Chapter 8

Magnetospheric Multiscale Mission:

Cross-scale Exploration of Complexity in the Magnetosphere

A. Surjalal Sharma
University of Maryland, College Park, Maryland, U.S.A.

Steven A. Curtis
NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

Abstract: The physical processes in the magnetosphere span a wide range of space and time scales and due to the strong cross-scale coupling among them the fundamental processes at the smallest scales are critical to the large scale processes. For example, many key features of magnetic reconnection and particle acceleration are initiated at the smallest scales, typically the ion gyro-radii, and then couples to meso-scale and macro-scale processes, such as plasmoid formation. The Magnetospheric Muliscale (MMS) mission is a multi spacecraft mission dedicated to the study of plasma physics at the smallest scales and their cross-scale coupling to global processes. Driven by the turbulent solar wind, the magnetosphere is far from equilibrium and exhibits complex behavior over many scales. The processes underlying the multi-scale and intermittent features in the magnetosphere are fundamental to sun-earth connection. Recent results from the four spacecraft Cluster and earlier missions have provided new insights into magnetospheric physics and will form the basis for comprehensive studies of the multi-dimensional properties of the plasma processes and their inter-relationships. MMS mission will focus on the boundary layers connecting the magnetospheric regions and provide detailed spatio-temporal data of processes such as magnetic reconnection, thin current sheets, turbulence and particle acceleration. The cross-scale exploration by MMS mission will target the microphysics that will enable the discovery of the chain of processes underlying sun-earth connection.

Key words: magnetosphere, multiscale phenomena, cross-scale coupling, multi-spacecraft mission, reconnection, particle acceleration, thin current sheets,

1. INTRODUCTION

The magnetosphere is driven by the turbulent solar wind and exhibits multiscale features over a wide range of spatio-temporal scales, ranging from the smallest scale of kinetic processes to the global scale of magnetohodrodynamic phenomena. There is strong cross-scale coupling among the different phenomena in the five main regions of geospace, viz. magnetosheath, tail lobes, plasma sheet, ring current and ionosphere. These regions are interconnected through boundaries, viz. the magnetopause, cusp, plasma sheet boundary layer and magnetotail current sheet, and the dominant dynamical processes are initiated at these boundaries. The magnetopause is a thin current sheet and magnetic reconnection there leads to the transfer of mass, momentum and energy from the solar wind into the magnetosphere. The magnetotail plasma sheet has a thin current sheet embedded in it and is the site of processes responsible for the onset of explosive release of energy during substorms. The processes at the boundaries and sheets are kinetic in nature and their coupling to the meso- and macro-scales are essential elements in unraveling the multiscale physics of geospace. The cross-scale coupling in the magnetosphere due arises due to the nonlinearity of its plasma and fields and consequently the multiscale behavior is an inherent feature.

The main dynamical features of the magnetosphere are storms and substorms, which are prevalent mainly when the solar wind is strongly coupled to the magnetosphere, e.g., due to enhanced magnetic reconnection at the magnetopause. The geospace storms and related processes have time scales of days and are associated with enhancements of the ring current in the inner magnetosphere. The substorms on the other hand have characteristic time scales of an hour or so and are associated mainly with the plasma processes in the magnetotail. While our understanding has advanced rapidly due to the recent multi-spacecraft and ground-based measurements, and theory and modeling, many outstanding questions remain due to the complexity of the magnetosphere arising from the plethora of processes with overlapping space and time scales.

The dynamics of magnetospheric boundaries during storms and substorms are essential elements in the chain of multiscale phenomena in geospace. The main reasons for the complexity of geospace are:

the inherent nonlinearity of the plasma and fields, and its nonequilibrium nature. The complicated fields and plasma with very short scale lengths make in-situ measurements as well as theoretical analysis difficult. Also the nonequilibrium nature of the magnetosphere introduces time variations that challenge the current capabilities of measuring short time scale processes in sufficient detail. The Magnetospheric Multiscale Mission (MMS) is designed to carry out such measurements with four spacecraft in strategically configured formations in the key regions (Curtis, 1999).

The dynamical behavior of the magnetosphere embodied in observational data has been studied extensively using nonlinear dynamical techniques (see reviews: Sharma, 1995, 2003; Klimas et al., 1996). The evidence of large scale coherence in magnetospheric dynamics, first obtained in the form of low dimensional behavior (Vassiliadis et al. al., 1990), is consistent with its morphology (Siscoe, 1991), and MHD simulations (Lyon, 2000). The multiscale behavior of the magnetosphere, on the other hand, has been recognized mainly through the power law dependences, e.g., in the AE index (Tsurutani et al., 1990), spacecraft images of the auroral region (Uritsky et al., 2002), bursty bulk flows (Angelopoulos et al., 1999), turbulence (Borovsky and Funsten, 2003), etc. These studies make extensive use of observational data to develop data-derived models of the complexity in the magnetosphere. The key advantage of these approach is its ability to model the inherent dynamical features without a priori assumptions, and complements the first principle models. The study of multiscale phenomena using these two approaches is expected to yield a more comprehensive understanding of the magnetosphere.

2. MAGNETOSPERIC COMPLEXITY: FROM MICROSCALE TO MACROSCALE

The most ubiquitous features of the magnetosphere during geomagnetically active periods are the global scale processes such as plasmoid formation and release. However these large scale phenomena originate from the microscale physical processes occurring at the boundary layers of the magnetosphere such as the magnetopause and magnetotail. A canonical example of such cross-scale coupling is a substorm in which the onset of reconnection occurs in the magnetotail thin current sheet, with thickness as small as an ion gyro radius (~ 400 km), and may involve processes at the electron gyro radius scale (~ 80 km). The reconnection onset, most likely due to the tearing instability (Sitnov et al., 1998, 2002), is followed by flows and turbulence on many scales, including those associated with Alfven waves, and leads to possibly flux ropes and a large scale plasmoid with a size of ~ 100 R_E. A simulation of the magnetosphere during a substorm (March 9, 1995) using an MHD code and its connection to the magnetic reconnection simulated using a particle code is shown in Figure 1 (Lyon, 2000). The small inset shows magnetotail current sheet where magnetic reconnection is initiated at the x-line in the magnetotail. The large inset is a particle code simulation of reconnection (Shay et al., 1999). The phenomena on the global as well as the micro-scales are strongly coupled through the multiscale processes.

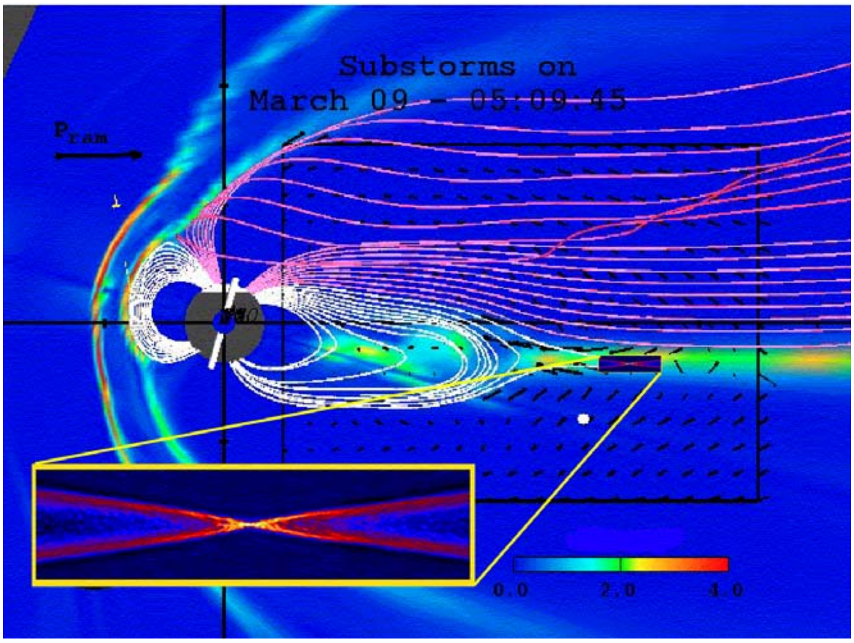

Figure 1. The magnetosphere as simulated using a global MHD code for the substorm of March 9, 1995 (Lyon et al., 2000) showing the global magnetospheric configuration. The background indicates the magnitude of the perpendicular current with a set of field lines showing the magnetic field geometry in the tail. The large inset shows a particle code simulation of magnetic reconnection (Shay et al., 2000) in a region indicated by the small inset. The plasma processes initiated at such narrow regions lead to large scale dynamics such as plasmoid formation.

The multi-scale behavior of the magnetosphere is evident in many studies of the distribution of scale sizes, typically in the form of power spectra. Most of these studies use the magnetospheric data such as the magnetic field and plasma flows, or geomagnetic indices (Tsurutani et al., 1990; Borovsky et al., 1997; Angelopoulos et al., 1999; Uritsky et al., 2002).

Considering the driven nature of the magnetosphere and the variability of the solar wind, it is however important to use the correlated data of the solar wind and the magnetospheric response. A widely used data set of the coupled solar wind-magnetosphere is the Bargatze et al. (1985) data set consisting of the solar wind induced electric field VB_s (B_s is the southward component of the interplanetary magnetic field and V is the component of the solar wind velocity along the Earth-Sun axis) and the magnetospheric response is the auroral electrojet index AL. This data set has been used to study the multi-scale behavior (Sitnov et al., 2000, 2001; Sharma et al., 2001).

A common technique for studying multiscale phenomena is the power spectrum analysis using Fourier transforms. For nonlinear systems such as the magnetosphere it is essential to use techniques with retain the nonlinear effects, such as phase space reconstruction from observational data. The singular spectrum analysis, based on the singular value decomposition, is often used to reconstruct the phase space of the coupled solar wind- magnetosphere system from the time series data by time delay embedding (Sitnov et al., 2000, 2001). The singular value decomposition of the VBs-AL data yields the orthonormal components in the reconstructed phase space with different strengths, expressed in terms of an eigenvalue spectrum, and exhibits multiscale behavior, with a spectrum close to 1/f (Sitnov et al., 2001). Similar distribution of scales is found in the global MHD simulations (Shao et al., 2003).

The magnetospheric response strongly depends on the solar wind conditions, with a wide variability in the nature of the response. Thus it is essential to study the magnetospheric response for specific types of solar wind conditions. Such a study can be readily carried out in the phase space reconstructed from the correlated solar wind – magnetosphere data. The global features of the magnetosphere are represented by the first few leading coordinates in this phase space. The multi-scale parts are naturally coupled among themselves and to the large-scale or global component, and appear as fluctuations of the data around an average state. The distribution of these fluctuations can be described in terms of conditional probabilities $P(O_{t+1} \mid \mathbf{x}_t)$ defined in the embedding space $\mathbf{x_t}$ for given solar wind conditions and the magnetospheric output O_{i+1} (Ukhorskiy et al., 2004).

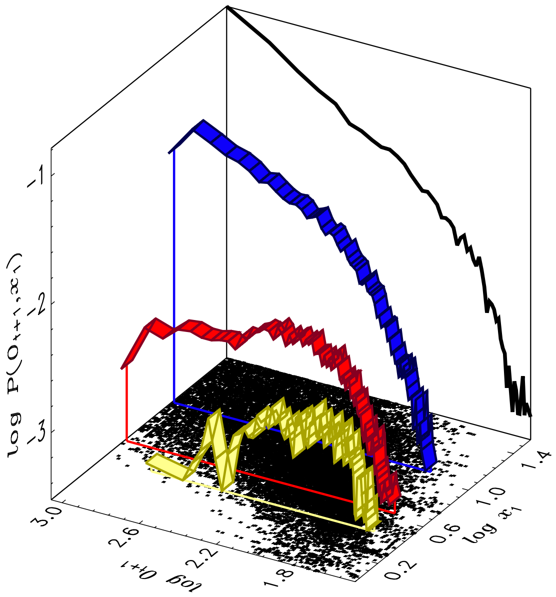

Figure 2. The conditional probabilities $P(O_{t+1}\,|\,\mathbf{x}_t)$ of the magnetosperic state O_{i+1} as a function of solar wind conditions, represented by $\mathbf{x}_t$. The yellow, red and blue curves correspond to strong (vBs > 9 mV), medium (0.6 < vB_s < 9 mV) and low (vBs < 0.6 mV) solar wind activity levels, represented by $\mathbf{x}_t$. The floor shows all the points in the data base, corresponding to the marginal probability distribution function shown in the back panel (Ukhorskiy et al., 2004).

The probability density distributions of the magnetospheric response are shown in Figure 2 and depend strongly on the solar wind conditions. The response has a nearly power law distribution when the solar wind driving is weak (blue curve, vB_s < 0.6 mV), deviates from power law and has a broad response for medium driving (red curve, 0.6 < vB_s < 9 mV) and has a more peaked response for stronger driving (yellow curve, vB_s > 9 mV) (Ukhorskiy et al., 2004).

3. MAGNETOSPHERIC MULTISCALE MISSION

The objective of Magnetospheric Multiscale mission is two-fold: exploration and understanding. It will study the microscale phenomena - the basic plasma processes that transport, accelerate, and energize plasmas in thin boundary and current layers. These are the processes that control the structure and dynamics of the Earth's magnetosphere and have been inaccessible so far. For example, the whole range of processes associated with magnetic reconnection will be studied. Magnetospheric Multiscale will measure 3D fields and particle distributions and their temporal variations and 3D spatial gradients, with high resolution, while dwelling in the key magnetospheric boundary regions, from the subsolar magnetopause to the distant tail. It will uniquely separate spatial and temporal variations over scale lengths appropriate to the processes being studied – from the electron gyro radius up to structures with sizes > 1000 km. From the measured gradients and curls of the fields and particle distributions, spatial variations in currents, density, velocities, pressures, and heat fluxes can be calculated. Magnetic reconnection will be directly observed in each of the regimes where it is thought to occur around the Earth. This process, initiated at thin current sheets, is vital for transferring energy from magnetic fields to plasmas, and for coupling different regimes. It is central to many astrophysical theories, yet its operation in collisionless space plasmas is very poorly understood. The goals of Magnetospheric Multiscale are different from those of the ESA Cluster mission, which will explore selected regions (bow shock, cusp, midtail) to spatial scales down to > 100 km from a single polar orbit. Magnetospheric Multiscale is designed to study boundary processes throughout the magnetosphere over scales down to < 100 km, commensurate with the scales of microphysical processes acting within many of the critical boundaries of interest.

The four identical spacecraft of Magnetospheric Multiscale will fly in a tetrahedral configuration with spacing variable from 10 km to more than 1000 km. Each spacecraft will contain an identical set of 3D instruments with high spectral and temporal resolution (plasma electron and ion composition, energetic electron and ion composition, magnetometer, electric fields and waves). Inter spacecraft ranging and communication will determine spacing and allow simultaneous high rate data recording on all spacecraft for maximum resolution of boundaries or events.

The thrust of the science objectives of MMS mission is to explore and understand fundamental processes on microscale that control the flow of energy, momentum, and mass within and across plasma boundaries.

The key science question that will be addressed by MMS mission is what physical processes contribute to magnetic reconnection? The broader questions it will address are: 1) How do microscale processes near plasma boundaries couple to larger scale dynamics and structures? 2) What controls the transport of magnetic fields, and thus energy, across plasma boundaries? 3) How are electric currents generated at boundaries to influence distant magnetospheric regions? 4) How do processes at plasma boundaries accelerate charged particles?

The MMS mission will consist of four spacecraft fly in close proximity to form a single probe that can uniquely separate space time and will use of interspacecraft ranging and communication to explore wide range of scales down to < 100 km. Four different orbital phases will be used to cover the entire magnetosphere.

The strategies for measurements in geospace dynamics is broadly divided into five mission types, viz. global configuration, microscope, networks, inner and outer boundaries, and solar plasma variations (Vondrak et al., 2003). The microscope type missions are MMS and Cluster, designed to carry out detailed measurements of plasma dynamics using tetrahedronal clusters of spacecraft. The strategic targets are unprecedented determination of values, gradients, curls, and divergences at all scale of interest in magnetic and electric fields, plasma, including composition; energetic particles; and plasma and radio waves.

4. KEY MICROSCALE PHYSICS PROBLEMS

4.1 Reconnection

Magnetic reconnection is one of the most widely studied phenomenon in the laboratory and natural plasmas. The laboratory plasmas are usually collisional and reconnection in this context is relatively well understood. However in the nearly collisionless plasmas in space, understanding reconnection remain a challenge. The main issues in the theory of collisionless reconnection are the mechanism of onset, rate of reconnection and saturation. Recent advances in simulations using particle-in-cell, hybrid, Hall MHD and MHD codes have shown that the reconnection rate is governed mainly by ion dynamics and the outflow region is crucial to the reconnection process (Birn et al., 2001). However these studies assume the existence of an X-line and thus avoid the issue of reconnection onset or X-line formation. The tearing mode is a natural candidate for the onset of reconnection and has been studied extensively since it was first proposed soon for the magnetotail current sheet (Coppi et al., 1966) soon after the discovery of the magnetotail. The complicated kinetic theory of tearing instability in the thin current sheet with very short scale lengths or sharp gradients and consequently complex particle orbits has a checkered history. Recent studies using kinetic stability codes capable of resolving these issues have shown that the tearing instability can be destabilized due to the presence of transient electrons along with those trapped in the current sheet (Sitnov et al., 2002). This implies that the tearing instability is a viable mechanism for reconnection onset. In order to understand the formation of X-line in more detail the nonlinear development of the instability and its saturation need to be studied. The development of analytic theory of kinetic instabilities and their nonlinear development in such a complicated situation is difficult and particle simulation codes may yield new advances. However such codes have not succeeded in showing the tearing instability in realistic geometry of the magnetotail current sheet. It should however be noted that although a system is linearly unstable it may be nonlinearly stable and the role of the instability is then limited. This implies that these phenomena are nonequilibrium in nature (Sitnov and Sharma, 1998) and this recognition has lead to new perspective for solar flares (Priest, 2000; Somov, 2000).

The crucial next advance in the understanding of reconnection can be expected from the detailed in-situ measurements of the plasma and field variables. Such measurements are expected from multispacecraft Cluster and MMS missions. Recent studies using multi-spacecraft observations have given direct confirmation of reconnection and associated processes at the magnetopause (Phan et al., 2000). Also single spacecraft passes such as by Geotail through the magnetopause

(Deng and Matsumoto, 2001) and the magnetotail current sheet by Wind (Oieroset et al., 2001, 2002) gave detailed in-situ measurements.

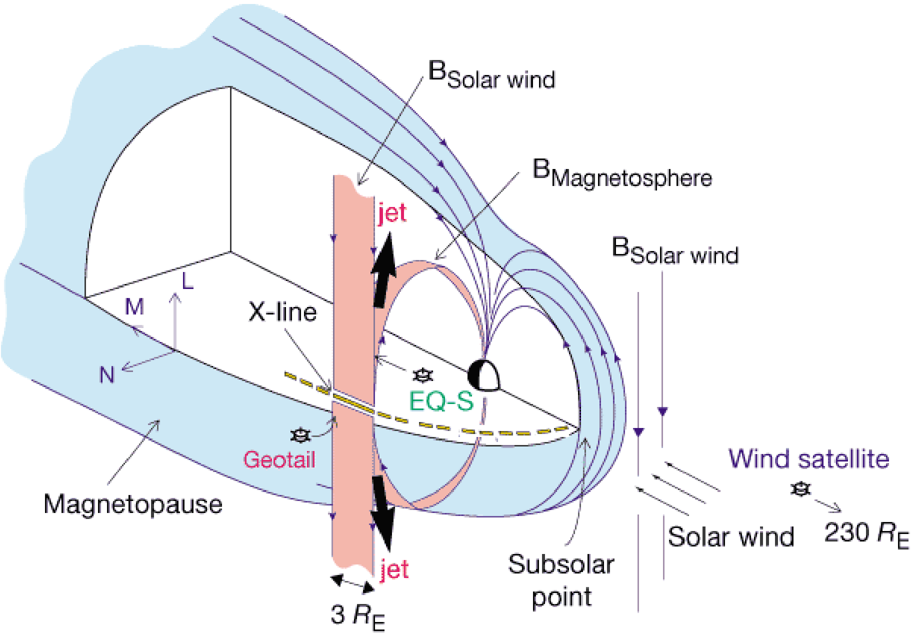

Figure 3. Three-dimensional cutaway view of the magnetosphere showing the spacecraft positions and the presence of an extended reconnection line. The separation between the Geotail satellite and the Equator-S (EQ-S) satellite was ~4 R_E in the north–south, and ~3 R_E in the east–west, direction. Bi-directional reconnection jets detected at both spacecraft locations indicate a reconnection X-line (yellow solid line) along the dawn flank magnetopause and slightly north of the equatorial plane. The inferred X-line (yellow dashed line) extends to the subsolar point and over to the dusk flank. The boundary normal (LMN) coordinate system is defined such that the N axis points outward along the magnetopause normal and the (L, M) plane is tangential to the magnetopause with L orientated due north and M due west (Phan et al., *Nature*, *404*, 848, 2000)

The bi-directional jets resulting from reconnection at the magnetopause were measured by Geotail and Equator-S satellites, separated by ~ 4 R_E in the north-south, and ~ 3 R_E in the east-west, direction. The X- line with a length of >3 R_E in the north-south direction and extending to the sub-solar point and over to the dusk flank, was ~ 40 R_E (Figure 3). These provide key measurements of the reconnection phenomena and more detailed measurements will require shorter spatial resolution as well as longer residence time of the spacecraft in the region. The MMS mission will have capabilities to measure many physical variables on space scales at least an order of magnitude smaller and with the strategically preplanned trajectories, much more encounters of the reconnection region are expected. The onset and saturation are two outstanding problems of reconnection, and multi-dimensional and short scale measurements are crucial for new advances in their understanding.

4.2 Thin current Sheets

Thin current sheets in many astrophysical, solar, planetary, magnetospheric and laboratory plasmas are the key regions where the release of stored magnetic energy is triggered. They are ubiquitous in the interfaces or boundaries between plasma and magnetic fields. The X-ray luminosity of the Sun and stellar bodies arise from processes in the thin current sheet sheets (Parker, 1994). The structure and dynamics of the current sheets play an important role in the understanding of the microscale processes and their cross-scale coupling to the meso- and macro-scale processes. Spacecraft experiments provide the only possibility of in-situ study of current sheets in collisionless plasmas. Before Cluster, most of our understanding of the current sheets have come from the measurements by single spacecraft, which has strong limitations in separating spatial and temporal changes, and thus of structure and dynamics. The closely spaced MMS spacecraft will present a unique opportunity to study the spatio-temporal changes of the plasma variables, e.g., in the magnetotail current sheet.

The current sheets can be as thin as the ion gyro radius, possibly the electron gyro radius, and as such needs a kinetic description of the microscale processes. Given the complexity of the magnetotail and the magnetopause, the theory of such regions pose significant challenges. For example, most studies are for the simplified one-dimensional structure of thin current sheets. Recent studies of such sheets have given a new understanding of their stability against many plasma instabilities, in particular the tearing instability. New theories and techniques of kinetic plasma equilibria in multi-dimensions are needed to develop multi-dimensional models to compare with MMS in a meaningful manner. Due to the complexity of such plasma configurations reliable results are expected to emerge mainly from studies that use judiciously the capabilities of analytic theory and numerical simulations. For example, the stability of these equilibria has been studied using the finite element techniques (Sharma, 1983; Sitnov et al., 2002), which can account for the strongly inhomogeneous magnetic field geometry and the consequently complicated particle orbits. A combination of such studies with simulations has the potential of yielding new results on reconnection onset and related processes.

The internal structure of current sheets and the details of particle populations are important to the understanding of their evolution. The possibility of the studies of such microphysical properties using single spacecraft measurements are rather limited and multi-spacecraft MMS mission can provide the relevant data to the required detail. In the case of the magnetotail, the particle distributions of the trapped or transient particles evolve and lead to changes in the self-consistent structure. Recent studies have found that the change of the particles from being transient to trapped lead to changes in the cross-tail current and eventually flattens the profile of the magnetic field near the midplane (Zelenyi et al., 2002). As a result the current profile attains a double humped profile (Figure 4), which in turn can play a major role in its evolution. This result is in agreement with the Geotail (Hoshino et al., 1996) and Cluster (Sergeev et al., 2003) observations of double-humped (also referred to as bifurcated) current sheets in the Earth's magnetotail. The understanding of the double humped current profiles and their role in the evolution of the current sheet will require measurements of the particle distributions, and the plasma and magnetic filed profiles, and such measurements are expected from MMS.

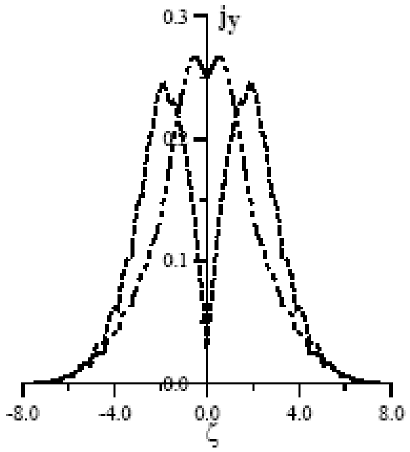

Figure 4. The normalized current density j_y as a function of the distance (normalized) across the sheet evolves from a peaked initial value to the double-humped or bifurcated profiles (Zelenyi et al., 2002).

4.3 Particle Acceleration

The magnetic energy released during reconnection leads to fast flows, heating and acceleration. While the fast flows and heating involve a large fraction of the particles, only a small fraction is accelerated to high energies. The acceleration process is often associated with sharp gradients in the plasma variables and occur in the electric and magnetic fields. The thin current sheets or the reconnection regions are characterized by plasmas with short scale lengths and thus are potential sites for particle acceleration. The energization processes need to be studied in detail as they can lead to an understanding of the microphysical processes at such boundaries and layers.

The accelearion of particles by localized electric fields is usually limited by the strength of the field, and higher energies are achieved by multiple steps mediated by either stochastic processes or coherent mechanisms. The processes of stochastic acceleration through scattering by waves and turbulence are well known (Terasawa and Scholer, 1989). On the other hand coherent mechanisms such as surfatron (Ragdeev and Shapiro, 1973) can produce very high energies.

In general particles are accelerated to high energies by a combination of mechanisms such as Fermi acceleration, betatron acceleration, wave-particle interactions, inductive electric fields, parallel electric fields. The manner in which these mechanisms work together to yield high energy particles will depend on the nature of the fields and plasma. MMS is targeted to make measurements of the distributions of the electrons and ions, and the electric and magnetic fields to enable an understanding of the different acceleration mechanisms operating at the magnetospheric boundaries and layers.

One of the unsolved puzzles of the geospace storms and substorms is the origin of energetic oxygens in the storm-time ring current. During many storms the ratio of the oxygen ion to proton densities are enhanced during substorms (Korth et al., 2003). While these oxygen ions may have come from the ionosphere (Daglis and Axford, 1996), the processes responsible for their acceleration from energies of ~ eV in the ionosphere to hundreds of keV in the ring current are not well understood. The ions are accelerated to by the field aligned electric fields as they flow out of the ionosphere and then by the reconnection related processes in the magnetotail. The dipolarization of the magnetic field, which transports them to the inner magnetosphere will further energize these ions. The understanding of the acceleration processes in the magnetotail, e.g., the required initial energies, different energization processes and final energies, will need detailed measurements at the micro-scale.

4.4 Turbulence

At the microscopic level the physics of reconection, thin current sheets, particle acceleration are intimately inter-connected. The presence of turbulent fields will affect the nature of reconnection, making it more like collisional reconnection through anomalous collisions that depend on the strength of the turbulence. Turbulence can affect the structure and dynamics of current sheets because of the altered particle trajectories and consequently the currents and fields. Also the stochastic acceleration can be due to the turbulent waves.

The measurement strategies of MMS (Curtis, 1999) target these issues to advance the understanding of the micro-scale physics.

The multiscale aspect of turbulence is important in the understanding of how processes at micro-scale level affect those at the global scale. The micro-scale component forms one end of the multiscale features and the scaling of turbulent fluctuations in the range of measurements by MMS will provide details of the micro- to meso-scale coupling.

Turbulence in the magnetosphere have been studied using many data sets and techniques. The statistics of chorus events seen in the groundbased and spacecraft data of particle injections in the near-Earth magnetosphere (Borovsky et al., 1993; Pritchard et al., 1996) show the intensity and occurrence rate of substorms to have a probability distribution with a well-defined mean. While many studies have been based on the auroral indices data, many other studies have used the spacecraft data. Studies of the magnetic field fluctuations during the disruption of the magnetotail current have shown power spectrum dependence (Ohtani et al., 1995; 1998). The plasma flow in the inner plasma sheet measured by Geotail and Wind spacecraft have been used to study the nature of the intermittency in the magnetosphere (Angelopoulos et al., 1999). The probability density of the magnitudes of the bursty bulk flows show power law dependence in time and their distribution is found to be non-Gaussian.

Turbulence in the distant tail has been modeled using percolation theory, which intimately connected with the fractal structure and multiscale behavior (Zelenyi et al., 1998). In this study the plasma turbulence in the distant magnetotail has been found to have self-organizing properties and these have been described in terms of the fractal properties (Zelenyi et al., 1998).

5. DISCUSSION

Geospace is a local cosmos that provides a uniquely accessible laboratory in which plasmas can be studied in a wide range of environments at scales not possible in the laboratory and in detailsnot accessible compared to astrophysical situations (National Research

Council Report, 2004). The understanding of the fundamental processes at the boundary layers is the prime target of MMS and in the same time it will yield unprecedented data for studying the complexity of the magnetosphere. The scaling of the physical phenomena that will be studied by varying the separation among the spacecraft will provide a new understaning of the multiscale phehenomena. The understanding achieved from MMS, a microscope type of geospace mission (Vondrak et al., 2003), is crucial to success of missions exploring phenomena at larger scales, such as Magnetospheric Constellation.

Acknowledgements. The research at the University of Maryland are supported by NASA and NSF grants.

References

Angelopoulos, V., T. Mukai, and S. Kokubun, Evidence for intermittency in Earth's plasma sheet and implications for self-oganized criticality, *Phys. Plasmas, 6,* 4161, 1999.

Asano, Y., T. Mukai, M. Hoshino, Y. Saito, H. Hayakawa, and T. Nagai. (2003). Evolution of the thin current sheet in a substorm observed by Geotail, J. Geophys. Res., 108, doi:10.1019/2002JA009785, 2003.

Baker, D. N., A. J. Klimas, R. L. McPherron, and J. Buechner, The evolution from weak to strong geomagnetic activity: An interpretation in terms of deterministic chaos, *Geophys. Res Lett.*, *17*, 41, 1990.

Baker, D. N., Pulkkinen, T. I., Angelopoulos, V., Baumjohann, W., McPherron, R. L., Neutral line model of substorms: Past results and present view. *J. Geophys. Res.*, *101*, 12,975, 1990.

Bargatze, L. F., Baker, D. N., McPherron, R. L., Hones, Jr., E. W., Magnetospheric impulse response for many levels of geomagnetic activity. *J. Geophys. Res*., *90*, 6387, 1985.

Borovsky, J. E., Nemzek, R. J. Belian, R. D., The occurrence rate of magnetospheric-substorm onsets: Random and periodic substorms. *J. Geophys. Res*., *98*, 3807, 1993.

Borovsky, J. E., Nemzek, R. J. Belian, R. D., The Earth's plasma sheet as a laboratory for flow turbulence in high beta MHD, *J. Plasma Phys., 57,* 1-34, 1997.

Borovsky, J. E., and H. O. Funsten, MHD turbulence in the Earth's plasma sheet: Dynamics, dissipation, and driving, *J. Geophys. Res., 108(A7),* 3807, doi :10.1029/2002JA009625, 2003.

Curtis, S. A., *The Magnetospheric Multiscale Mission: Resolving Fundamental Processes in Space Plasmas,* NASA/TM-2000-209883, National Aeronautics and Space Administration, 1999.

Daglis, I. A., and W. I. Axford, Fast ionospheric response to enhanced activity in geospace: Ion feeding of the inner magnetotail, J. Geophys. Res., 101, 5047, 1996.

Deng, X. H., and H. Matsumoto, Rapid magnetic reconnection in the Earth’s magnetosphere mediated by whistler waves, Nature, 410, 557, 2001.

Drake, J. M..,

Freeman, M. P., Watkins, N. W., D. J. Riley, Evidence for a solar wind origin of the power law burst lifetime distribution of the AE index, *Geophys. Res. Lett., 27,* 1087, 2000.

Hoshino, M, R. L. Stenzel and K. Shibata (eds.), *Magnetic Reconnection in Space and Laboratory Plasmas,*Terra Sci. Pub., Tokyo, 2001.

Huang, C.-S., G. D. Reeves, J. E. Borovsky, R. M. Skoug, Z. Y. Pu, and G. Le , Periodic magnetospheric substorms and their relationship to with solar wind variations, *J. Geophys. Res*., *108(A6)*, 3807, doi :10.1029/2002JA009704, 2003.

Jensen, H. J., *Self-Organized Criticality: Emergent Complex Behavior in Physical and Biological Systems*, Cambridge, University Press, 1998.

Klimas, A. J., J. A. Valdivia, D. Vassiliadis, D. N. Baker, M. Hesse, and J. Takalo, Self-organized criticality in the substorm phenomenon and its relation to localized reconnection in the magnetospheric plasma sheet, *J. Geophys. Res.*, *105*, 18,765, 2000.

Korth, A., Friedel, R. H. W., M. G. Henderson, F. Frutos-Alfaro, and C. G. Moukis, O+ transport into the ring current: Storm versus substorm, in *Disturbances in Geospace: The Storm-Substorm Relationship, Geophysical Monograph series, Vol. 142*, eds., A. S. Sharma, Y. Kamide and G. S. Lakhina, Amer. Geophys. Union, 2003.

Lyon, J. G., The solar wind – magnetosphere – ionosphere system, *Science*, *288*, 1987, 2000.

National Research Council, *Plasma Physics of the Local Cosmos*, The National Academies Press, Washington, DC, 2004.

Ohtani, S., Higuchi, T., Lui, A. T. Y., Takahashi, K., Magnetic fluctuations associated with tail current disruption: Fractal analysis. *J. Geophys. Res.*, *100*, 19,135, 1995.

Ohtani, S., Higuchi, T., Lui, A. T. Y., Takahashi, K., AMPTE/CCE-SCATHA simultaneous observations of substorm associated magnetic fluctuations. *J. Geophys. Res*., *103*, 4671, 1998.

Oieroset, M., T. D. Phan, M. Fujimoto, R. P. Lin, and R. P. Lepping, In situ detection of collisioless reconnection in the Earth’s magnetotail, *Nature*, *412*, 414, 2001.

Oieroset, M., R. P. Lin, T. D. Phan, D. E. Larson and S. D. Bale, Evidence for elctron acceleration up to ~300 keV in the magnetic reconnection diffusion region of Earth's magnetotail, *Phys. Rev. Lett., 89,* 195001, 2002 .

Parker, E. N., Magnetic reconnection and the lowest energy state, in *Magnetic Reconnection in Space and Laboratory Plasmas,* pp. 411-416, Terra Sci. Pub., Tokyo, 2001.

Parker, E. N., *Spontaneous Current sheets in Magnetic Fields,* Oxford Univ. Press., Oxford, 1994.

Phan, T. D., L. M. Kistler, B. Klecker, G. Haerendel, G. Paschmann, B. U. O. Sonnerup, W. Baumjohann, M. B. Bavassano-Cattano, C. W. Carlson, A. M. DiLellis, K. H. Fornacon, L. A. Frank, M. fujimoto, E. Geogescu, S. Kokubun, E. Moebius, T. Mukai, M. Oieroset, W. R. Paterson, and H. Reme, Extended magnetic reconnection at the Earth's magnetopause from detection of bi-directional jets, *Nature, 404*, 848, 2000.

Priest, E. R., Solar flare theory and the status of flare understanding, in *High Energy Solar Astrophysics – Anticipating HESSI*, eds. R. Ramaty and N. Mandzhavidze, ASP Conf. Ser. 206, pp. 13-26, Astron. Soc. Pacific, 2000.

Pritchard, D., Borovsky, J. E., Lemons, P. M., Price, C. P., Time dependence of substorm recurrence: An information theoretic analysis. *J. Geophys. Res*., *101*, 15,359, 1996.

Rostoker, G., Implications of the hydrodynamic analogue for the solar-terrestrial interaction and the mapping of high latitude convection pattern into the magnetotail, *Geophys. Res. Lett., 11*, 251, 1984,

Sergeev, V. A., Pulkkinen, T. I., Pellinen, R. J., Coupled mode scenario for the magnetospheric dynamics. *J. Geophys. Res*., *101*, 13,047, 1996.

Sergeev, V. A., A. Runov, W. Baumjohann, R. Nakamura, T. L. Zhang, M. Volwerk, A. balogh, H. reme, J. A. Sauvaud, M. Andre, and B. Klecker, Current sheet flapping motion and structure observed by Cluster, *Geophys. Res. Lett., 30,* 1327, doi:10.1029/2002GL016500, 2003.

Shao, X., M. I. Sitnov, A. S. Sharma, K. Papadopoulos, C. C. Goodrich, P. N. Guzdar, G. M. Milikh, M. J. Wiltberger, and J. G. Lyon, Phase transition-like behavior of magnetospheric substroms: Global MHD simulation results, *J. Geophys. Res*., *108(A1),* 1037, doi:10.1029/2001JA009237, 2003.

Sharma, A. S., Assessing the magnetosphere's nonlinear behavior: its dimension is low, its predictability, high. *Reviews of Geophysics (Suppl.)*, *35*, 645-650, 1995.

Sharma, A.S., Sitnov, M. I., and Papadopoulos, K., Substorms as nonequilibrium phase transitions, *J. Atmos. Sol. Terr. Phys., 63,* 1399, 2001.

Sharma, A.S., Vassiliadis, D. V., Papadopoulos, K., Reconstruction of low-dimensional magnetospheric dynamics by singular spectrum analysis. *Geophys. Res. Lett*., *20*, 335, 1993.

Sharma, A.S., Sitnov, M. I., Ukhorskiy, A. Y., and J. A. Valdivia, Modelling the magnetosphere from time series data, in *Disturbances in Geospace: The Storm-substorm Relationship, Geophysical monograph series, vol. 142*, edited by A. S. Sharma, Y. Kamide and G. S. Lakhina, Amer. Geophys. Union, pp. 231 – 241, 2003.

Shay., M. A., J. F. drake, B. N. Rogers and R. R. E., The scaling of magnetic reconnection for large systems, *Geophys. Res. Lett., 26*, 2163, 1999.

Sitnov, M. I., and A. S. Sharma, Role of Transient Electrons and Microinstabilities in the Tearing Instability of the Geomagnetic Current Sheet and the General Scenario of the Substorm as a Catastrophe, in *Substorms-4: Proc. 4th Internl. Conf. on Substorms*, edited by S. Kokubun and Y. Kamide, Terra Sci., Tokyo, pp. 539-542, 1998.

Sitnov, M. I., Sharma, A. S., Papadopoulos, K., Vassiliadis, D., Valdivia, J. A., Klimas, A. J., and Baker, D. N., Phase transition-like behavior of the magnetosphere during substorms. *J. Geophys. Res*., *105*, 12,955, 2000.

Sitnov, M. I., L. M. Zelenyi, H. V. Malova, and A. S. Sharma, Thin current sheetembedded within a thicker plasma sheet: Self-consistent kinetic theory, *J. Geophys. Res., 105*, 13,029, 200b.

Sharma, A. S., Papadopoulos, K., Vassiliadis, D., Valdivia, J. A., Klimas, A. J., and Baker, D. N., Phase transition-like behavior of the magnetosphere during substorms. *J. Geophys. Res*., *105*, 12,955, 2000b.

Sitnov, M. I., Sharma, A. S., Papadopoulos, K., Vassiliadis, D., Valdivia, J. A., Klimas, A. J., and Baker, D. N., Modeling substorm dynamics of the magnetosphere: From self-organization and self-organized criticality tononequilibrium phase transitions, *Phys.. Rev. E*., *65*, 016116, 2001.

Somov, B. V., *Cosmic Plasma Physics*, Kluwer Academic Pub., 2000.

Siscoe, G. L., The magnetosphere: A union of independent parts. *EOS, Trans. AGU*, *72*, 494-497, 1991.

Terasawa, T., and M. Scholer, The heliosphere as an astrophysical laboratory for particle acceleration, *Science, 244*, 1050, 1989.

Ukhorskiy, A. Y., M. I. Sitnov, A. S. Sharma and K. Papadopoulos 2004, Global and multiscale dynamics of the magnetosphere, *Geophys Res. Lett., 31*, L08802, doi:10.1029/2003GL018932, 2004.

Uritsky, V.M., A.J. Klimas, D. Vassiliadis, D. Chua, and G.D. Parks, Scale-free statistics of spatiotemporal auroral emissions as depicted by POLAR UVI images: The dynamic magnetosphere is an avalanching system, *J. Geophys. Res.*, *107* (A12), 1426, 2002.

Vassiliadis, D., Sharma, A. S., Eastman, T. E., Papadopoulos, K., 1990. Low-dimensional chaos in magnetospheric activity from AE time series. *Geophys. Res. Lett*., *17*, 1841.

Vondrak, R., J. Slavin, L. Zelenyi, M. Guhathakurta, S. Curtis and B. Tsurutani, Measurement strategies for future missions to understand geospace dynamics, in *Disturbances in Geospace: The Storm-substorm Relationship, Geophysical monograph series, vol. 142,* Eds. A. S. Sharma, Y. Kamide and G. S. Lakhina, Amer. Geophys. Union, pp. 255 – 268, 2003.

Zelenyi, L. M., D. C. delcourt, H. V. Malova, and A. S. Sharma, “Aging” of the magnetotail thin current sheet, *Geophys. Res. Lett., 29, (12),* 49-1, doi:10.1029/2001GL013789, 2002.