asymmetric reconnection theory was tested at the dayside with Cluster (Wang). Reconnection with out of plane flow was studied (Ma).

Pressure anisotropies modify the Petschek slow shock picture (Drake, Liu). An electron pressure anisotropy is sufficient to lead to the 0.1 rate (Cassak). A model giving insight on why the reconnection rate tends to be close to 0.1 was presented, which relies on the coupling of micro-scales to the macro-scales (Liu). It was also shown that solar wind reconnection exhausts have Hall magnetic fields extending very far downstream, past where it would be expected for MHD to be valid (Mistry). It was shown that MHD overpredicts energy fluxes relative to PIC in magnetotail onset simulations (Birn).

There are a number of groups capturing at least some aspect of kinetic physics in global simulations, in addition to the global hybrid simulation technique used previously. New approaches include fluid simulations coupled with particle-in-cell simulations for both ions and electrons (Daldorff), ten moment fluid-models that retain full pressure tensors (Wang, Germaschewski), and Vlasov-hybrid simulations where ions are treated as distributions (Hoilijoki). One-way coupling of global MHD with PIC was also discussed (Berchem). Particle-in-cell simulations were incorporated into NASA's CCMC (Rastaetter, Kuznetsova, Liu).

Topic 2 - *How does reconnection proceed at the dayside and how does it contribute to solar wind-magnetospheric coupling? Topics include the role of asymmetries and shear flow in setting the efficiency of reconnection and the role of flux transfer events. Deliverables include quantitative predictions of dayside reconnection efficiency as a function of solar wind conditions that can be fed into solar wind -magnetospheric coupling functions as in the Borovsky coupling function and expected properties of flux transfer events in kinetic simulations and observations.*

Brief Summary

We made great progress on these questions. There was excellent discussion and progress made on what controls the efficiency of dayside reconnection and solar wind-magnetospheric coupling. There is some clarity now that local effects from the magnetospheric side of the magnetopause can change the local rate, but it is still not clear this changes the global rate. Global changes to the magnetosphere can change the global rate, which underscores our previous understanding that it is not the solar wind boundary condition that controls the coupling, but both the outer (solar wind) and inner (magnetosphere) boundaries that play a role. There is ongoing research on the question of whether local effects can change the global rate for fixed boundary conditions.

The rate of reconnection with asymmetries and in-plane flow shear was derived analytically and confirmed with local numerical simulations. The results suggested that under typical conditions, the magnetosheath flow does not greatly alter the local efficiency of reconnection. This prediction contrasts a prevailing model and is an interesting area for future work, including testing in global simulations.

Details

A key topic discussed by the focus group was what controls the dayside reconnection rate. Evidence shows plasmaspheric plumes slowing reconnection locally (Borovsky, Walsh), but this need not change the global reconnection rate (Lopez). Mass loading from the ionosphere can change the global rate (Zhang). The result of the findings is that the solar wind is not the only controller of the dayside reconnection rate. It remains unknown if local effects can change the global rate. An analytical prediction was presented (Dorelli).

A quantitative prediction of the reconnection rate with asymmetries and shear flow was presented, and it was argued that magnetosheath flow would not greatly alter solar wind-magnetospheric coupling (Cassak). The prediction compares favorably with Cluster observations (Wilder).

FTEs were studied using observations and simulations. A statistical study of FTE orientation was performed (Lynnuk). FTEs can be formed by two simultaneous X-lines (Maynard). MMS was used to study FTE generation, showing that the layer between two FTEs can be unstable to tearing (Hwang). It was shown that there is a hemisphere effect for FTEs (Trattner) and their motion depends on interplanetary conditions (Collado-Vega).

Topic 3 **-** *How does three-dimensional reconnection proceed, especially at the dayside? Numerical deliverables include answering these questions - What is the location of reconnection on the dayside and its efficiency as a function of solar wind conditions? What differences are there between 2D and fully 3D reconnection? Observational deliverables include signatures of the dissipation region in fully 3D settings and their meso- and macro-scale ramifications.*

Brief Summary

Significant progress was achieved on these deliverables. A number of approaches for locating reconnection sites at the dayside magnetopause in global magnetospheric simulations were presented and have now been implemented at NASA's CCMC where all users can request this information as output. It was shown that the local asymmetric reconnection prediction is reasonably good in the scaling sense at describing the local reconnection rate for oblique interplanetary magnetic fields and with and without a dipole tilt. On the observational side, it was shown that the Maximum Magnetic Shear model is quite good at predicting the reconnection site except for a parameter regime when the empirical models on which it is based break down.

A number of qualitative differences between 2D and 3D reconnection were discussed, both observationally and numerically. A lower bound on the extent of the dissipation region in the out-of-plane direction was given, and the nature of 3D reconnection between two nulls was observed with Cluster.

Details

An algorithm to find reconnection lines in global magnetospheric simulations was proposed, which has been incorporated into the Runs-On-Demand feature at NASA's CCMC (Komar, Glocer). These tools were used to study reconnection efficiency for different solar wind clock angles (Komar). It was shown that the Hall effect has important consequences for solar wind-magnetospheric coupling in simulations of Ganymede's magnetosphere (Dorelli).

Measurements from Cluster were employed to find a secondary island between two magnetic nulls (Guo). A Geotail/MMS conjunction suggests the magnetopause reconnection line shifts toward the winter hemisphere for southward IMF (Kitamura).

It was shown that the ends of localized 3D reconnection act like an energy sink, preventing reconnection X-lines from being shorter than about 10 ion inertial lengths (Shay). The spreading of localized dayside reconnection was studied by comparing THEMIS data with SuperDARN data of ionospheric signatures (Zou). The X-line bisects the total magnetic shear angle (Liu).

Topic 4 - *How does reconnection onset and what is the physics of transient reconnection events such as bursty bulk flows, dipolarization fronts, entropy bubbles, and flux transfer events? Deliverables include how their properties depend on magnetospheric conditions, their role in energy and mass transport, how they expand and spread as a function of time, and comparisons with observational data from the THEMIS/ARTEMIS mission.*

Brief Summary

This was a key topic of discussion for a number of years of the focus group, and both observations and theory/simulations have been invaluable for this topic. Numerical studies of tail reconnection revealed the importance of including three-dimensions and kinetic physics in the models. A number of modes related to onset were discussed, including reconnection, interchange, flapping, and kinetic instabilities. A class of magnetotail equilibria with a hump in B_z was studied for their role in onset.

Observationally, the properties of dipolarization fronts, and their tailward directed partners, were categorized using THEMIS and ARTEMIS observations. In addition to their size and occurrence rate, their temperatures and associated anisotropies were investigated. Simulations were used to study particle acceleration and heating in fronts.

Details

There are multiple events that can disrupt the magnetotail, including flapping, reconnection, interchange, and lower hybrid drift instabilities (Sitnov, Pritchett, Birn, Lui). The kink instability is also important (Liu). An analytical study of tail stability including spatial dependence in B_z was presented (Merkin, Sitnov). Temperature variations in PIC simulations are similar to those in THEMIS observations (Sitnov).

The nature of the B_z dip in dipolarization fronts was discussed observationally and theoretically (Runov, Drake). In dipolarizing flux bundles, electrons and ions have different temperatures (Runov), ion distributions often display anisotropies (Runov, Birn, Pritchett), and they expand in the cross-tail direction (Liu). Global simulations were used to study their cross-tail extent (Wiltberger). The structure of reconnection flow bursts and how particles are heated there was discussed (Drake). Pressure anisotropies in reconnection exhausts at lunar distances was discussed using ARTEMIS and particle-in-cell simulations (Hietala). Flow channels at the dayside can trigger magnetotail reconnection (Nishimura).

Topic 5 - *How are energetic particles produced during reconnection? This includes mechanisms based on reconnection electric fields and secondary islands. Deliverables include the relative importance of various particle acceleration mechanisms and the observational signatures that result, and observations of these events from THEMIS/ ARTEMIS and MMS.*

Brief Summary

Significant progress on our understanding of the acceleration of energetic particles and their subsequent thermalization was made. Observations of heating at the dayside implied that the heating is proportional to the amount of available magnetic energy per particle. PIC simulations revealed a similar result, even in 2D. This was explained by investigating particle dynamics near the reconnection site. Particle acceleration in dipolarization fronts was also addressed. MMS is being used to study energetic particles.

Details

The nature and cause of electron and ion heating due to reconnection was discussed both observationally and theoretically (Birn, Phan, Shay, Egedal, Haggerty, Wang). It was shown that heavy ions from plasmaspheric plumes get picked up and accelerated at dayside reconnection sites (Lee). The acceleration of oxygen in tail reconnection was discussed (Liu, Liang). Secondary islands in the tail were discussed (Bhattacharjee, Facsko). The temperature increase in dipolarizing flux bundles was studied observationally and numerically (Runov, Sitnov). Ion acceleration in dipolarization fronts was studied in global hybrid simulations (Lin). MMS observations of dipolarization fronts (Sibeck) and energetic particles (Jaynes) were presented. A guide field can change the mechanism for heating in reconnection (Shay). There are different acceleration mechanisms tailward and Earthward of magnetotail reconnection sites (Birn).

Other Accomplishments

In addition to these core goals, many accomplishments have occurred during the time the focus group existed. The interaction of the Kelvin-Helmholtz instability and reconnection at the dayside and its implications for mass transport was discussed (Zhang, Nakamura, Ma, Kavosi, Nykyri, Ukhorskiy); MMS observed flank reconnection in KH waves (Hwang). MMS revealed reconnection in the magnetosheath (Mistry, Wilder). Forces in reconnection were studied with MMS (Zhao). The signatures of reconnection at lunar orbit as found by ARTEMIS and in simulations (Kiehas, Hietala, Ge). Tripolar out-of-plane magnetic field signatures were discovered (Eriksson). The relation of dayside and tail reconnection and its ionospheric signatures were discussed (Nishimura, Zou, Foster, Maimaiti). The effect of auroral potential drops and the ionosphere can impact tail reconnection (Lotko). Waves associated with dayside reconnection as measured by MMS were discussed (Zhou). How to identify the proper reference frame to study reconnection from data (Denton) and an approach to infer the deep tail reconnection site (Zhang) were discussed. Inverse ion dispersions were discovered using MMS (Lee). Reconnection in the turbulent magnetosheath was studied (Shay). A high-speed jet potentially triggering dayside reconnection was observed with THEMIS (Hietala). Waves launched by reconnection were studied with hybrid simulations (Lin).

Overall Summary

In the assessment of the final focus group leaders, this focus group was immensely successful scientifically. The focus group enabled research on the important topics discussed above and fostered communication between many of other focus groups. We were pleased with the levels of attendance at the sessions. We feel like we made a number of successful decisions about preserving the GEM workshop style and achieved some positive results.

We also did experience some struggles with avoiding the AGU-style talks and recommend that future focus groups on reconnection employ old and new ideas to maintain the workshop style that is a hallmark of GEM.

The final focus group leaders believe that despite all that has been accomplished, there are a number of exciting developments to arise in the coming years (such as the MMS nightside campaign with conjunctions with other satellites such as THEMIS, as well as the hope of an extended MMS campaign). Such future opportunities suggest that a new, but distinct focus group on appropriately chosen aspects of magnetic reconnection would be of use to the GEM community.

Resulting Publications

1. Birn, J., M. Chandler, T. Moore, and A. Runov, "Ion velocity distributions in dipolarization events: Beams in the vicinity of the plasma sheet boundary," *J. Geophys. Res. Space Physics,* **122**, 8026–8036 (2017)
2. Birn, J. and M. Hesse, "Forced reconnection in the near magnetotail: Onset and energy conversion in PIC and MHD simulations," *J. Geophys. Res. Space Physics*, **119**, 290–309 (2014)
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4. Birn, J., Yi-Hsin Liu, W. Daughton, M. Hesse and K. Schindler, “Reconnection and interchange instability in the near magnetotail,” *Earth, Planets and Space*, **67**, 110 (2015)
5. Birn, J., A. Runov, and M. Hesse, “Energetic electrons in dipolarization events: Spatial properties and anisotropy,” *J. Geophys. Res. Space Physics,* **119**, 3604–3616 (2014)
6. Birn, J., A. Runov, and M. Hesse, “Energetic ions in dipolarization events,” *J. Geophys. Res. Space Physics,* **120**, 7698–7717 (2015)
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8. Borovsky, J. E. and J. Birn, “The solar wind electric field does not control the dayside reconnection rate,” *J. Geophys. Res. Space Physics*, **119**, 751–760 (2014)
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