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Abstract Book

Influence of cold ions on magnetotail Hall physics

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The classical picture of magnetic reconnection is that it occurs as a two-scale process, one where ions are demagnetized and one where the electrons are demagnetized. However, plasma containing multiple ion populations, or species, can in some cases introduce additional length scales.

We investigate a partial plasma sheet crossing, observed on July 7, 2018. Initially, MMS observed a cold ion population originating in the lobes. As MMS crossed the separatrix of a reconnection exhaust, these cold ion were observed alongside hot plasma sheet ions.

Spacecraft motion determined using the Spatio-Temporal difference method indicate that MMS was within ~150 km (~0.2 di) from the center of the current sheet. At this point, the cold ions accounted for approximately 35% of the total ion density. Approximately 30% of the initial cold ion population had become sufficiently heated to no longer be magnetized. Using the generalized Ohm's law to estimate the Hall electric field showed that treating the ions as a single population lead to overestimating the Hall electric field by a factor ~1.8. The Hall electric field was mainly supported by a combination of $j \times B - v_c \times B$ and grad(P_e). The hot ions, while making up a majority of the total ion density, did not make a significant contribution to the Hall electric field.

Our results shows that the cold ions can reach a significant distance inside the plasma sheet and account for a significant portion of the total ion density. This indicates that they may play an important role in modifying the Hall physics of magnetic reconnection.

Cold ions at the magnetopause: Effects at various scales

Mats Andre

Statistics from the Cluster spacecraft show that low-energy ions with energies less than tens of eV originating from the ionosphere are common just inside the magnetopause. During magnetopause magnetic reconnection events, these low-energy ions remain magnetized down to smaller length-scales than the hot (keV) magnetospheric ions, introducing a new scale. When magnetized low-energy ions are present, the Hall currents carried by electrons can be partially cancelled by these ions. The electrons and the magnetized low-energy ions E×B drift together. We use MMS spacecraft observations of magnetic reconnection separatrices to verify that when a mixture of ions of very different temperatures is present in reconnecting plasmas, the Hall effect is significantly modified. In addition, at smaller scales, the relative drift between hot (unmagnetized) ions and cold (magnetized) ions can cause lower hybrid waves, heating the initially cold ions. However, some of the cold ion populations can remain at low temperature. At larger scales, jets of cold ions can be observed hundreds of ion inertial lengths from the reconnection X-line. We discuss recent observations and conclusions concerning the effects of cold ions at the magnetopause.

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MMS observations of kinetic entropy in the reconnection diffusion region

Matt Argall

We examine kinetic entropy during MMS encounters of the electron diffusion region at the magnetopause and in the magnetotail. Kinetic entropy density, computed via Boltzmann's H-function, is compared to the kinetic entropy of a Maxwellian distribution with the same density and temperature. A Maxwellian distribution is in equilibrium and possesses the maximum entropy for a given thermodynamic state. Deviations of the measured distribution from a Maxwellian indicate regions where energy dissipation and irreversible processes may be occurring. We find that kinetic entropy of the measured distribution differs from that of a Maxwellian distribution in the same regions where agyrotropy and energy dissipation parameters are large within the EDR.

Particle acceleration in dipolarization fronts

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The jet fronts of the outflow from reconnection sites in the magnetotail are characterized by sharp gradients of the magnetic field, which on the earthward side are called dipolarization fronts. These fronts are the site of significant particle acceleration, in addition to the reconnection site itself. An MHD simulation of tail reconnection and dipolarization is used as basis for particle tracing. We contrast characteristics of the resulting velocity distributions of electrons, protons, and heavy ions.

3D ion-scale dynamics of BBFs and their associated emissions in Earth's magnetotail using 3D hybrid simulations

H. Breuillard

Transient and localized jets of hot plasma, also known as Bursty Bulk Flows (BBFs), play a crucial role in Earth’s magnetotail dynamics because the energy input from the solar wind is partly dissipated in their vicinity, notably in their embedded dipolarization front (DF). This dissipation is in the form of strong low-frequency waves that can heat and accelerate energetic particles up to the high-latitude plasma sheet. The ion-scale dynamics of BBFs have been revealed by the Cluster and THEMIS multi-spacecraft missions. However, the dynamics of BBF propagation in the magnetotail are still under debate due to instrumental limitations and spacecraft separation distances, as well as simulation limitations. The NASA/MMS fleet, which features unprecedented high time resolution instruments and four spacecraft separated by kinetic-scale distances, has also shown recently that the DF normal dynamics and its associated emissions are below the ion gyroradius scale in this region. Large variations in the dawn-dusk direction were also observed. However, most of large-scale simulations are using the MHD approach and are assumed 2D in the XZ plane. Thus, in this study we take advantage of both multi-spacecraft observations by MMS and large-scale 3D hybrid simulations to investigate the 3D dynamics of BBFs and their associated emissions at ion-scale in Earth's magnetotail, and their impact on particle heating and acceleration.

Electron Scale Physics of Symmetric and Asymmetric Reconection from MMS

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The Magnetospheric Multiscale (MMS) mission has made comprehensive electron-scale measurements within a large number of reconnection diffusion regions at the dayside magnetopause, where reconnection is asymmetric, and in the geomagnetic tail, where it is symmetric. Examples of phenomena observed in both types of reconnection include electron crescent-shaped distributions, which result from acceleration by an electric-field component in the N direction of boundary-normal (LMN) coordinates and subsequent meandering motions as the electrons gyrate across a boundary separating magnetic fields with different directions. Only single crescents have been observed at the magnetopause while double and even triple crescents are observed in the tail. On the day side E_N accelerates magnetosheath electrons into the reconnecting layer, while in the tail E_N accelerates neutral-sheet electrons toward the lobes with the subsequent meandering motion resulting from their alternating motion between positive and negative B_L. On the day side energy conversion by reconnection occurs at the electron stagnation point and the X-line, but X-line conversion or dissipation is only significant for moderate to strong guide fields. This difference has been shown to result from two different channels for out-of-plane current—crescent distributions at the stagnation point and field-aligned flow along the guide field at the X-line. In the tail the X-line and the electron stagnation point are coincident, and the out-of-plane current is carried by crescent distributions throughout the diffusion region. Other regions of strong dissipation in the tail are located in the tailward and Earthward exhaust regions at the edges of the EDR. Strong wave activity occurs in both asymmetric and symmetric reconnection with lower-hybrid waves, electrostatic waves, whistlers, and upper hybrid waves commonly occuring in both geometries. Because of the lower values of density and magnetic field strength in the tail, the characteristic frequencies are much lower so that upper hybrid and Langmuir waves associated with electron crescent distributions are more often observable. These and other distinguishing characteristics of asymmetric and symmetric reconnection are explored in this paper.

Kinetic Entropy as a Diagnostic in Particle-in-Cell Simulations of Magnetic Reconnection

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ABSTRACT

Kinetic entropy is a vastly under-utilized diagnostic of kinetic plasma systems. We argue that kinetic entropy, commonly written as the phase space integral of $-f \ln f$, where f is the distribution function, is crucial: it is the natural metric of irreversible dissipation since it is conserved in ideal isolated systems and increases when there is dissipation. This suggests kinetic entropy can address important unsolved questions on the nature of irreversible dissipation in magnetic reconnection. In this work, we carry out an initial study to develop the diagnostic. We perform 2.5D collisionless particle-in-cell (PIC) simulations of anti-parallel reconnection. First, we calculate the traditional kinetic entropy and the full Boltzmann entropy related to the logarithm of the number of microstates. The latter is accurate for systems with any number of particles, and is also appealing because it can be broken up into complementary pieces for velocity space and configuration space. During reconnection, configuration space entropy decreases while velocity space entropy increases. We find that total entropy in the simulations is preserved quite well (better than one percent) and use the departure from exact conservation to quantify the effective numerical dissipation. Electrons and ions have slightly different effective collision frequencies. Finally, we use kinetic entropy to identify regions with non-Maxwellian distributions and compare the results with other approaches. Note, our work uses collisionless simulations, so we cannot yet address physical dissipation mechanisms; nonetheless, the infrastructure developed here will be useful for future studies in collisional systems. It should also be useful for plasma turbulence and collisionless shocks and is being applied to Magnetospheric Multiscale (MMS) data.

Substructure of an ion-scale flux rope observed in the magnetotail on 17 July 2017

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We report MMS observations of a magnetic flux rope in the magnetotail on 17 July 2017. The enhanced magnetic field strength and an increase of the total pressure at the center of the B_z reversal indicate that the transient structure is the magnetic flux rope. Four-spacecraft timing analyses suggest that the scale size of the flux rope is on the order of an ion inertial length. This ion-scale flux rope features frozen-in electrons but non-frozen-in ions. The pressure force dominates the magnetic curvature in both leading and trailing sides of the flux rope. In the leading side, strong electron jets along the background magnetic field lead to the current enhancement. In particular, we find an electron-scale layer inside the leading edge where the electric field peaks and Joule dissipation and electron heating occur. This event indicates that the ion-scale flux rope has an electron-scale substructure where the energy conversion mainly takes place.

Diffusion region's structure at the subsolar magnetopause using MMS data

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Magnetic reconnection is the only process in a plasma able to rearrange the global magnetic field topology eventually leading to a strong conversion from magnetic energy to acceleration of particles, to "heating". To allow for magnetic field reconfiguration, both ions and electrons must be demagnetized. The demagnetization process takes place in the ion and electron diffusion regions respectively, in both cases at kinetic scales. For the first time, MMS spacecraft observations at inter-spacecraft separation $\sim 10\ km$ (corresponding to $\sim 5\ d_e$ at the magnetopause) allow to make multi-point studies of the electron diffusion region (EDR). Here we present MMS observations of a magnetopause crossing close to the subsolar point showing signatures consistent with an EDR encounter nearby a magnetic field minimum. The proximity to the reconnection site is further substantiated by the results obtained using the First Order Taylor Expansion (FOTE) method applied to the magnetic field data. Observations suggest that all spacecraft passed through the EDR. Despite of the small inter-spacecraft separation (7 km), the observations show important differences among spacecraft. The most striking differences are observed in magnetic field, electric field, current density and dissipation parameter $E' \cdot J$. Furthermore, all satellites observe crescent-shaped electron distribution functions on the magnetospheric side of the boundary but these distribution functions are observed for intervals with different durations on each spacecraft. The dissipated energy $E' \cdot J$ is also different among spacecraft and two satellites measure negative values of $E' \cdot J$. These observation suggest that $E' \cdot J$ is patchy over electron kinetic scales in the EDR. These differences between observations by the four MMS spacecraft indicate that the EDR is rather structured over scales of a few electron inertial lengths and that it may be a turbulent region.

Determining the velocity of a magnetic structure, with application to the 11 July 2017 magnetotail reconnection event

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A crucial part of the process of understanding magnetic reconnection is determining the velocity of the structure relative to the spacecraft because this velocity must be subtracted from the plasma velocity in order to determine the flows into or out of the reconnection X point. Here we examine the Shi et al. (2006) method to get the structure velocity from multi-spacecraft magnetic field data. We explain the problem of singularities that occurs when the spatial gradient is small in a particular direction and make suggestions about how to deal with this problem. We discuss different approaches to solving for the velocity and apply the methods to examine the velocity for a magnetotail magnetic reconnection event observed on 11 July 2017.

Multiple plasma wave modes in the magnetotail separatrix region on 17 July 2017

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We present MMS observations of magnetotail reconnection accompanied by a magnetotail flapping on 17 July 2017. Before MMS passed by near X-line region, the four spacecraft are located in the exhaust region tailward of the X-line, observing a flapping motion of the magnetotail. The flapping led MMS to cross the northern- and southern-side separatrix regions, repeatedly. At the seperatrix, multiple waves modes are observed simultaneously: lower-hybrid waves (LHW), electron cyclotron waves (ECW), Langmuir waves (LW), and broadband electrostatic waves (ESW). Corresponding to the high-frequency modes, the electron distribution function displays a parallel crescent shape with a certain level of agyrotopy. In this paper, we focus on the correlation between these multiple wave modes and the deformed electron distribution functions observed in the magnetotail separatrix region.

PIC simulation study of nonlinear upper-hybrid waves near EDR

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Recently, MMS spacecraft observed upper-hybrid (UH) wave activities near the electron diffusion region (EDR) of dayside asymmetric reconnection. Agyrotropic electron beam and/or crescent distributions are found together and analysis of linear instability shows that agyrotropic electrons are free energy sources of UH waves. Because observed UH waves are very intense, it is believed that nonlinear phenomena, such as wave-particle and wave-wave interactions, can play important roles in EDR dynamics.

We investigate nonlinear evolutions of UH wave activities using 2-D electromagnetic particle-in-cell (PIC) simulation. Our simulation shows that the nonlinear beam-plasma interaction by the agyrotropic beam leads fundamental and second harmonic of electrostatic UH modes and radio emissions. Simulation results are well explained by the sequential processes of wave-wave interactions, which account the electromagnetic radiation of the solar type-II and type-III radio burst. The electromagnetic decay of the fundamental UH mode generates the fundamental radio emission, while the electrostatic decay generates the backscattered mode propagating backward direction to the beam. The coalescence of the fundamental UH mode and the backscattered mode leads 2^{nd} harmonics radio emission.

A 3D Simulation of a MMS Magnetopause Reconnection Event with a strong guide field

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An important goal of the MMS mission is to understand the role that turbulence plays in the development of reconnection. The observations have revealed surprisingly strong turbulence during magnetopause reconnection events, including intense, localized parallel electric fields, especially on the magnetospheric side of the x-line and along the magnetospheric separatrix. 3D PIC simulations of the October 16, 2015, event suggest that a long-wavelength variant of the lower-hybrid-drift instability (LHDI) is the dominant driver of the measured turbulence and that this turbulence both limits the width of the reconnection-driven current layer at the x-line and contributes to breaking the frozen-in condition. An important question is whether such turbulence persists when the magnetic fields are no longer anti-parallel. Magnetic shear might stabilize the drift-type turbulence, leading to a more laminar reconnecting system. We have carried out 3D simulations of the December 8, 2015, reconnection event in which the reconnecting and ambient guide fields are comparable. A surprise is that the resulting LHDI turbulence remains strong along the magnetospheric separatrix but not close to the x-line. The key physics is that the magnetic shear across the separatrix is weak while the ambient density gradient is strong. The environment is therefore favorable for the development of the LHDI even when the ambient guide field is strong. This turbulence controls the local density gradient. A greater surprise is the development of a filamentation instability at the x-line. This produces a highly localized anomalous viscosity but no turbulent induced drag. The turbulence that develops in this configuration and its impact on reconnection and associated energy dissipation will be contrasted with that of the October 16 event.

Guide field reconnection: exhaust structure and heating

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Abstract

Solar wind reconnection exhausts are a potentially important site for heliospheric plasma heating and particle acceleration. The majority of in situ encounters have been made near the Earth, where observations show that there is considerable variability in exhaust properties. However, most measurements have been made with relatively low-cadence plasma measurements, and the fine-scale structure required to understand the physics controlling heating and acceleration is not resolved. Novel Magnetospheric Multiscale (MMS) high-time resolution measurements now provide the opportunity for further progress; although MMS has mainly focused on magnetopause and magnetotail reconnection, it has also encountered examples of reconnecting solar wind current sheets.

Here we present the results of a new case study using MMS data to probe the structure and temperature profile of a guide field reconnection exhaust observed ~100 ion inertial lengths downstream from the X-line in the Earth's magnetosheath. A density cavity, confined near one edge of the exhaust and containing electron flow toward the X-line, was detected, together with asymmetric Hall electric and magnetic field signatures. Within the cavity, electron cooling and enhanced parallel ion heating were observed. Electron holes were detected both on the cavity edge and at the Hall magnetic field reversal. We discuss the relationship between the observed heating, structure and guide field, as well as implications for the use of simple empirical scaling laws to describe reconnection heating.

The kinetic structure of the electron diffusion region observed by MMS during asymmetric reconnection.

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In situ observation by NASA's Magnetospheric Multiscale (MMS) spacecraft mission has prompted renewed interest in the properties of asymmetric reconnection at the Earth's dayside magnetopause [1]. Supported by a kinetic simulation, we derive an exclusion energy parameter, providing a lower kinetic energy bound for an electron to cross from one inflow region to the other during magnetic reconnection. As by a Maxwell demon, only high-energy electrons are permitted to cross the inner reconnection region, setting the electron distribution function observed along the low-density side separatrix during asymmetric reconnection [2]. The analytic model accounts for the two distinct flavors of crescent-shaped electron distributions observed by spacecraft in a thin boundary layer along the low-density separatrix [1]. In addition, the fully kinetic simulation reveals the presence of magnetic-field-aligned beams of electrons flowing toward the topological magnetic x-line. Within the ~$6d_e$ electron diffusion region, the beams become oblique to the local magnetic field, providing a unique signature of the electron-diffusion region where the electron frozen-in law is broken. These numerical and theoretical predictions are also confirmed through detailed analysis of the electron distribution functions recorded by MMS [3].

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Electron energization at a reconnecting magnetosheath current sheet

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We present observations of electron energization within a sub-ion scale thin magnetosheath current sheet (CS). A number of signatures indicate ongoing reconnection, including the thickness of the CS (~ 0.7 ion inertial length), non-zero normal magnetic field, Hall magnetic fields with electrons carrying the Hall currents, and electron heating. We observe localized electron acceleration and heating parallel to the magnetic field within the separatrix regions. Electrostatic waves observed in these regions have low phase velocity and small wave potentials, and thus cannot provide the observed acceleration and heating. Instead, we find that the electrons are accelerated by a parallel acceleration potential, similarly to what has been earlier observed at the magnetopause and magnetotail. Thus, a similar electron acceleration mechanism and corresponding heating is operating under very different plasma conditions.

Title: MMS Observations of Magnetic Reconnection Exhausts in the Solar Wind Associated with Tripolar Perturbations of the Out-of-Plane Magnetic Field

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Abstract: MMS have sampled a large number of solar wind current sheets in burst mode since the 15 Nov 2017 implementation of a new solar wind energy table by the FPI instrument. This presentation will focus on reconnection exhaust signatures across solar wind current sheets with an emphasis on the out-of-plane (B_M) magnetic field. We present WIND and MMS satellite observations of bipolar B_M perturbations across individual solar wind exhausts consistent with our understanding of Hall magnetic fields. We also present WIND and MMS observations of a lesser-known tripolar B_M perturbation signature across solar wind exhausts. The tripolar perturbation typically consists of a guide-field enhancement in the exhaust and guide-field depressions at each exhaust boundary. We propose a scenario, supported by particle-in-cell simulations, whereby each B_M guide-field depression is due to a pair of oppositely directed J_L currents. The outermost J_L current forms adjacent to an expanding region of two coalescing magnetic islands. For the first time, MMS can now confirm the in-plane J_L current structure of tripolar B_M perturbations based on the curlometer technique.

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Cluster MMS conjunctions tail 2018 and Cluster constellation 2019

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Cluster-MMS conjunctions in summer 2018 and the planned configuration of Cluster for 2019 are presented.There are six intervals when separation between C4 and MMS1 are less than 4 Re. between July and October 2018 and when both spacecraft are in the nominal plasmasheet location. Cluster is planned to be put on burst mode during these intervals.Unprecedented multi-scale multipoint observations are expected to be realized during these intervals. The planned 2019 configuration of Cluster enable to study magnetosheath structure with a local solar wind monitor and to measure both hemispheric lobes and plasmasheet simultaneously.

Four-spacecraft measurements of the size and dimensionality of magnetic structures

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In space physics, much interest has been devoted to the identification of three-dimensional structures through the confrontation of models with characteristic in situ signatures observed in 1-D time series from satellite data. Only recently such studies have benefitted from the advent of multi-spacecraft missions such as Cluster, THEMIS, MMS. Here we present a large-scale analysis of structures as observed by MMS in various near-Earth regions using a multi-spacraft method called MRA (Magnetic Rotational Analysis). This method, developed by Shen et al. (2007), was previously applied to Cluster measurements of neutral sheet and flux ropes crossings in the magnetotail. It is applied here on MMS data, allowing for the determination of the local size and dimensionality of structures at much higher cadence and much smaller spacecraft separation, thereby allowing a much better resolution and accuracy in resolving plasma structures. Our analysis permits to obtain a global overview of plasma structures in different near-Earth environments. We provide a classification of the type of structures observed and illustrate them through case studies. This tool allows us to see the magnetospheric environment and the nature of near-Earth plasmas from a new perspective.

How accurately can we measure the reconnection rate E_M for the MMS diffusion region event of 2017-07-11?

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We investigate the accuracy with which the reconnection electric field E_M can be determined from in-situ plasma data. We focus on the magnetotail electron diffusion region observed by NASA's Magnetospheric Multiscale (MMS) on 2017-07-11 at 22:34 UT. Specifically, we characterize the often very large errors in E_M that can result from the mis-determination of an LMN boundary-normal coordinate system. We have found 14 LMN coordinate systems for this MMS event using a number of different methods. We use these M axes to determine 14 estimates of the reconnection rate. Though the spread in E_M is large, there is some consensus that the reconnection rate is roughly 2.5< E_M<4 mV/m, which corresponds to a normalized reconnection rate of 0.14<R<0.22. We find that minimum variance analysis of the electron velocity (MVA-v_e), MVA of the electric field, minimization of Faraday residue, a calibrated version of the maximum directional derivative of the magnetic field (MDD-B) technique all produce reasonably similar coordinate axes for this event. We use virtual MMS data from a particle-in-cell simulation of this event to estimate the errors in the coordinate axes and reconnection rate associated with MVA-v_e and MDD-B. MVA-v_e is a more reliable method for finding the L and M directions when the spacecraft is near the neutral sheet and observed a clear (electron jet reversal) maximum variance direction. The calibrated MDD-B technique is reasonably reliable throughout the EDR, but less reliable for determining the invariant M direction than MVA-v_e. When the magnetic field data has errors as small as 0.5% of the background field strength, the M direction obtained by MDD-B technique may be off by as much as 35 degrees. The normal direction, however, is most accurately obtained by MDD-B. Overall, we found that these techniques were not able to identify E_M from the virtual data with error bars of less than ~20%. Large errors in the reconnection rate were observed when the measured M axis had a finite projection onto the boundary normal.

MULITBEAM ENERGY TRANSPORT

M. GOLDMAN, J. EASTWOOD, D. NEWMAN, G. LAPENTA, S. SCHWARTZ

Velocity moments of particle distributions, f($\mathbf{v}$), have been a useful level-2 product in MMS reconnection studies of electron and ion energy transport. However, moment algorithms currently in use extract only *one* velocity (flow) moment, $\mathbf{u}_0 = \int d^3\mathbf{v}f(\mathbf{v})\mathbf{v}$, for a given FPI-measured f($\mathbf{v}$), even though recently found distributions appear to consist of multiple "beams," $f_j(\mathbf{v})$, adding up to $f(\mathbf{v}) = f_1(\mathbf{v}) + f_2(\mathbf{v}) + ... + f_N(\mathbf{v})$, and each with its own flow velocity, $\mathbf{u}_j$. Moment algorithms currently in use yield *higher order moments* based on the same assumption of a single "beam" with flow velocity, $\mathbf{u}_0$. These include *co–herent moments,* such as the bulk energy density, $U_{bulk} = n_0 m u_0^2/2$, and the energy flux, $\mathbf{Q}_{bulk} = n_0\mathbf{u}_0\, m u_0^2/2$ and *incoherent moments*, such as the thermal energy density, U_{th}, the enthalpy flux, $\mathbf{Q}_{enthalpy}$ and the heat flux, $\mathbf{Q}_{heat}$. We use analytic kinetic theory and numerical studies of FPI-measured multibeam velocity distributions to elucidate *three features of multibeam transport:*

1. Energy and flux moments which are *equally meaningful and useful* for single beam or multibeam distibutions are $U = \int d^3\mathbf{v}f(\mathbf{v})mv^2/2$ and $\mathbf{Q} = \int d^3\mathbf{v}f(\mathbf{v})\mathbf{v}mv^2/2$. These moments are not usually calculated from FPI distributions.
2. In the familiar single beam treatment one substitutes $\mathbf{v} = \mathbf{u}_0 + \delta\mathbf{v}_0$ to recover the *usual* coherent and incoherent parts: $U = U_{bulk} + U_{th}$ and $\mathbf{Q} = \mathbf{Q}_{bulk} + (\mathbf{Q}_{enthalpy} + \mathbf{Q}_{heat})$.
3. For a *multibeam* velocity distribution it is better to substitute $\mathbf{v} = \mathbf{u}_j + \delta\mathbf{v}_j$ into each beam contribution to f($\mathbf{v}$). Once again U and $\mathbf{Q}$ each decompose into a sum of coherent and incoherent parts but the relative sizes of the two parts are different and arguably more physical.

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The role of lower hybrid waves in magnetic reconnection

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Magnetic reconnection is a fundamental plasma process, which transforms magnetic field energy into particle energy by changing the magnetic field topology. At the magnetopause, lower hybrid waves are one of the most intense waves associated with magnetic reconnection. Lower hybrid waves can lead to anomalous effects, particle diffusion, and heating of the plasma, which can affect magnetic reconnection. We investigate the anomalous effects, including anomalous resistivity and transport, generated by lower hybrid waves using the Magnetospheric Multiscale (MMS) spacecraft. Using high-resolution fields and particle measurements from MMS we estimate the anomalous resistivity and particle diffusion directly from observations. We show that the anomalous fields generated by lower hybrid waves do not contribute to the reconnection electric field. However, the lower hybrid waves generate cross-field electron diffusion, resulting in mixing between magnetospheric and magnetosheath, broadening of the current layer, and reducing the electron pressure divergence.

Large-amplitude high-frequency waves at Earth's magnetopause

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Large-amplitude waves near the electron plasma frequency are found by the Magnetospheric Multiscale (MMS) mission near Earth's magnetopause. The waves are identified as Langmuir and upper hybrid (UH) waves, with wave vectors either close to parallel or close to perpendicular to the background magnetic field. The waves are found all along the magnetopause equatorial plane, including both flanks and close to the subsolar point. The waves reach very large amplitudes, up to 1 V/m, and are thus amongst the most intense electric fields observed at Earth's magnetopause. In the magnetosphere and on the magnetospheric side of the magnetopause the waves are predominantly upper hybrid (UH) waves although Langmuir waves are also found. When the plasma is very weakly magnetized only Langmuir waves are likely to be found. Both Langmuir and UH waves are shown to have electromagnetic components, which are consistent with predictions from kinetic wave theory. These results show that the magnetopause and magnetosphere are often unstable to intense wave activity near the electron plasma frequency. These waves provide a possible source of radio emission at the magnetopause.

Reconstruction of the magnetotail reconnection region seen by MMS on 11 July 2017

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We show results from the reconstruction of the electron diffusion region of magnetotail reconnection detected by the Magnetospheric Multiscale (MMS) spacecraft at 22:34 UT on 11 July 2017. In the event the conditions were suited for the reconstruction method (Sonnerup et al., JGR, 2016) that is based on a two-dimensional form of electron magnetohydrodynamic equation and assumes an approximately symmetric current sheet and negligible guide magnetic field. Our reconstruction results indicate that although the X point was not captured inside the MMS tetrahedron, MMS approached the X point as close as one electron inertial length of order 10 km. The stagnation point of electron flow was shifted toward the earthward side of the X point. Although the estimated non-dimensional reconnection rate is high (0.19), the corresponding electric field is modest (of order 1 mV/m), suggesting the possibility that the observed reconnection has not reached the exterior lobe field. We also present a new single-spacecraft method based on Ampere's law to estimate the orientation of two-dimensional, steady magnetic field structures using direct measurements of the magnetic field and electric current.

Sonnerup, B. U. Ö., H. Hasegawa, R. E. Denton, and T. K. M. Nakamura, Reconstruction of the electron diffusion region, J. Geophys. Res. Space Physics, 121, 4279-4290, doi:10.1002/2016JA022430, 2016.

The role of separatrix instabilities in heating the outflow region

Michael Hesse, Cecilia Norgren, Paul Tenfjord, Jim Burch, Yi-Hsin Liu, Li-Jen Chen, Naoki Bessho, Shan Wang, and Roy Torbert

It is generally agreed that the reconnection diffusion region plays a critical role in regulating and mediating the reconnection process. However, do to its size, it is unlikely to play a major role in the energy conversion from magnetic to particles on the large scale. While in MHD models this role is taken by slow shocks or variants thereof, we know that these structures do not exist at all, or are strongly modified, in kinetic plasmas. There have to be other processes assuming a similar role to facilitate the heating needed for force balance between the out- and inflow regions. In this presentation we discuss one such mechanism – a shear flow-driven electron-electron mode, around the outflow separatrix. We will show that the collective effect of this instability is indeed to provide substantial electron heating by a quasi-viscous process.

Observations of a small-scale flux rope-like structure next to an EDR at the dayside magnetopause

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We present results of a dayside magnetopause reconnection event when MMS passes through an electron diffusion region (EDR) close to the equatorial plane. Within the EDR MMS observes agyrotropic crescent shaped electron velocity distribution functions. Right after passing the EDR, all the MMS spacecraft encounter a structure that has bipolar magnetic field in the direction normal to the magnetopause current sheet. Inside the structure three of the spacecraft observe increase in the B_M component and corresponding increase in the total magnetic field magnitude. These features suggest that the structure may be a small-scale flux rope forming next to an EDR. During this event the MMS spacecraft separation is ~8km, which is much smaller than the ion skin depth d_i ~ 40 km. This allows us to study the electron scale details of this structure, which has a diameter approximately one ion inertial length (~0.5-2 d_i) based on four-spacecraft timing analysis.

Interior structure of strong electron phase-space holes

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Electron phase-space holes are nonlinear plasma structures characterized by a unipolar trapping potential with a radial electric field. They commonly form via streaming instabilities and other turbulent processes in many plasma environments. Electron hole size is usually on the order of 10 λ_{De} parallel to the magnetic field, ranging from meter to kilometer scales in space plasmas. Perpendicular size has only been measured via multi-point measurements in a small number of cases (Pickett et al. 2008, Norgren et al. 2015), primarily limited by large spacecraft separations. The Magnetospheric MultiScale mission maintains a tetrahedron formation with spacecraft separations down to ≈ 7 km. In one particular event, MMS encountered a stream of phase-space holes correlated across all four spacecraft. By fitting a 3D model to the measured electric fields, we estimate the size and position of each electron hole with respect to the spacecraft formation. In several instances, an MMS spacecraft passes near the center of the structure, consistently finding an unexpected flattening of the perpendicular electric field signal. This is likely due to trapping or bunching of electrons via resonance between a combination of the gyro-frequency, electron-hole bounce frequency, and the position-dependent $\mathbf{v}\times\mathbf{B_0}$ drift frequency.

Magnetotail reconnection following a flapping motion of the magnetotail on 17 July 2017

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We report a magnetotail reconnection event observed by MMS on 17 July 2017. The event was preceded by multiple fluctuations of a magnetotail flapping indicated by repeated changes in the sign of the x component of the magnetic field. Significant outflow jets appeared immediately after an initial fluctuation of the flapping motion, indicating a possibility of its effect on regulating reconnection processes. During following periods of the tail flapping, MMS was located in the exhaust region tailward of an X-line. The flapping motion led MMS to traverse the northern and southern sides of the exhaust and separatrix region, repeatedly. Then, MMS passed by near the X-line from tailward to earthward, observing strong electron jets along the negative y direction, crescent distribution functions, and dissipative signatures. Using this unique event observed by MMS, we investigate 1) effects of an MHD-scale fluctuation on magnetotail reconnection, 2) sub-layers of the exhaust region, as indicated by particle distribution functions and different wave modes, along the normal direction of the current sheet, and 3) the electron diffusion region of reconnection with a small guide field.

FTE generated in the velocity shear layer of Kelvin-Helmholtz vortices

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We present two new generation mechanisms for flux transfer events (FTEs) observed in (a) the reconnection outflow region and (b) the velocity shear layer associated with Kelvin-Helmholtz vortices, during magnetopause crossings. In the two cases, the four MMS spacecraft detected isolated regions with the enhanced magnetic field and bipolar B_n that indicate FTEs. In the first event, observed on the duskside, FTEs were initially embedded within the exhaust region northward of an X-line, but were located southward/downstream of a subsequent X-line. The presence of an X-line in the exhaust region southward of the second X-line results from the southward drift of the initial X-line and the formation of a new X-line northward of the spacecraft. The north-south-elongated current layer between the two X-lines is unstable to the tearing instability, generating multiple ion-scale flux-rope-type secondary islands. In the second case, detailed analyses of the field variations and plasma moments during the isolated dawnside event suggest that it developed along the Kelvin-Helmholtz wave boundary between two coalescing/compressing flow vortices. We use these two events to demonstrate a path to determination of parameters enabling us to distinguish between the different generation mechanisms and evolutionary phases of FTEs.

Shock Ripples Observed by the MMS spacecraft: Ion Reflection and Dispersive Properties

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Shock ripples are ion-inertial-scale waves propagating within the front region of magnetized quasi-perpendicular collisionless shocks. The ripples are thought to influence particle dynamics and acceleration at shocks. With the four Magnetospheric Multiscale (MMS) spacecraft, it is for the first time possible to fully resolve the small scale ripples in space. We use observations of one slow crossing of the Earth's non-stationary bow shock by MMS. From multi-spacecraft measurements we show that the non-stationarity is due to ripples propagating along the shock surface. We find that the ripples are near linearly polarized waves propagating in the coplanarity plane with a phase speed equal to the local Alfvén speed and have a wavelength close to 5 times the upstream ion inertial length. The dispersive properties of the ripples resemble those of Alfvén ion cyclotron waves in linear theory. Taking advantage of the slow crossing by the four MMS spacecraft, we map the shock-reflected ions as a function of ripple phase and distance from the shock. We find that ions are preferentially reflected in regions of the wave with magnetic field higher than the overshoot average while in the regions of lower magnetic field, ions penetrate the shock to the downstream region.

Poloidal and Toroidal Mode Field Line Resonances Observed by MMS

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Field line resonances (FLRs) are magnetosphere's responses to solar wind forcing and internal instabilities generated by solar wind-magnetospheric interactions. They are standing waves along the Earth's magnetic field lines oscillating in either poloidal or toroidal modes. The two types of waves have their unique frequency characteristics. The eigenfrequency of FLRs is determined by the length of the field line and the plasma density, and thus gradually changes with L. For toroidal mode oscillations with magnetic field perturbations in the azimuthal direction, ideal MHD predicts that each field line oscillates independently with its own eigenfrequency. For poloidal mode waves with field lines oscillating radially, their frequency cannot change with L easily as L shells need to oscillate in sync to avoid efficient damping due to phase mixing. Observations, mainly during quiet times, indeed show that poloidal mode waves often exhibit nearly constant frequency across L shells. Our recent observations, on the other hand, reveal a clear L-dependent frequency trend for a long lasting storm-time poloidal wave event, indicating the wave can maintain its power with changing frequencies for an extended period. The spatial variation of the frequency shows discrete spatial structures. The frequency remains constant within each discrete structure that spans about 1 RE along L, and changes discretely. In the follow-up study, we examine poloidal and toroidal waves using multipoint observations from MMS, in particular the FLRs with both poloidal and toroidal components. We compare their frequency and occurrence characteristics for insights into their generation mechanisms.

Analysis of kinetic structures embedded in a fast earthward flow during a substorm event

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In July 2017, the MMS constellation was evolving in the magnetotail with an apogee of 25 Earth radii and an average inter-satellite distance of 10 km (i.e. at electron scales). On 23rd of July around 16:19 UT, MMS was located at the edge of the current sheet which was in a quasi-static state. Then, MMS suddenly entered in the central plasma sheet due to the local onset of a small substorm as indicated by the AE index (~400 nT). Fast earthward plasma flows were measured during about 1 hour starting with a period of quasi-steady flow and followed by a saw-tooth like series of plasma jets ("bursty bulk flows"). In the present study, we analyze a short sequence of successive kinetic structures embedded in the quasi-steady flow such as an ion scale current sheet, an ion-scale flux rope and an electron vortex magnetic hole and discuss how and with which physical processes they could be interlinked.

Abstract for 2018 MMS Bergen workshop

Electron Bernstein Waves driven by electron crescents near the electron diffusion region

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Abstract

Magnetic reconnection is a fundamental and universal process to transfer energy stored in the magnetic field to kinetic energy of charged particles. Magnetic reconnection powers eruptive processes in space and laboratory plasmas. Earth's magnetosphere provides an unique environment to study magnetic reconnection by analyzing in-situ spacecraft measurements. NASA's Magnetospheric Multiscale (MMS) spacecraft aim to investigate the electron diffusion region (EDR), which is the core region of magnetic reconnection where the magnetic field lines break and reconnect. MMS encounter an EDR of asymmetric magnetic reconnection at Earth's magnetopause on December 24th, 2016. The EDR is characterized by agyrotropic electron velocity distributions on both sides of the neutral line. Large-amplitude electron Bernstein waves (EBWs) are found at the electron-scale boundary of the Hall current reversal. The EBWs are driven by the agyrotropic crescent-shaped distributions. The amplitude of the EBWs is sufficiently large to thermalize and diffuse electrons around the EDR. The EBWs may scatter electrons back to central diffusion region. They may contribute to the cross-field diffusion of the electron-scale boundary from electron diffusion region to ion diffusion region.

Orientation and stability of asymmetric magnetic reconnection x-line
Yi-Hsin Liu

Abstract: The orientation and stability of the reconnection x-line in asymmetric geometry is studied using three-dimensional (3D) particle-in-cell simulations. We initiate reconnection at the center of a large simulation domain to minimize the boundary effect. The resulting x-line has sufficient freedom to develop along an optimal orientation, and it remains laminar. Companion 2D simulations indicate that this x-line orientation maximizes the reconnection rate. The divergence of the non-gyrotropic pressure tensor breaks the frozen-in condition, consistent with its 2D counterpart. We then design 3D simulations with one dimension being short to fix the x-line orientation, but long enough to allow the growth of the fastest growing oblique tearing modes. This numerical experiment suggests that reconnection tends to radiate secondary oblique tearing modes if it is externally (globally) forced to proceed along an orientation not favored by the local physics. The development of oblique structure easily leads to turbulence inside small periodic systems.

Current sheet structure and evolution of 20170711 EDR event

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Using four-point magnetic field data we examined the changes of the current sheet structure along the MMS orbit during 2017 07/11 Electron Diffusion Region (EDR) to determine the MMS location relative to the X-line, moving tailward. This orbit information is used to deduce the spatial gradient of the normal component of the magnetic field relative to the current sheet and the electron jet profile and to estimate the possible reconnection electric field due to non-gyrotropic pressure. It is shown that the observation is consistent with the theoretical expectation of 2D reconnection in the vicinity of the X-line. The magnetic field gradient scale length is comparable to the scale of the gyro-scale of the thermal electrons. Such a picture of a steady quasi-2D reconnection region moving tailward was, however, visible only for about 1.5 s due to transient signatures such as an Earthward traveling front or outflow signatures, possibly produced by other X-lines. Hence the observed EDR region is likely to be one of multiple reconnection sites within the thin current sheet event.

Fully kinetic simulation of an EDR crossing event observed by MMS on 11 July 2017

Takuma Nakamura (IWF/OeAW)

We show results from a two-dimensional fully kinetic particle-in-cell (PIC) simulation to model an electron diffusion region (EDR) crossing event observed by the Magnetospheric Multiscale (MMS) mission in the magnetotail on 11 July 2017. The simulation was performed under realistic conditions inferred from the MMS observations around the EDR crossing interval. We compared the virtual observations in the simulation and the MMS observations in detail and found many quantitative consistencies, which confirms the adequacy of the simulation and various important signatures of steady reconnection seen in the simulation. Based on the consistencies, we also obtained reasonably reliable values of both the normalized reconnection rate R_0 and the unnormalized rate (the reconnection electric field, E_r) from the direct measurements near the EDR and the remote estimations at the separatrix using recently proposed remote sensing techniques of the rates. The obtained rates are R_0~0.15-0.2 and E_r~2-3 mV/m, indicating that fast reconnection with a normalized rate of the order R_0~0.1 really occurred during this MMS event. We also show results from an additional three-dimensional PIC simulation of this event. The simulation demonstrates a very weak effect from the three-dimensionality near the EDR and much stronger three-dimensional electric field fluctuations along the downstream separatrix. This further confirms the adequacy of using the two-dimensional simulation to compare with this EDR crossing event by MMS.

Electron acceleration and thermalisation at magnetotail separatrices

Cecilia Norgren (1), Michael Hesse (1,4), Yin Xu (2), Daniel Graham (3), Yuri Khotyaintsev (3), Joo Hwang (4), Jin Choi (4), Konrad Steinvall (3), Love Alm (3), Mats André (3), Paul Tenfjord (1), and the MMS team

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In this study we investigate the electron acceleration and beam formation occurring along the separatrices in the inflow region of magnetic reconnection. Initially cold electron populations are accelerated to energies corresponding to a substantial fraction of the electron thermal energy inside the exhaust. The accelerated populations are unstable to the formation of electrostatic waves with amplitudes large enough to help thermalize the beam.

Strongly driven magnetic reconnection with flux pileup at the interface of colliding jets at the magnetopause

M. Øieroset[1] et al.

Abstract

We report MMS observations of reconnection in a thin current sheet at the interface of colliding reconnection jets at Earth's magnetopause. The guide field of the interface current sheet was 3 times the reconnecting magnetic field and the inflow conditions were moderately asymmetric, with a factor of two difference in the inflow densities. The ion skin depth-scale width of the interface current sheet and the non-frozen-in ions indicate that MMS crossed the reconnection layer near the X-line, inside the ion diffusion region. The plasma and field profiles across the reconnection exhaust show combined effects of large guide field and asymmetric inflows. Pileup of the reconnecting component of the magnetic field in both inflow regions suggests that the asymptotic inflowing magnetic flux may have exceeded the reconnection rate. The field pileup led to enhanced available magnetic energy per particle, and resulted in large electron heating in the interface current sheet.

Properties of electron-scale structures at a dipolarization front

Dong-Xiao Pan[1,2], Yuri V. Khotyaintsev[1], Daniel B. Graham[1], Andris Vaivads[1], Xu-Zhi Zhou[2], Mats André[1], Per-Arne Lindqvist[3], Robert E. Ergun[4], Olivier Le Contel[5], Christopher T. Russell[6], Roy B. Torbert[7], Barbara Giles[8] and James L. Burch[9]

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We use the Magnetospheric Multiscale (MMS) mission to investigate the properties of electron-scale structures at a dipolarization front (DF). The four spacecraft are separated by electron scales and observe surprisingly large differences in plasma and field parameters within the DF. Due to the distorted DF layer, strong Hall electric field and electron pressure term have both M and N components. All these signatures are reproduced by a simple model of lower-hybrid type disturbance on DFs, which can be understood by ripple structures generated by lower hybrid drift instability (LHDI). Wave analysis for short-wavelength lower hybrid waves ($k\rho_e \simeq 1-3$) suggest those waves propagating to the flux pileup region. In addition, we find high-frequency (100-2000 Hz) electrostatic bursts which are related to lower frequency electric field intensification. The power spectra associated with these waves show evidence of ongoing turbulent cascade.

Dominic Payne
Poynting's Theorem During a Magnetotail EDR Encounter by MMS

Poynting's theorem is a statement of the conservation of energy in the field of electrodynamics. Each of the three terms in Poynting's theorem are evaluated and compared in multiple reference frames using high resolution MMS data from the EDR encounter on July 11th, 2017. These terms are also compared with Poynting flux and electron kinetic energy flux to identify three distinct regions of energy transfer between particles and fields in both the MMS data and a 2D PIC simulation. For this event, the terms in Poynting's theorem do not balance perfectly, but the imbalance between them is well below an order of magnitude.

Abstract – MMS Workshop

On the Occurrence of Magnetic Reconnection Along the Dawn and Dusk Magnetopause

S M Petrinec

Observations from the MMS mission are used to investigate in a statistical study the occurrence of quasi-steady magnetic reconnection along the dawn and dusk regions of the magnetopause. Parameters such as the orientation of the interplanetary magnetic field (IMF), the dipole tilt angle of the Earth, the local Alfven Mach number, and the local change in plasma beta between the magnetosheath and magnetosphere are all expected to play a role in the occurrence and stability of magnetic reconnection. It is also investigated whether the effect of magnetosheath variations (e.g., downstream of the quasi-parallel shock versus downstream of the quasi-perpendicular shock) also play a role in the observed occurrence of magnetopause reconnection along the dawn and dusk magnetopause.

MMS Observations of Electron Magnetic Reconnection without Ion Coupling in the Turbulent Magnetosheath

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In the standard model of magnetic reconnection, the process occurs in a minuscule electron-scale diffusion region. On larger scales, the ions couple to the newly-reconnected field lines and are ejected away from the diffusion region in the form of bi-directional ion jets at the ion Alfvén speed. Much of the magnetic energy is converted into ion jetting and heating in spatially extended ion exhausts.

In turbulent plasmas, which contain a large number of small-scale current sheets, reconnection has long been suggested to play a major role in the dissipation of turbulent energy at kinetic scales. In this talk, I will describe MMS observations of reconnection which involves only electrons in the turbulent magnetosheath. These observations reveal a form of reconnection that can drive turbulent energy transfer and dissipation in electron-scale current sheets without ion coupling.

Energization and Movement of Electrons within an EDR with Emphasis on E_N

K. Pritchard

By using data from a unique dayside asymmetric reconnection event observed by MMS on 29 December 2016 during which all four spacecraft encountered an EDR in a sequential fashion, an in depth analysis of the acceleration of magnetosheath electrons through the X line, forming the crescent distributions is reported. The role of E_N is shown to initiate the initial path of electrons caught in an EDR with their following movement fully expressed by $E_N \times B_L = V_M$. The energy gain of observed crescents will also be analyzed and a model is proposed.

Using CCMC Modeling as Context for MMS Events

Patricia Reiff, Antoun Daou, James Webster, Andrew Marshall, Lutz Rastaetter

We use the unprecedented spatial and temporal cadence of the Magnetospheric Multiscale Mission to study three events (June 23, 2015; November 23, 2016, and July 11, 2017) and infer important physical properties of their respective magnetic reconnection processes. We couple these observations with numerical simulations using tools such as SWMF with RCM, and RECON-X, from the Coordinated Community Modeling Center, to provide, for a first time, a coherent temporal description of the magnetic reconnection process through tracing the coupling of IMF and closed Earth magnetic field lines, leading to the corresponding polar cap open field lines. We note that for the November dayside event, the reconnection geometry is far from slab-like: the IMF field lines drape over the magnetopause, lending to a stretching of the field lines. The stretched field lines become parallel to, and merge with the dayside separator. Surprisingly, the inner closed field lines also distort to become parallel to the separator. This parallel geometry allows a very sharp boundary between open and closed field lines, making creation of electron crescents quite easy. We also use CCMC to give context to dipolarization events in the magnetotail, including June 23, 2015 and July 11, 2017. In both cases, the model and the MMS data put the spacecraft very close to the nightside reconnection line and/or separatrix. This can lead to modeling of ionospheric outflow into the reconnection region.

The Case for Dust Comets Striking the Magnetosphere

C.T. Russell, H.R. Lai, Yi Qi, U.G. Schneck, and R.J. Strangeway*

*Presenter

The smaller rocky bodies orbiting the Sun exist in a destructive collisional environment that produces ever smaller particles, until those particles either spiral into the Sun or are carried outward by the solar wind. We have long detected magnetic structures in the solar wind that have a strong current sheet centered on a magnetic field maximum and attributed them to the coherent pickup of charged dust produced in collisions. The dimension along the solar wind varies from about 2×10^5 km to over 50×10^6 km. Assuming that the volume of these structures is proportional to R^3, the mass could therefore range over a factor of 15×10^6. A more conservative estimate in which the dust lay in a plane, not a sphere, would produce a range of 6×10^4. Matching observations versus the expected collision rate requires a knowledge of the acceleration time scale, since such structures should not be detected as magnetic pressure objects except when they are accelerating or decelerating. These structures are also seen in the magnetosheath by MMS. They have a very similar magnetic field enhancement, a central current sheet, and a structured plasma. Here they are decelerating as they encounter the pressure gradient of the magnetopause. The pressure generated in deceleration can be as large as a factor of five over the magnetosheath pressure and they are seen more often, as would be expected for a smaller (1-minute) structure. These “dust comets” are contributing to the magnetic turbulence in the solar wind and the buffeting of the magnetosphere.

Kinetic Aspects of a Hot Flow Anomaly: MMS Observations

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Abstract

Hot Flow Anomalies (HFAs) are a class of transient events observed at or upstream of collisionless shocks such as the terrestrial bow shock. They form from the interaction of the bow shock with an interplanetary current sheet convected by the solar wind. Although the primary interpretation relies on kinetic processes associated with the interruption of the return of reflected ions back to the bow shock, the short duration, strong heating and near-Maxwellian state have made direct observations of this process difficult. "Young" HFAs retain a distinct solar wind component, but in the past have been too brief to be resolved by particle instruments requiring several seconds to accumulate a full 4π distribution. We employ high resolution measurements by NASA's Magnetospheric Multiscale (MMS) mission to probe HFA microphysics. These observations reveal evidence for shock-reflected ions travelling along the current sheet, although these ions are not energetic enough to propagate farther upstream. Instead, these particles are swept up by the trailing HFA compression so that, despite the turbulent nature of the HFA interior, there are smooth density and pressure gradients across the entire HFA. The solar wind proton (and alpha) beam remains highly collimated and visible throughout the interior, but reduced in density well below what would be expected from 2D expansion transverse to the magnetic field. In the latter stages of the HFA, that beam is accompanied by denser coherent clumps of ions that form velocity space arcs around the anti-sunward direction.

MMS Community Workshop
11-14 June 2018, Bergen, Norway

Resolving Terms of the Vlasov Equation with MMS

Jason R. Shuster, Daniel Gershman, John Dorelli, Naoki Bessho,
Shan Wang, Li-Jen Chen, William Paterson, Barbara Giles, Adolfo Viñas

Abstract

The unprecedented spatiotemporal resolution of the sixty-four dual electron and ion spectrometers comprising the Fast Plasma Investigation (FPI) onboard the four Magnetospheric Multiscale (MMS) spacecraft enables us to compute terms of the Vlasov equation and thus compare MMS measurements directly to kinetic theory. Here we discuss our techniques for determining spatial and velocity-space gradients of the ion and electron distribution function from the skymaps provided by FPI. We present initial results validating and comparing the contributions from $\mathbf{v}\cdot\nabla f$ and $\mathbf{a}\cdot\nabla_v f$ for a variety of kinetic plasma contexts including both reconnection and non-reconnection events, such as electron diffusion regions (EDRs), magnetic holes, and thin electron-scale current sheets. Both the finite-gyroradius effect in a well-magnetized plasma near an electron-scale boundary [*Egedal et al.*, 2016] and the meandering orbits of unmagnetized particles accelerated in the EDR are known to produce crescent distributions [*Bessho et al.*, 2016]. The ability to resolve gradients of the distribution function motivates comparison of MMS observations to predictions from gyro-kinetic theory and particle-in-cell (PIC) simulations as an approach for determining which physical mechanism is responsible for generating the observed crescents.

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Status of MMS GI program
James Spann, Acting Chief Scientist, Heliophysics Division, NASA HQ

Abstract:
The status of the current MMS Guest Investigator Program will be presented.

MMS Observations of He+ pick-up ions at Earth's perpendicular bow shock

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Abstract:
Interstellar pick-up ions (PUI) are interstellar neutrals, which have been ionized in transit through the Heliosphere, via charge exchange or photoionization. These new PUI's then 'freeze' into the solar wind (SW) and move with the bulk SW velocity (V_{SW}). They also begin to gyrate around the local magnetic field with V_{SW}, resulting in a maximum PUI velocity of $2V_{SW}$. PUI's are thought to be suprathermal seed particles for higher energy particles such as anomalous cosmic rays via shock acceleration processes. Understanding the evolution of PUI distributions across shocks in space will thus provide valuable insight into shock dynamics and the source of high-energy ion populations. In this study we analyze the upstream and downstream velocity distributions of H^+ and He^+, at Earth's perpendicular bow shock, using MMS observations on Dec. 05, 2018. We derive average 2-D pitch angle distributions in the field aligned SW frame, as well as reduced 1-D velocity distributions, for selected upstream and downstream intervals. By comparing the upstream and downstream distributions, we find that the shock accelerates H^+ in both perpendicular and parallel directions (relative to the magnetic field) while He^+ is only accelerated in perpendicular direction. We also find acceleration of PUI He^+ beyond that due to adiabatic motion.

Title: Intense electric fields and electron-scale substructure within magnetotail flux ropes as revealed by the Magnetospheric Multiscale mission

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Abstract:
On 11 July 2017, the four Magnetospheric Multiscale (MMS) spacecraft encountered the electron diffusion region of a magnetic reconnection event in the near-Earth magnetotail. Three flux ropes associated with this reconnection event are analyzed and new electron-scale substructure within the flux ropes is discovered, enabled by the unique high-resolution measurements of MMS. The flux ropes are found to be Earthward propagating with sizes ranging from ~3-11 ion inertial lengths. Differing axial orientations are observed for the flux ropes, suggesting potential spatiotemporal variability in the magnetic reconnection or flux rope dynamics. Within one of the flux ropes, an electron-scale vortex is discovered, associated with a small-scale enhancement in the magnetic field (B) and one of the most intense electric fields (E) in the entire reconnection event. The electric field is outwardly directed from the vortex and ExB drifting electrons are found to carry the perpendicular current in the structure. The vortex is ~16 electron gyroradii in size perpendicular to the magnetic field and may be extended along the magnetic field. As the electrons are frozen-in to the magnetic field within the vortex, the vortical motion could drive parallel electric fields at the ends of the structure that may have implications for particle acceleration. The results reveal new questions about the electron-scale substructure of flux ropes.

Multi-Spacecraft Observations of Electron Holes

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Electron holes (EHs) play an important role in plasmas by providing a mechanism for phase space mixing and heating of the electrons. The strength of the electron-EH interaction is determined by the EH's potential and spatial extent. Accurate measurements of the EH velocity and its associated electric fields are required to calculate these quantities. In comparison to single-spacecraft methods, multi-spacecraft observations provide a much larger baseline which improves the accuracy of the velocity estimate, as well as providing information on the perpendicular extent of the EHs. We use multi-spacecraft observations by MMS to determine the velocity and consequently the potential and length scales of EHs near the magnetopause. Our preliminary results show that the observed EHs are weak, $e\Phi/k_BT_e \lesssim 1\%$, and have parallel length scales of around $2.5\lambda_D \leq l_\parallel \leq 5.5\lambda_D$ supporting previous results based on single-spacecraft methods. In most cases we find the perpendicular length scale to be much larger than the parallel length scale, but we are unable to provide an upper bound. However, for a few cases we find perpendicular length scales larger than the parallel length scale by a factor of around 4, corresponding to approximately $20\lambda_D$.

MMS observations of electron crescent distributions at the flank magnetopause

Binbin Tang, W. Y. Li, D. B. Graham, A. C. Rager, C. Wang + MMS team

Electron crescent distributions perpendicular to the magnetic field are important indicators of electron diffusion region in the magnetic reconnection, which can be formed by the finite gyro-radius effect at plasma/magnetic field boundaries and non-ideal electron behaviors. In this study, we present MMS observations of electron crescents at the flank magnetopause on 2017-09-20, where electrons are still roughly magnetized. These crescents are generated by the finite gyro-radius effect after electron curvature scattering around the magnetic minima, which are further confirmed quantitatively by the crescent opening angle with the help of 7.5 ms electron data. Upper hybrid waves accompanied with the electron crescents are observed by all MMS spacecraft, and they are excited by these agyrotropic electron distributions. This study suggests electron crescents can be more universally existed on the magnetopause, enabling mass and energy transfer.

Impact of oxygen on the reconnection rate

Paul Tenfjord, Michael Hesse, Cecilia Norgren

We investigate the role of a background oxygen population in magnetic reconnection, using Particle-In-Cell (PIC) simulation with time-dependent inflow. In three simulations, using three different temperatures, we insert oxygen at two distances from the current sheet, and study how it is captured by the reconnection process as time evolves. Our simulation setup is designed to mimic magnetotail conditions during enhanced geomagnetic activity which can lead to a significant oxygen concentration. We show that oxygen density striations form as a consequence of ballistic acceleration of oxygen by the Hall electric field. Horizontal density layers form as a consequence of pre-accelerated oxygen in the inflow reaching the Hall electric field. The evolution of the oxygen is dominated by electric forces, while the smaller contribution from the Lorentz force is large enough to trap the population in the potential well. We also show the formation of oxygen waves. This results from the spatio-temporal evolution of the Hall electric field; as the Hall fields expands to the regions where oxygen is available, the population is accelerated, resembling a wave-front leaving a wake of nearly zero density behind. We show that both the horizontal density layers, and the oxygen wave form for different initial oxygen temperatures.

In the second part we study the effect of oxygen on the reconnection rate. The energization of oxygen, as described above, should lead to a smaller energy reservoir available for the protons. We compare our oxygen simulations to a fourth simulation containing protons only. We show that the reconnection rate is significantly slower for the simulations containing oxygen. We present an energy analysis to quantify the amount of energy going into the oxygen population, and consequently unavailable for the protons.

Balance of the Ohm's law under the presence of cold ions of ionospheric origin in magnetic reconnection: PIC simulations and MMS observations

S. Toledo-Redondo, J. Dargent, N. Aunai, B. Lavraud, M. Andre, W. Li, B. Giles, P.-A. Lindqvist, R. Ergun, C. T. Russell and J. L. Burch

Magnetic reconnection is one of the primary coupling mechanisms between the shocked solar wind and the magnetosphere, enabling the exchange of mass and energy between them. Cold ions that escape from the ionosphere and plasmasphere often populate various regions of the magnetosphere, including the interface with the solar wind. When this occurs, they mass-load the magnetospheric side of the boundary and reduce the reconnection rate. In addition, cold ions introduce new microphysics effects owing to their small gyroradius that allow them to remain magnetized inside regions where the hot ring current ions are demagnetized. One of the reported effects concerns the reduction of the perpendicular currents associated to the Hall effect and the JxB/en term in the Ohm's law. In this work, we compare two full PIC simulations with and without cold ions to study the effect at large scales of the current reduction. We compare the Ohm's law terms that balance the Hall electric field along the magnetospheric separatrix region, and confirm the ubiquity of the current reduction owing to cold ion presence. Finally, we compare the simulations to MMS observations of the reconnecting magnetopause with different amounts of cold ions, to give further evidence of the current reduction.

Studying reconnection in Earth's magnetosphere using a global MHD with embedded PIC model

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We report our progress on developing and using our MHD-EPIC model. We have improved the algorithm of the iPIC3D model in several ways. We implemented the energy conserving semi-implicit method (ECSIM) (Lapenta 2016), which improved the numerical stability by ensuring the energy conservation and eliminated some of the numerical oscillations present in the original iPIC3D method. In addition, we improved the ECSIM algorithm to further reduce spurious oscillations and better satisfy Gauss' law. The MHD-EPIC coupling has been generalized to allow rotated PIC domains. Using these improved tools we modeled the southward IMF event on 2015-11-18, which was selected by the GEM dayside kinetic focus group as the challenge event. This event has been observed by MMS as well as by Geotail and the SuperDARN radar. Our simulations show reasonable agreement with the observed features. The 3D MHD-EPIC model allows studying the reconnection dynamics near the dayside magnetopause in detail. In particular, we looked into the formation and evolution of X lines. Most recently, we started investigating reconnection in the magnetotail with idealized solar wind and IMF drivers. We compare the ideal MHD, Hall MHD and MHD-EPIC simulation results and study the reconnection process in the magnetotail environment.

The transition between anti-parallel and component magnetic reconnection at the Earth's dayside magnetopause

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Magnetic reconnection at the Earth's magnetopause is discussed and has been observed at times as anti-parallel and as component reconnection. While anti-parallel reconnection occurs between magnetic field lines of (ideally) exactly opposite polarity, component reconnection (also known as the tilted X-line model) has classically predicted the location of the reconnection line to be anchored at the magnetopause standoff location, extending continuously along the dayside magnetopause. The ratio of the IMF By to Bz components determines the tilt of the X-line relative to the equatorial plane.
A reconnection location prediction model known as the Maximum Magnetic Shear Model combines these two scenarios. The connection points between the anti-parallel and the component reconnection lines are known as 'Knee' regions. Using a MMS data base of confirmed magnetopause X-line locations from Phase 1a of the mission, this study shows that the location of the Knee region depends strongly on the local draping conditions of the IMF across the magnetopause. From these locations, we conclude that magnetic reconnection at the Earth's dayside magnetopause preferentially occurs in the anti-parallel locations, and only occurs along component reconnection line segments when the draped IMF field lines no longer have contact to an anti-parallel reconnection region at the magnetopause.

Field-Aligned Currents as Observed by Magnetospheric Multiscale

R. J. Strangeway, C. T. Russell, C. Zhao, B. J. Anderson, J. M. Weygand, and W. R. Paterson.

Magnetospheric Multiscale has observed field-aligned currents (FACs) in the magnetotail with current densities of the order 10s of nA/m^2. These are at least an order of magnitude smaller than FACs observed at the dayside magnetopause. But, given the difference in magnetic field strength, the corresponding ionospheric current densities would be expected to be of the order of 100s of micro-Amps/m^2 for both the magnetotail and magnetopause related FACs. This is much larger than typical field-aligned currents as observed in the ionosphere. In addition, most of the current carriers (usually electrons) have pitch angles outside of the loss-cone, and are likely to be reflected before reaching the ionosphere. If that is the case, then the question becomes one of current diversion and what processes cause the current to be diverted. Large scale fluid models do not take into account individual particle motion, and resolution of this question may require the development of meso-scale kinetic models that take into account structure in the velocity space distribution.

The two-fluid dynamics and energetics of the asymmetric magnetic reconnection in space and laboratory plasmas

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Abstract

Both in space and laboratory plasmas, the physical mechanisms of conversion of magnetic energy to plasma particles is studied, in the context of two-fluid kinetic physics. Despite huge difference of the scale lengths of the reconnection layers of two ion skin depths [2di~10 cm in MRX, versus ~100 km in the magnetopause], remarkably similar characteristics are observed regarding the dynamics of electrons and ions as well as energy deposition profiles. In a strongly asymmetric reconnection layer in which one side of the inflow density is significantly larger ($\geq$10) than the other such as seen in he magnetopause. Both in MRX and in the magnetopause, it was found that without guide field, the energy deposition to electrons primarily occurs through $\mathbf{j}_e \cdot \mathbf{E}$ near the electron diffusion region as well as in the separatrix of the low density side (magnetosphere). A modified saddle-back-shaped large potential well is observed in the reconnection plane due to the dynamics (Lorenz force) of electron current in the layer and ions are accelerated at the exhaust region resulting in a strong ion heating. Furthermore this paper quantitatively studies the conversion and partitioning of the magnetic energy to plasma particles for asymmetric magnetic reconnection We find that more than 50% of magnetic energy is converted to ions and electrons almost in equal portion while a sizable amount of magnetic energy flows out to the exhaust region.