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Focus Group Final Reports

Table of Contents

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The Magnetosheath Focus Group (2010-2014): Final Report

Steven M. Petrinec and Katariina Nykyri

History and Focus Group Objective:

A five-year Magnetosheath Focus Group was proposed during the December 2009 mini-GEM workshop held at the Westin hotel in San Francisco. This GEM Focus Group was selected to further advance a research topic that had been explored by two expiring Focus Groups (primarily by the Foreshock, Bow Shock, Magnetosheath Focus Group, chaired by N.Omidi, D.G.Sibeck, and K.J.Trattner; and secondarily by the Reconnection Processes at the Dayside Magnetopause Focus Group, chaired by J.Berchem, N.Omidi, and D.G.Sibeck) in the Dayside Research Area of GEM (now known as the Solar Wind – Magnetosphere Interaction (SWMI) Research Area).

The primary objective of the Magnetosheath Focus Group was to bring together researchers from the observation, modeling, and theory communities to coordinate research on long-standing questions related to the magnetosheath region and its geophysical boundaries. More specifically, the Magnetosheath Focus Group was to address three general research subjects, each comprised of (though not exclusive to) several specific outstanding science questions:

1. **Magnetosheath structure and properties:** To produce more comprehensive models of large scale magnetosheath flow and field patterns, and geometry of the magnetosheath region

    - What is the large scale magnetosheath plasma and magnetic field structure during various IMF orientations and solar wind conditions?
    - Is the IMF Parker-Spiral (PS) versus Ortho-Parker Spiral (OPS) orientation the determining factor generating dawn-dusk asymmetries on magnetosheath and plasma sheet plasma properties by affecting the location of the quasi-parallel bow-shock and resulting wave-particle interactions? Is the dawn (dusk) flank statistically hotter during PS (OPS) orientation?
    - How do ion and electron distribution functions evolve downstream from the quasi-parallel bow shock?

2. **Physical processes in the magnetosheath:** To improve understanding of magnetosheath plasma instabilities and wave particle interactions: Spatial distribution and characteristics

    - How typical is the small-scale reconnection in the magnetosheath and how effectively can this heat magnetosheath plasma?
    - What is the physical mechanism keeping the ion to electron temperature ratio close to 6 in the magnetosheath? Are there any conditions which alter this ratio?
    - Is the turbulent spectra in the magnetosheath dominated by the mirror-mode waves and does the recently observed -8/3 spectra continue to electron scales?

3. **Impact on magnetospheric processes:** To develop a better understanding of the effects on magnetospheric dynamics due to processes occurring in the magnetosheath and due to characteristic magnetosheath properties

   - What is the impact of magnetosheath turbulence levels (*dB* and *dV*) on magnetospheric transport processes? Does the cold, dense plasma sheet form faster when the seed turbulence level in the magnetosheath is large? Is the reconnection rate enhanced for increased magnetosheath turbulence levels?

   - How are the reconnection and Kelvin-Helmholtz instability (location and growth rates) affected by magnetosheath plasma beta and Alfvén Mach number?

   - How does the ionospheric convection change as a function of magnetosheath plasma properties?

It is also noted that during the tenure of this Focus Group, additional Focus Groups with synergistic research subjects to this Focus Group were established.

Below is a summary of some of the presentations of the Magnetosheath Focus Group and their relevance to the research subjects/questions. In the section below we give some background with relevant references on the physical problem and describe the progress done during GEM magnetosheath FG activities presented at the oral and poster sessions.

1. Magnetosheath Structure and Properties

The first-listed research subject of this Focus Group was to improve on our understanding of the structure of the magnetosheath. This encompasses understanding the locations and shapes of the boundaries, and the variation of plasma parameters and fields between these boundaries. During the initial sessions of this Focus Group, Mike Schulz described a new coordinate system for constructing analytical streamline (Euler-potential) models of the magnetosheath surrounding a magnetopause of rather general prescribed shape. He showed how to obtain the corresponding cylindrical coordinates of any point in the magnetosheath by solving a simple algebraic equation. By specifying distance from the magnetopause along an outward normal of calculable direction, the new system also shows promise for organizing *in situ* magnetosheath data obtained from spacecraft.

The 3D shape of the geophysical boundaries determined from spacecraft observations was also explored by Jan Merka, Yongli Wang, and David Sibeck. The determination of the boundary shapes involved a ‘Support Vector Regression Machine’ (SVRM) methodology. The basic strategy of the SVRM is to map multidimensional data into a high-dimensional feature space via nonlinear mapping through a selected kernel function, and to perform a linear regression in this space. In this manner, optimal shapes based upon the observations are determined without the need for prescribing a predefined analytical shape or function. This work evolved over the course of the GEM Focus Group, and a description of the magnetopause based on the SVRM was recently published (*Wang et al.*, 2013).

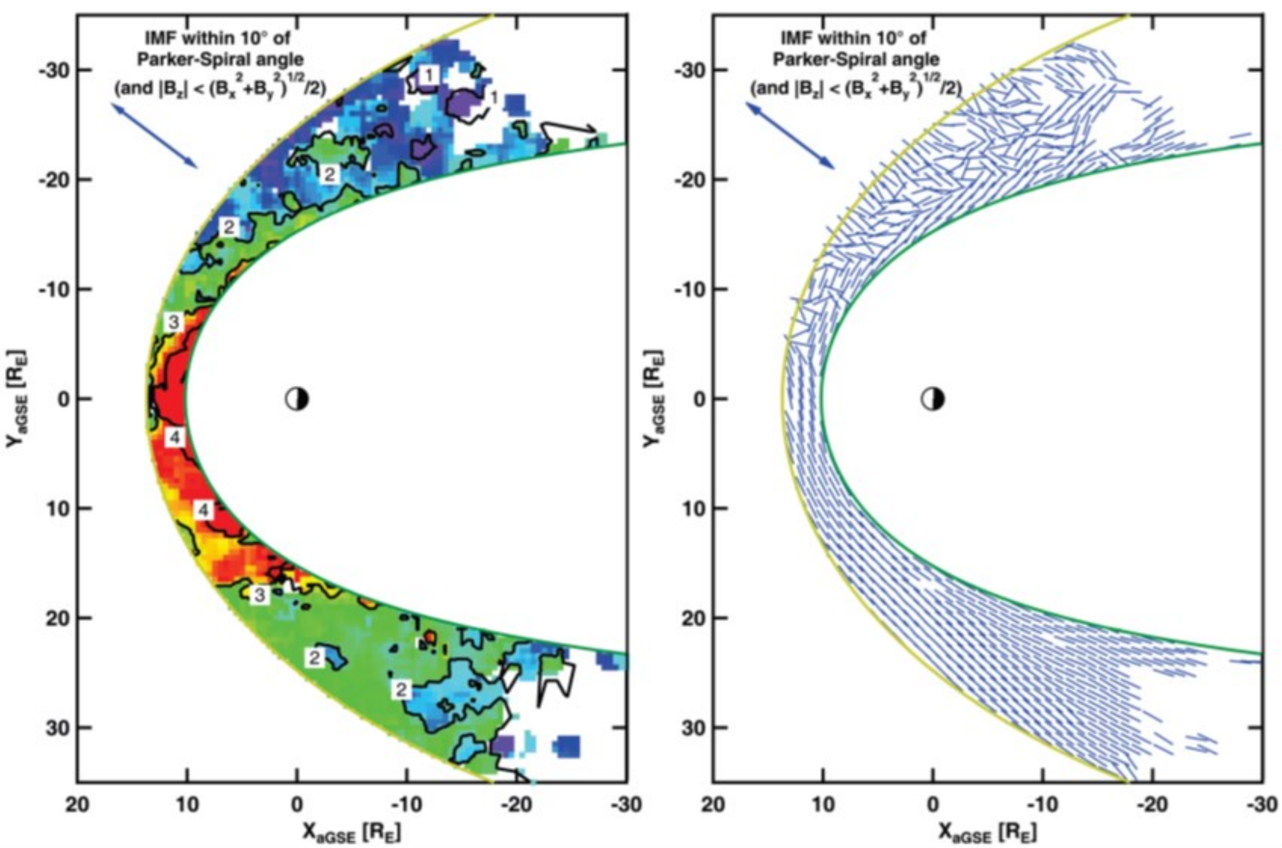
Global MHD simulations of the size and shape of the distant magnetotail (at lunar distances) were investigated and reported upon by David Sibeck. The anisotropic pressure of the IMF magnetic field lines flattens the magnetotail cross section in the direction perpendicular to the IMF in the numerical model, but elongates the magnetotail dimension in the direction which is in the same plane that also contains the

IMF. For a typical ecliptic IMF orientation, the northern and southern magnetosheath thickness is greater than the dawn and dusk magnetosheath dimension.

Empirical studies of the location and shape of the magnetosheath boundaries have to date been limited to *in situ* observations by orbiting spacecraft. There is, however, significant interest in being able to observe the magnetosheath region remotely and in a global context. Steve Petrinec showed observations of the magnetosheath in neutral atoms as measured by the IBEX mission. These observed neutral atoms are a result of charge exchange of the solar wind plasma with the geocorona; variations of the ion density across the bow shock and magnetopause demark the boundaries of the magnetosheath (*Fuselier et al*., 2010; *Petrinec et al*., 2011). The IBEX mission was designed to observe neutral atoms from the outer reaches of the solar system; so the angular resolution is insufficient to provide high spatial resolution images of the magnetosheath in a reasonable time period (composite images can be created over several hours; but cannot discern dynamic processes).

Another method by which it is thought that the magnetosheath can be imaged is via soft X-ray emissions generated through charge-exchange. Brian Walsh presented modeling and instrument development concepts for the global imaging of the magnetosheath region in soft X-ray emissions.

<u>Magnetic field</u>: The general macroscopic behavior of magnetosheath plasma parameters and fields received considerable attention during this Focus Group. Steve Petrinec used several years of Geotail magnetic field observations to create synoptic maps of the normalized field intensity and vector direction, for various IMF configurations (*Petrinec*, 2013). Similar maps of field intensity using several years of THEMIS observations were created by An-



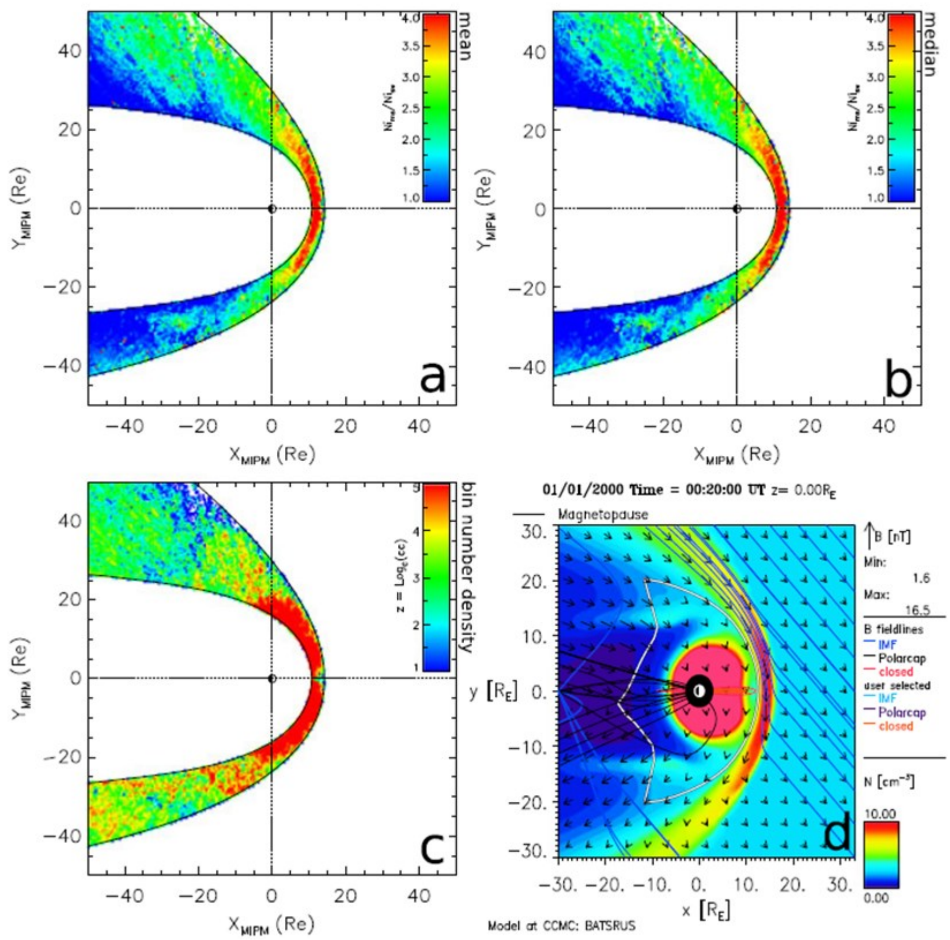
Statistical maps of the magnetosheath magnetic field intensity (left) and orientation as observed by Geotail and normalized by the solar wind (from *Petrinec*, 2013).

drew Dimmock and Katariina Nykyri (*Dimmock and Nykyri*, 2013).

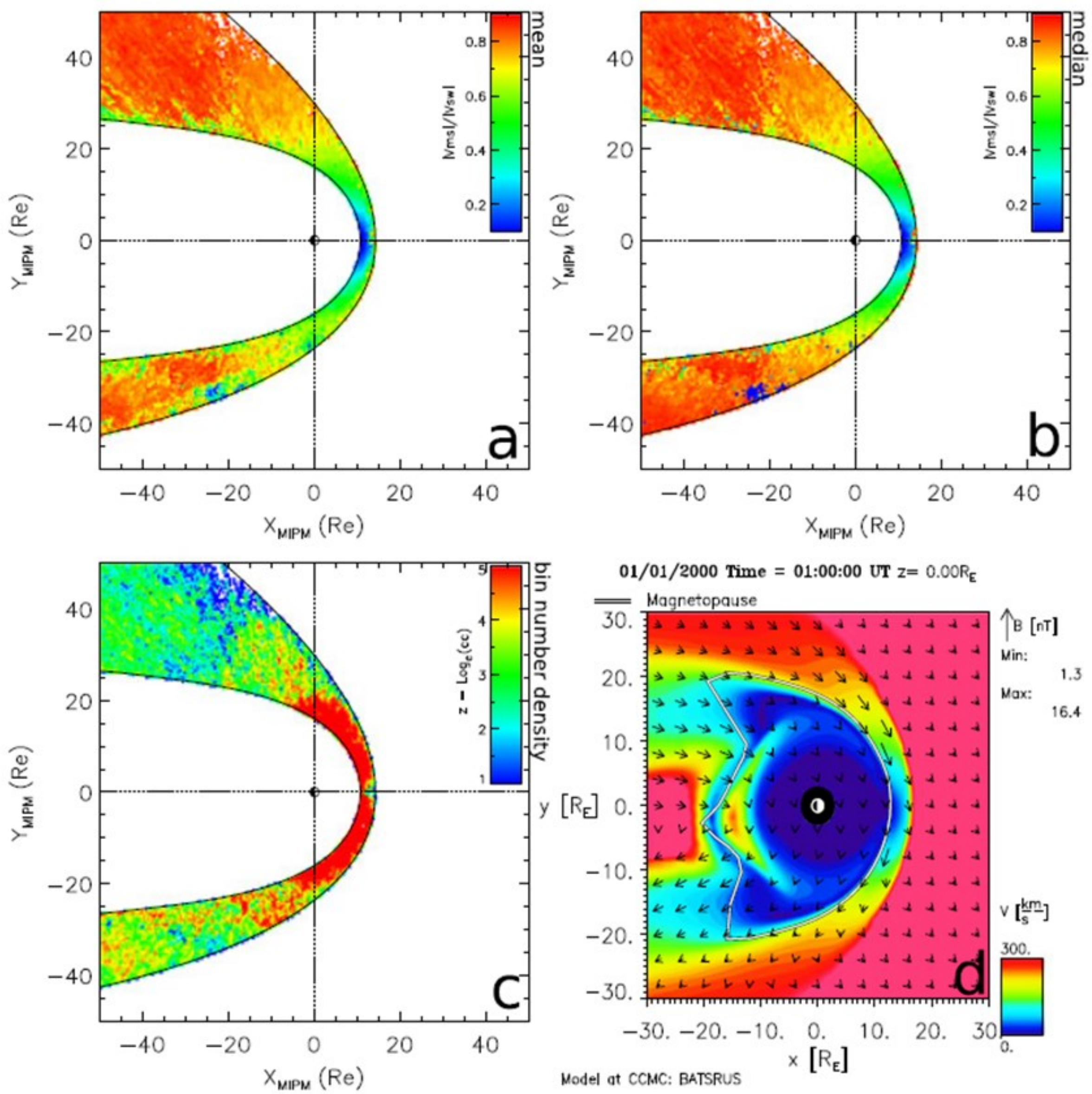
In addition to the intensity and direction of the ambient magnetic field, the magnetosheath is host to a large number of plasma instabilities, which are manifest by variations in the magnetosheath field and other parameters. Katariina Nykyri and Andrew Dimmock used several years of THEMIS observations rotated into the Magnetosheath InterPlanetary Medium (MIPM) reference frame to map these variations within the magnetosheath (*Dimmock and Nykyri*, 2013).

Ion density and speed: Multiple years of THEMIS observations were also used to create statistical maps of the magnetosheath plasma moments in the MIPM coordinate system (*Dimmock and Nykyri*, 2013). These maps were compared favorably with the BATS-R-US numerical model at the CCMC.

Ion/electron temperature ratios: Chih-Ping Wang presented statistical magnetosheath ion and electron temperature profiles from three years of THEMIS observations. Ion and electron temperatures as well as ion-to-electron temperature ratios were found to be directly correlated with solar wind speed. While ion and electron temperatures decreases with downtail distance,



Statistical maps of normalized ion density for all experiment data using the (a) mean and (b) median values within 0.5 x 0.5 R_E bins. (c) The count per bin (cc) and (d) the MHD simulated result for magnetosheath ion number density during a Parker spiral IMF orientation (from *Dimmock and Nykyri* [2013]).

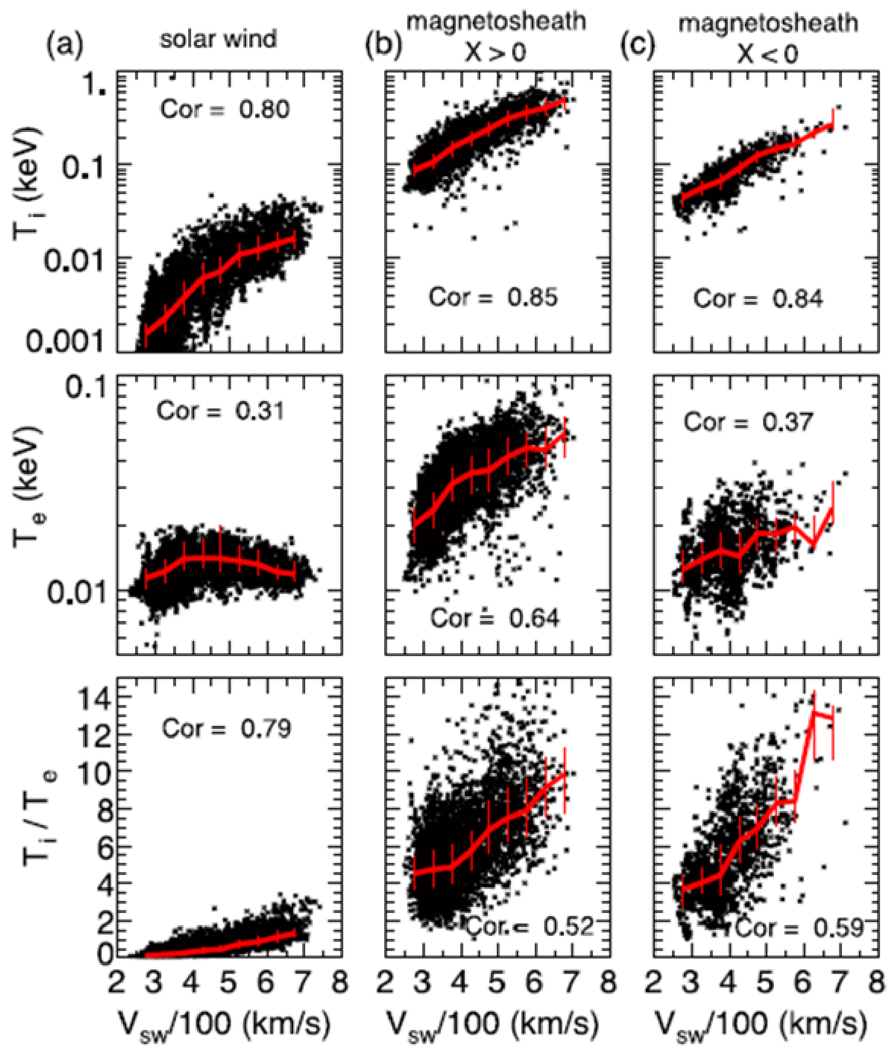


Same as the previous figure, but for the magnetosheath speed normalized by the solar wind speed (from *Dimmock and Nykyri* [2013]).

the temperature ratio remains almost constant (*Wang et al.*, 2012).

<u>Specific entropy</u>: In the Earth's magnetosphere, the specific entropy (non-adiabatic heating), $S=T/n^{2/3}$, increases by about two orders of magnitude from

2.5-70 eV-cm^2 in the magnetosheath (for ions) to 700-16000 eV-cm^2 in the magnetosphere *(Borovsky and Cayton, 2011).* The origin of this non-adiabatic heating is not well understood. Recently, (*Ma and Otto*, 2014) showed that specific entropy increase in magnetic reconnection at the Earth's magnetopause is possible only if the magnetosheath plasma beta is low (□ << 1). A recent statistical study of magnetosheath specific entropy using seven years of THEMIS spacecraft measurements in the MIPM reference frame shows that in the

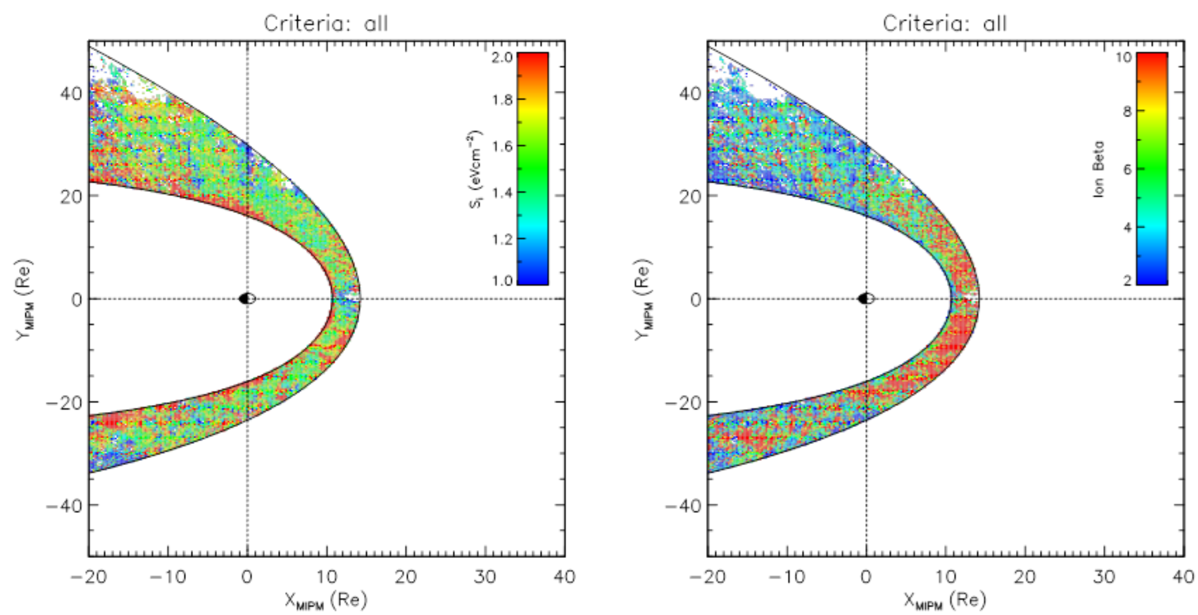


T_i, T_e, and T_i/T_e versus the solar wind speed in the region of the (a) solar wind, (b) dayside magnetosheath, and (c) nightside magnetosheath (from *Wang et al.*, 2012).

magnetosheath, the specific entropy is enhanced downstream of the quasi-parallel bow shock and close to the magnetopause *(Nykyri and Dimmock, 2014).* While these enhanced entropy regions close to the magnetopause correlate with regions of reduced plasma beta when compared to typical beta values in the central magnetosheath, the average beta in these 'low' beta regions is still above unity (□ > 1). This suggests that also other physical mechanisms such as wave particle interactions (see Section 3) may be at work, contributing to non-adiabatic heating at the magnetopause.

Wing showed during summer GEM 2014 that plasma sheet does not have a dawn-dusk entropy asymmetry because the both the density and temperature are more enhanced at the dawnside plasma sheet.

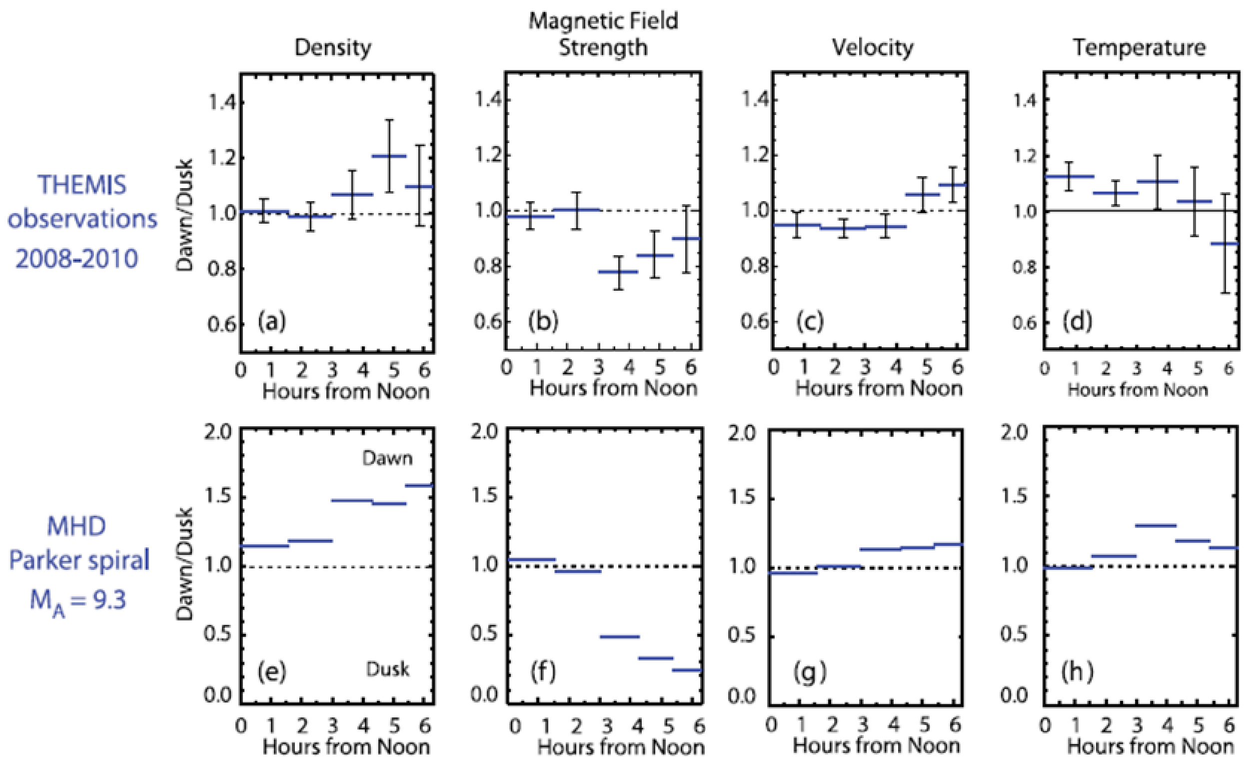
Dawn/dusk asymmetries: In addition to improving our understanding of the variation of magnetosheath field intensity and plasma parameters as a function of distance from the boundaries and distance downstream, it is also important to understand dawn-dusk asymmetries of the magnetosheath. This is because processes at the magnetopause such as magnetic reconnection and Kelvin-Helmholtz instabilities influence the state as well as the dynamics of the magnetosphere, and these processes are controlled in large part by local magnetosheath characteristics.



Statistical map of magnetosheath mean specific entropy for ions (left panel) and mean ion beta (right panel) using 7 years of THEMIS spacecraft measurements in MIPM frame. Each bin is 0.25 × 0.25 *RE* and has about 1000 (100) three minute THEMIS data intervals/bin close to the dayside (flank) magnetopause In MIPM frame the magnetosheath downstream of quasi-parallel (perpendicular) shock is on dawn (dusk)-side (*Nykyri and Dimmock 2014)*.

The above-cited studies which resulted in the creation of maps of magnetosheath properties inherently include the differences along the magnetosheath flanks, in addition to variation with downstream distance and with distance from the boundaries. A detailed analysis presented by Brian Walsh (and later published (*Walsh et al*., 2012)) demonstrated in a concise manner the dawn/dusk ratios of various magnetosheath properties as a function of local time away from noon. This analysis was based upon multiple years of THEMIS observations, and found to be qualitatively consistent with the same analysis performed using a global MHD model.

Another interesting asymmetry which also ties together with the physical mechanisms in the magnetosheath is the observed asymmetry in the magnetosheath specific entropy. The magnetosheath downstream of quasi-parallel shock has larger specific entropy than downstream of quasi-perpendicular shock, which may be indicative of additional heating mechanisms downstream of quasi-parallel shock. One such mechanism are possibly enhanced wave particle interactions as magnetosheath downstream of quasi-parallel shock has increased level of magnetic field fluctuations when compared to magnetosheath



Dawn-dusk asymmetries from the magnetosheath just outside the magnetopause with distance from local noon. THEMIS observations (top) and values from MHD (bottom) are shown for a Parker spiral IMF configuration. The compared parameters are density, magnetic field strength, velocity, and temperature (from *Walsh et al*., 2012).

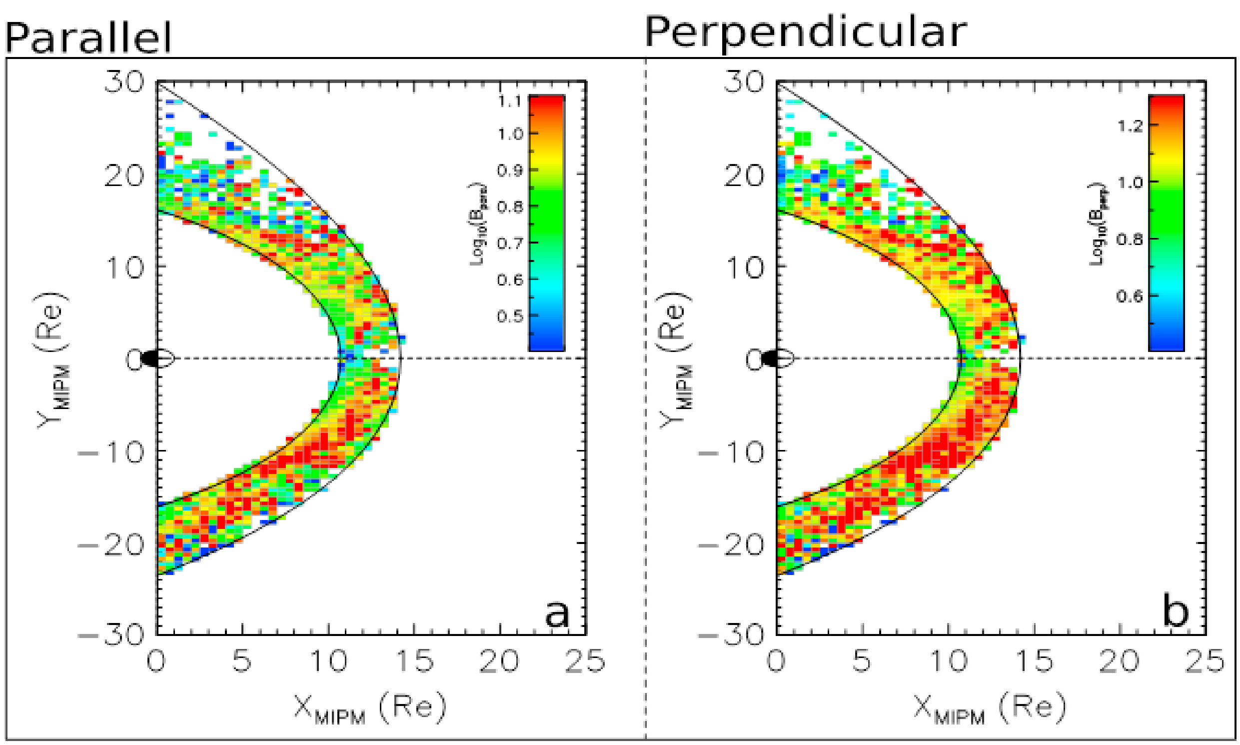
downstream of quasi-perpendicular shock (Dimmock et al, 2014).

The other possible asymmetric magnetosheath heating mechanism is the reconnection in the thin current sheets which favors magnetosheath downstream of quasi-parallel shock (see next section).

2. Physical Processes in the Magnetosheath

The magnetosheath region is host to a wide variety of physical processes over a large span of spatial and temporal scales. During the tenure of the GEM Magnetosheath Focus Group, many of the processes under study were those that originated at or upstream of the bow shock and then passed through the bow shock, becoming manifest within the magnetosheath.

Foreshock cavities and bubbles, and hot flow anomalies: THEMIS spacecraft

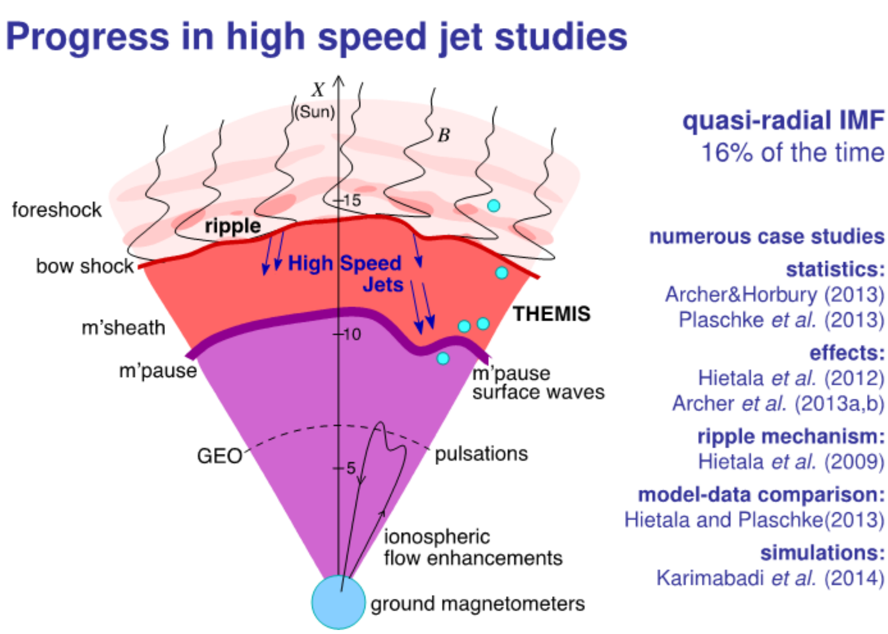


Statistical maps of parallel and perpendicular magnetic field fluctuations in the range of 0.1 Hz → 2 Hz binned for all upstream solar wind conditions. The dawn (quasi-parallel) flank is visibly prone to higher-amplitude magnetic perturbations compared to the dusk (quasi-perpendicular) region. From *Dimmock et al., 2014a.*

observations had been used by Hui Zhang to explore a variety of foreshock and magnetosheath phenomena, with these observations being compared to recent numerical models. One such observed structure started as a foreshock cavity and evolved into a hot flow anomaly (HFA). Foreshock cavities may thus be the early stages of HFAs. Examples of two types of structures at the foreshock were also shown. Some are foreshock cavities consistent with *Schwartz et al.,* [2006], and some are Foreshock Compressional Boundaries (FCB) consistent with numerical simulations described by *Omidi et al.,* [2009].

Global hybrid simulations [*Omidi et al.*, 2010] also predicted a new type of event (foreshock bubbles) that forms in Earth's foreshock and can affect the magnetosheath and magnetosphere. It forms as IMF discontinuities sweep up the ion foreshock region upstream of the bow shock, convect with the solar wind, and efficiently accelerate energetic particles. Drew Turner presented the first clear evidence of these events using THEMIS observations. The distinguishing features between foreshock bubbles and HFAs and their effects on the magnetosheath were presented, including global expansion of the bow shock and magnetopause followed by a sudden compression and the introduction of very energetic ions and electrons to the system.

High-speed jets: Another transient phenomenon within the magnetosheath region was presented by Heli Hietala. Supermagnetosonic jets within the subsolar magnetosheath are generated from ripples at the quasi-parallel bow shock resulting in dynamic pressure pulses leading to the presence of jets with typical transverse dimension of as large as 1-3 R_E, but less than 6 R_E. Observations of such jets have been shown with the Cluster mission (*Hietala et al.*, 2012). Such jets also have far-reaching impacts, causing irregular pulsations of the magnetic



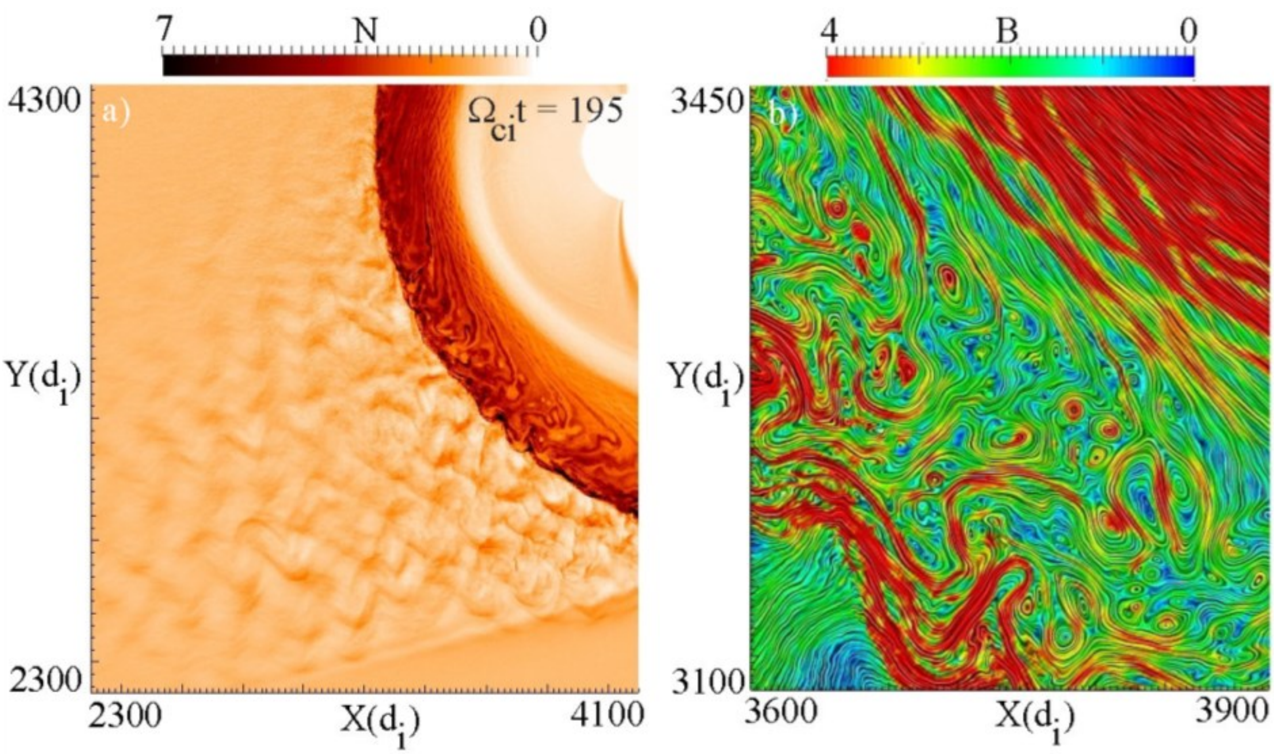
Generation of magnetosheath high-speed-jets, from Hietala GEM 2014 presentation.

field at geosynchronous orbit, and localized flow enhancements in the ionosphere.

Generation of Magnetosheath flux ropes and associated magnetic reconnection in thin current sheets: H. Karimabadi et al. performed Global hybrid (electron fluid, kinetic ions) and fully kinetic simulations of the magnetosheath and showed how magnetic flux ropes can be generated very effectively downstream of quasi-parallel bow-shock. Because IMF is statistically in Parker Spiral orientation, the reconnection and turbulence in the thin current sheets between flux ropes could provide more heating in the dawn-side magnetosheath (which for Parker Spiral IMF orientation is downstream of quasi-parallel shock).

3. Impact on Magnetospheric Processes and Properties

This last-listed research subject overlaps with the previous research subject in the sense that many impulsive or transient phenomena generated upstream of or at the bow shock, or occur within the magnetosheath proper can have noticeable effects on magnetopause processes and within the magnetosphere, and can even influence the ionosphere.



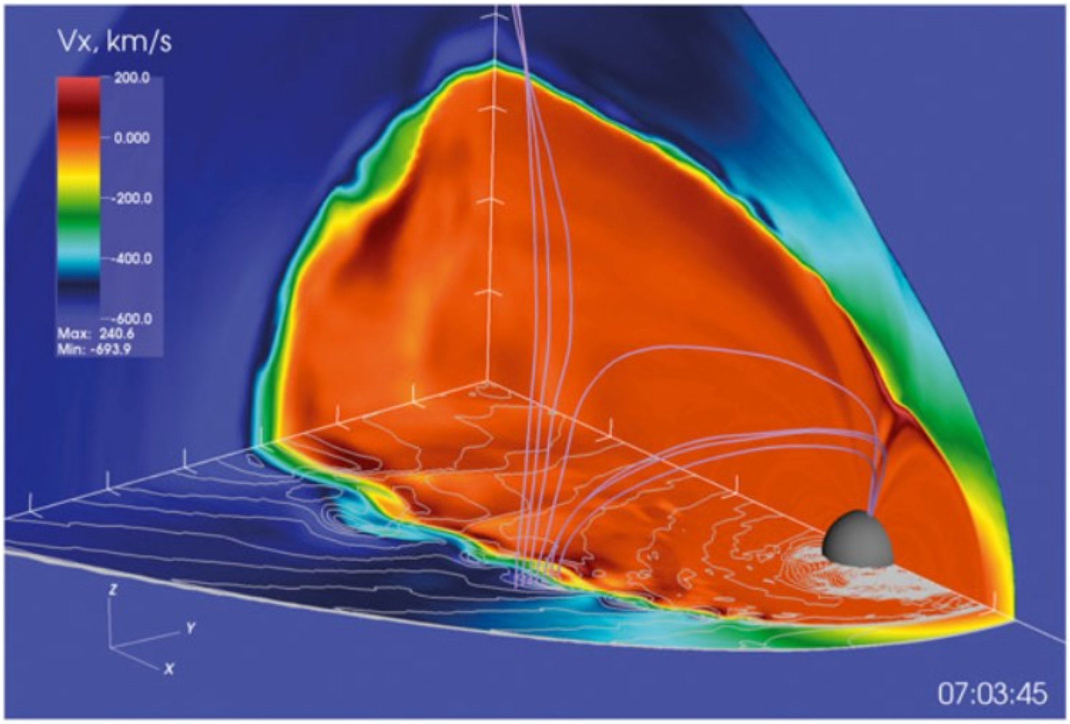
Formation of turbulence and associated magnetic islands in global hybrid simulation. The formation of the magnetic islands seems to be a common feature of Q▯ magnetosheath turbulence in regimes where Brms ▯ 1. a) Intensity plot of density. The presence of upstream waves is clearly evident. In the magnetosheath, current sheets and magnetic island can also been seen. b) A close up of Q▯ magnetosheath using Line Intergal Convolution (LIC) to show magnetic field lines colored by B. Many magnetic islands are observed at the shock surface all the way to the vicinity of the magnetopause (from *Karimabadi et al. 2014*).

On the origin of plasma sheet asymmetry: The cold component ions are hotter by 30-40% at the dawnside plasma sheet compared to the duskside plasma sheet, as described by Simon Wing (*Wing et al*., 2005). Statistical study by *Dimmock et al. 2014b* of magnetosheath temperatures using 7 years of THEMIS data indicates that ion magnetosheath temperatures downstream of quasi-parallel (dawn-flank for Parker-Spiral IMF) bow shock are only 10-15% higher than downstream of the quasi-perpendicular shock. This magnetosheath temperature asymmetry is therefore likely inadequate to cause the observed level of the plasma sheet temperature asymmetry. The origin of this asymmetry is not well understood, however *Johnson and Cheng, 2001* have theoretically shown that stochastic ion heating (perpendicular to the magnetic field) via kinetic Alfvén wave (KAW) turbulence is possible and efficient. *Johnson et al. 2001* have shown that an amplification of perpendicular wave power can be explained by mode conversion of compressional magnetohydrodynamic (MHD) waves into KAWs at the magnetopause. A recent statistical study by *Yao et al., 2011* shows that the spectral energy densities of ion gyroradii scale electromagnetic waves in the vicinity of the magnetopause are larger on the dawn than dusk-side. They report that these fluctuations may facilitate additional plasma transport and heating across the magnetopause which can contribute to the observed dawn-dusk plasma sheet temperature and density asymmetry. A recent statistical study by *Dimmock et al, 2014b* of the amplitude of magnetic field fluctuations in the range of 0.1-2 Hz in the dayside magnetosheath using six years of THEMIS data supports this conclusion and shows that the amplitude of magnetic field fluctuations in the dayside magnetosheath are typically larger on the quasi-parallel (dawn) flank during a Parker-spiral interplanetary magnetic field (IMF) orientation. While the fluctuation amplitude appears to increase for periods of fast solar wind conditions (>400 km/s) and during intervals of southward IMF, there appears to be no significant dawn/dusk asymmetry. This strongly suggests that the IMF orientation and prevailing upstream shock geometry has a crucial role on magnetosheath fluctuation properties.

On the evolution of the KHI:

The Kelvin-Helmholtz Waves (KHWs) are ultra-low frequency waves at the magnetopause that could lead to excitation of KAWs via mode conversion. Kelvin Helmholtz Instability (KHI) has been observed under strongly northward IMF [Fairfield et al., 2000; Otto and Fairfield, 2000; Hasegawa et al., 2004] and mass transport across the magnetopause associated with reconnection *(Nykyri and Otto, 2001, 2004)* and ion diffusion (*Cowee et al*., 2010) in KH vortices has been quantified in two-dimensions and shown to be efficient in generating a cold-dense plasma sheet within a time scale of about two hours during strongly northward IMF. KHI has also been observed for Parker-Spiral (PS) orientation *(Nykyri et al., 2006)* and with a strongly southward IMF component (*Hwang et al., 2011; Yan et al., 2014*). It was also shown that Lyon-Fedder-Mobarry (LFM) global MHD model is able to resolve KHI at the Low Latitude Boundary Layer. *Merkin et al., 2013* showed during steady northward IMF that the distribution of wave power in the equatorial plane is consistent with the existence of a double-vortex sheet, with KH vortex trains propagating along the inner and outer edges of the boundary layer. They calculated the spatial growth rate for the dominant frequency mode in this region (⍰4.4 mHz) to be ⍰0.19RE^{-1}, which is in excellent agreement with linear theory of Kelvin-Helmholtz Instability.

Moore, 2012 performed a statistical of the KHI using Cluster data and found 5 new KHI events at the dawn flank magnetopause during Parker-Spiral IMF. In the subsequent study (presented in summer GEM 2014) he found frequent intervals with heated ion distribution functions and higher frequency waves embedded in the KH vortices (*Moore et al., 2014*). *Nykyri, 2013* utilized BATSRUS global simulations and local MHD simulations to study the



An overview of the LFM MHD simulation at 07:03:45 simulation time. The background shows the x component of the plasma velocity in three planes: equatorial, noon-midnight meridian, and the YZ plane placed at X = –30 RE . The KH waves can be seen at the dawn-flank magnetopause (from *Merkin et al., 2013*).

effect of magnetosheath properties on the Kelvin-Helmholtz Instability as function of SW conditions during Parker-Spiral and Ortho-Parker Spiral IMF. The simulations showed that the magnetosphere flank at the dawn-dusk terminator is more unstable to the KHI than the dusk flank during Parker-Spiral IMF orientation, because the tangential magnetic field along the magnetopause is smaller at the dawn-side compared to the dusk-side. The statistical observational study by *Taylor et al, 2012,* which found more KHI events at the dayside dusk-flank magnetopause, is not in contrast with this result because many of their solar wind conditions did not occur under Parker-Spiral IMF orientation, but rather for a Ortho-Parker-Spiral orientation. This would cause a smaller tangential magnetic field along the dusk-side magnetopause for many of their events. Because the IMF is more frequently oriented in a Parker Spiral configuration (see for example solar wind and IMF distributions in *Dimmock and Nykyri, 2013*) the dawnside magnetosphere flank statistically has a smaller tangential magnetic field. This may lead to more plasma heating at the dawnside flank associated with reconnection in KH vortices (*Nykyri et al., 2006; Nishino et al. 2007, Taylor and Lavraud, 2008*) or heating via plasma waves associated with KHI (such as KAW created by mode conversion). *Hwang* suggested during summer GEM that the cold dense plasmaspheric plume (which is predominantly on the dayside dusk magnetosphere) may increase the KHI growth at dusk flank magnetopause. The effect of the plasmaspheric plume on the growth and evolution of the KHI remains to be carefully investigated.

On magnetic reconnection: The magnetic

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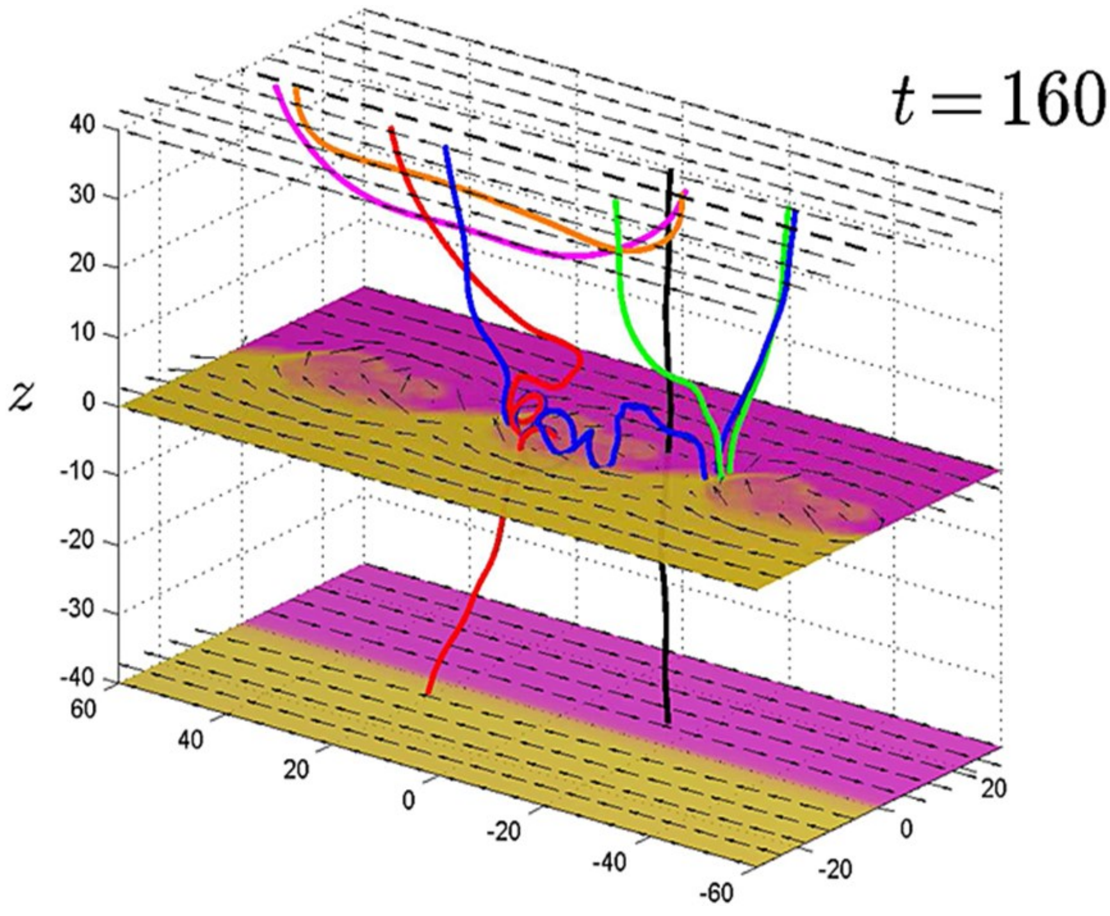
reconnection is strongly affected by magnetosheath properties. Ma et al. (2014a) demonstrated using 3-D high resolution local MHD code that magnetic reconnection is driven and strongly modified by nonlinear KH waves. The highest reconnection rate in this case is close to the Petschek rate, but the total open flux is limited by the size of the nonlinear KH wave. Most of the total open magnetic flux has no flux rope structure and originates from MR at thin current layers which connect adjacent vortices.

The magnetosheath fluctuations and waves in the range of 0.1-2 Hz may directly play role in plasma heating via wave particle interactions, but may also do so in an indirect manner by helping to excite macroscopic KHI more readily on the flank where the seed fluctuation amplitude is larger. Indeed, recent macro-scale 2.5-D high-resolution simulations (presented in summer 2014 GEM meeting) in the magnetosphere inertial frame indicate that even for the same magnetosheath and magnetosphere boundary conditions, the growth of the KHI and the time at which secondary reconnection starts in KH vortices can vary depending on the fre-



Typical structure of 3-D magnetic reconnection modulated by the KHI for southward IMF conditions, where the color index represents the magnetic *Bz* component. In this configuration, nonlinear KH waves generates multiple thin current layers in the vortex region and thereby triggering patchy reconnection. As such, an open (e.g., blue line) or closed (e.g., red line) field line experienced multiple reconnections and has a complex flux loop structure. Image is Courtesy of *X. Ma.*

quency and amplitude of the magnetosheath velocity fluctuations. Statistical study using 7 years of THEMIS data shows that higher velocity field fluctuation-amplitudes are observed on the magnetosheath downstream of quasi-parallel shock, which may lead to a more favorable excitation of the KHI at the dawn-flank magnetopause statistically (*Nykyri et al, 2014a*).

On the ionospheric properties: During magnetosheath FG activities *Dougal et al., 2013* also showed that magnetospheric KHI can map into high-latitude ionosphere and produce ground magnetometer, optical and radar signatures in agreement with previous studies. *Zhang* showed (using FUV and particle observations) that under a long (~4 hours) and strong northward IMF Bz (> 20 nT), the polar cap was filled with discrete arcs (including proton precipitations a few to ~10 keV). Possibly double lobe reconnection created new closed field lines on the dayside and extended to the night-side causing the polar cap (open field lines) to disappear. *Wilder* showed (using MHD simulations with DMSP and SuperDARN observations) that faster lobe circulation in the summer hemisphere occurs during northward IMF. Results suggest that reconnection between the IMF and the lobe field be more common in the summer hemisphere, while winter hemisphere lobe flux remains largely stagnant. This leads to hemispheric asymmetries in the ionospheric potential that are not dependent on ionospheric conductivity.

Deliverables:

Many new magnetosheath data sets have become available, including instrument observations and empirical results of the variation of magnetosheath parameters (normalized to the solar wind) as a function of IMF orientation, distance downstream, distance from the boundaries, as well as systematic differences between the dawn and dusk flanks. In addition, several studies of transient phenomena and plasma instabilities (often focusing on the KHI at the magnetopause) have been conducted. These results are available in the public literature.

A white paper detailing the modeling and data analysis of the 'steady-state' magnetosheath including a comprehensive description of the challenges and issues involved had been written and placed on the GEMwiki site for public comment and consideration.

Future work:

Although much work has been conducted relevant to the magnetosheath region during the past five years of the Focus Group, there remains a considerable amount of work to be done. Dynamic processes within the magnetosheath and interactions with the magnetopause and magnetosphere still require further study. Some of these future efforts are being addressed by the newly established Focus Groups. However, some subjects may benefit from additional attention. For example, the magnetosheath regions associated with other magnetized bodies have not been well-represented during this Focus Group. It is anticipated that much can still be learned from the study of such regions and applied to the broader understanding of the Earth's magnetosheath. It also remains to be quantitatively determined which is the dominant heating mechanism in the magnetosheath: wave heating or heating due to reconnection in thin current sheets.

References:

There have been more than two hundred publications in peer-reviewed journals since January 2010 for which the magnetosheath region is of primary relevance to the study. This large body of work illustrates that the physics of the magnetosheath region continues to be an important area of research. Provided below is a non-exhaustive list of published papers related to presentations given at GEM Magnetosheath Focus Group sessions:

Archer, M. O., and T. S. Horbury (2013), Magnetosheath dynamic pressure enhancements:

Occurrence and typical properties, *Ann. Geophys., 31*, 319–331, doi:10.5194/angeo-31-319-2013.

Archer, M. O., T. S. Horbury, and J. P. Eastwood (2012), Magnetosheath pressure pulses: Generation downstream of the bow shock from solar wind discontinuities, *J. Geophys. Res., 117*, A05228, doi:10.1029/2011JA017468.

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Radiation Belts and Waves Focus Group (2010-2014): Final Report

Yuri Shprits, Scot R. Elkington, Jacob Bortnik, Craig A. Kletzing

Summary of goals and activities. The Radiation Belts and Waves (RBW) focus group was incorporated into the GEM program as part of the Inner Magnetosphere and Storms (IMS) Research Area in 2010, and concluded their final formal sessions at the 2014 GEM Summer Workshop in Portsmouth, Virginia. This Final Report summarizes the RBW focus group's goals, activities, and accomplishments in that period.

The RBW group was organized and run by Yuri Shprits, Scot Elkington, Jacob Bortnik, and Craig Kletzing. The effort focused on the investigation of physical processes active within the Earth's radiation belts, with the goal of providing quantitative descriptions of the dynamics of the trapped radiation environment within the framework of first-principles physical models and in situ observations. This involved fundamental investigations identifying and quantifying the contributions and effects of various sources of heating, transport, and loss of radiation belt ions and electrons, and developing global and local models of the radiation belts. An essential element of this effort involved the investigation and modeling of the excitation, propagation, and distribution of magnetospheric plasma waves known to affect the radiation belts.

Specific questions addressed by the RBW were detailed in the focus group description on the GEM homepage (http://aten.igpp.ucla.edu/gemwiki), and include: (1) What are the quantitative effects of various waves on radiation belt acceleration and loss? (2) What are the physical processes responsible for wave excitation? (3) What is the wave distribution and what are its spatiotemporal characteristics? (4) What is the role of non-diffusive processes in the radiation belts? (5) What are the relative quantitative effects of transport and heating in the radiation belts? (6) What role do seed populations play in the dynamics of the radiation belts? and (7) Why do some storms produce increases in the radiation belt fluxes while others produce no net change?

In addressing the overarching goals and specific questions posed above, the RBW focus group conducted numerous oral and poster sessions across the GEM Summer Workshops and Fall AGU mini workshops. The effort included defining two community-wide modeling challenges, namely: (i) a 'particle challenge', with the goal of furthering the development of global models describing the particle dynamics in the radiation belts, and (ii) a 'waves challenge', addressing the origin, growth, and propagation of plasma waves in the inner magnetosphere. The goals and accomplishments associated with each of these challenges are outlined below.

Community interest in the activities of RBW group was very high. This was no doubt due in part to the development and successful launch of the NASA Van Allen Probes mission, which spanned the lifetime of this focus group. However, the high level of interest in this focus group presented particular organizational problems, which will be discussed below.

The RBW Particle Challenge. At the 2010 GEM Summer Workshop RBW Planning Session it was decided to organize a Global Radiation Belt Modeling Challenge, with the intent of better understanding the relative strengths of available physical and analytical models in capturing global radiation belt dynamics, defining necessary data inputs and model requirements, and working towards defining appropriate comparative metrics in evaluating the various models.

The challenge defined an interval of time comprising several CRRES-era geomagnetic storms which were associated with changes in the trapped space radiation environment. The challenge provided for a "tune-up" or training interval of time, independent of the challenge interval, for adjusting model inputs and settings. The training interval spanned three geomagnetic storms in the August 1990 to October 1990 period, while the challenge interval spanned 6 periods of geomagnetic activity in the February 1991 to July 1991 period. The goal of the challenge was to accurately simulate variations in the trapped radiation environment for either the entire challenge interval or for select storms within the interval, in terms of CRRES-observed phase space densities as a function of L* for specified first and second adiabatic invariants. Data sets providing likely input parameters (particle boundary and initial conditions, CRRES magnetic and electric field observations, solar wind conditions, etc) were posted to the ViRBO web site, http://www.virbo.org/rbw.

The purpose of the challenge was not to declare a “winner” among the models participating in the challenge, but to learn what physics and numerics are important for reproducing real observations.

Several groups applied their models to the RBW Particle Challenge. Broadly, each model solved the Fokker-Planck equations describing the evolution of the radiation belt phase space density using implicit or explicit differencing methods. An advantage of this framework is the ability to selectively ‘turn off’ different physical processes in each model to investigate the relative importance of each process.

Detailed results of the RBW Particle Challenge can be found in several of the publications listed at the end of this document; in the spirit of the challenge’s goal of understanding the physical processes needed for reproducing observations, we list a few broad ‘lessons learned’ below.

- There was relative success in modeling the qualitative dynamics of the radiation belts on the longer timescales covering the entire challenge interval; quantitative simulations of the detailed dynamics of individual storms within the interval were generally less successful.
- Radiation belt models tended to do better in modeling the dynamics of strongly-driven geomagnetic storms. Weakly-driven events and quiet periods were relatively more challenging to model. Future GEM challenges and studies should focus also on quiet-time dynamics.
- There was difficulty in reproducing radiation belt particle dropouts, suggesting the need for improved understanding and parameterization of the processes that lead to radiation belt losses (e.g. loss to magnetopause, effect of outward radial diffusion, influence of magnetospheric EMIC and chorus waves, etc).

- Simulation of higher-energy (>2 MeV) populations was more error-prone than simulation of lower energy populations. New observations from Van Allen Probes presented detailed observations of multi –MeV particles and presented new challenges for global models. The need to simulate a broad range of energies pitch angles and L-shells was discussed. Several different improvements that may help model multi-MeV fluxes was suggested and discussed (e.g. inclusion of a more realistic density models, inclusion of scattering by EMIC scattering that may affect only multi-MeV energies) .

- There is room for improved parameterization of input parameters, e.g. solar-wind driven, or AE-based scaling of chorus activity as opposed to simple Kp-based parameterization.

- Introduction of observed, rather than empirical input parameters tended to improve the modeling of individual storms. Examples include

    - Use of real solar wind data in calculating the last-closed field line for magnetopause losses.

    - Use of observed magnetic fields in calculating first invariants and local pitch angles, rather than model magnetic fields.

    - Use of observed low-energy ‘seed populations’ as boundary conditions.

    - Use of observed cold plasma densities as opposed to averaged models.

The RBW waves challenge. The second community-wide modeling challenge of the RBW focus group involved the simulation of a spontaneously-excited whistler mode ‘chorus’ wave, given only a specification of an unstable distribution of energetic electrons and background plasma properties. An initial draft of the waves challenge was circulated in the community and discussed at the 2012 GEM mini-session, which was part of the Fall AGU. The complete waves challenge was initiated at the 2013 GEM summer workshop and was to be run for a period of 1 year, with all results being reported at the 2014 GEM summer workshop.

The waves challenge drew involvement from the majority of the world’s wave-simulation community, and served as an impetus for a number of young scientists to focus their research efforts on the problem of wave excitation. We held a GEM mini-session at the 2013 Fall AGU meeting where interim results of the wave challenge were shown and discussed.

The final presentation of the wave simulation results was held at the 2014 GEM summer workshop held in Portsmouth, Virginia. There were a variety of approaches used to solve the problem, ranging from purely analytical, to Vlasov-hybrid simulations in 1D (spatial), to full PIC simulations in 1-D, and various hybrid-code approaches in 1D and 2D. In general, the codes obtained results that were realistic-looking, namely the emergence of whistler-mode noise in the frequency band ~0.2-0.5 f_{ce}, but there was disagreement amongst the codes regarding the final saturation amplitude, ranging anywhere from ~200 pT to >1 nT. Structures in the frequency-time domain predominantly showed unstructured (hiss-like) emissions, though some code also had rising tones embedded within the hiss-like emissions, with a rate of 1-10 kHz/sec. We highlight a particularly interesting approach to this waves simulation problem which struck a balance between speed and accuracy: this involved performing a 'coarse' simulation of a 2D hybrid code with relatively few particles spanning the whole of velocity space, and then identifying the precise region in velocity space that is involved in the wave excitation process and then performing a second simulation with a large number of particles loaded only into the velocity space region that is affected by the wave. One of the interesting conclusions that emerged from various simulation codes, is that it appears there was 'too much' free energy in the initial parameters, which transitioned the simulation output results from discrete chorus-like rising tones, to a more incoherent hiss-like noise.

To summarize the results of our waves challenge, we are currently considering a few options, i.e., either the production of a single, comprehensive review paper that will summarize the results of all codes, or a special issue of a journal, which will include contributed papers from the various wave challenge participants, reporting on the results of their own codes.

RBW workshop organization: lessons learned. Community interest in RBW activities was very high throughout the lifetime of the focus group. While the high level of community participation was a pleasant development, it did lead to several challenges in organizing workshop sessions. Many of our sessions were severely oversubscribed, often with many more people requesting speaking time than we were able to accommodate in a given session. We list some approaches that the RBW group leads used to deal with these organizational and communications challenges, in the hopes that they may be more broadly applied as GEM grows in the coming years.

- *Create a centralized location for posting simulation inputs and results.* The RBW group worked with Prof. Robert Weigel to create a website for hosting group-specific documents, simulation results, and meeting resources on the ViRBO (Virtual Radiation Belt Observatory) website.

- *Use web resources to organize sessions.* The RBW group used simple web resources (e.g. as available via google) to construct a centralized spreadsheet of requested talks and titles. This limited the confusion associated with requests sent to the individual session leads that might lead to forgotten or double-booked requests

- *Limit allowed oral presentation time.* While we initially thought this contrary to the original GEM philosophy of extended and informal discussion, the large number of contributed presentations resulted in strict time limits (e.g. 3 slides/5 minutes) in some sessions. This approach seemed to be surprisingly well-received (or at least, not poorly-received) according to a vote by the RBW focus group participants in sessions where it was deemed necessary.

- *Schedule designated discussion periods.* Where possible, we scheduled time within sessions, or (on occasion) dedicated complete sessions to discussion. In addition to providing the community time to air views and debate research results, this also provided some amount of 'overflow' time for talks that were unable to be accommodated in a session dedicated to a particular topic.

- *Limit speakers to one oral presentation,* unless speakers were invited to discuss a particular topic in a given session or wished to speak on multiple, widely-disparate topics in the RBW focus group.

- *Discourage speakers from orally presenting material that would also be covered in a poster session.* We made exceptions for student presenters, who could request limited time (e.g. 1 slide/2 minutes) in a discussion session to introduce their research and advertise their poster presentations.

Summary of focus group accomplishments.

- Developed a framework for the objective comparison of observations and models during GEM under the umbrella of the RBW particle challenge.

- Developed a set of scale scores for code validation.

- Identified important physical mechanisms and identified future directions for model development.

- Attracted a number of people to focus on specific events and compare the results.

- Validated existing codes, improved existing codes, developed new codes of particle evolution and wave generation.

- Identified a number of potentially important physical mechanisms for wave growth, developed new approaches to speed up simulations, compared different methods.

- Helped appreciate the complexity of the generation of waves.

GEM RBW publications.

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