

Advances in Magnetic Reconnection with Magnetospheric Multiscale

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Magnetospheric Multiscale (MMS) has completed its exploration of magnetic reconnection at the Earth's dayside magnetopause. It has now begun the complementary exploration of reconnection in the magnetotail. At the dayside magnetopause MMS has demonstrated the central role played by electron kinetic-scale physics. Mixing of magnetosheath and magnetospheric electrons leads to non-gyrotropic distributions that produce the reconnection current and electric field. Dissipation caused by these phenomena ($\mathbf{J} \cdot \mathbf{E} > 0$) absorbs magnetic energy causing build-up of heat and particle kinetic energy mainly through wave-particle interactions. Reconnection was also observed to occur within Kelvin-Helmholtz vortices and within flux-transfer events. Numerous bow-shock crossings have revealed electron acceleration by whistler waves and localized $\mathbf{J} \cdot \mathbf{E}$ dissipation. This paper provides highlights of the accomplishments of MMS to date and describes how reconnection proceeds through intense and highly localized events within the larger electron dissipation region.

Keywords: Magnetic Reconnection, Earth's Magnetopause, Wave-particle Interactions

MMS Fast Plasma Investigation (FPI) observations at and near the electron and ion diffusion regions as a function of guide field

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Observed ion and electron distributions are compared for asymmetric reconnection events, categorized by weak-, moderate-, and strong-guide field. Several of the structures noted have been demonstrated in simulations and others have not been predicted or explained to date. We report on these observations and their persistence. In particular, we highlight counter streaming low-energy ion distributions that are seen to persist regardless of increasing guide-field. Distributions of this type were first published by *Burch and Phan* [GRL, 2016] for an 8 Dec 2015 event and by *Wang et al.* [GRL, 2016] for a 16 Oct 2015 event. *Wang et al.* showed the distributions were produced by the reflection of magnetosheath ions by the normal electric field at the magnetopause. This report presents further results on the relationship between the counter streaming ions and electron distributions and show the counter streaming ions traversing the magnetosheath, X-line, and in one case the electron stagnation point. We suggest the counterstreaming ions become the source of D-shaped distributions at points where the field line opening is indicated by the electron distributions. In addition, we suggest they become the source of ion crescent distributions that result from acceleration of ions by the reconnection electric field.

Keywords: magnetic reconnection, Magnetospheric Multiscale mission, Fast Plasma Investigation

Cold ion heating in the vicinity of the Hall field region in dayside magnetic reconnection

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Magnetic reconnection is a plasma process that enables exchange of mass and energy between the solar wind and the Earth's magnetosphere. The magnetospheric side of the subsolar magnetopause is often populated by cold (10 eV) plasma of ionospheric origin, in addition to the common hot (10 keV) magnetospheric plasma. We present MMS observations of magnetic reconnection with the presence of ionospheric cold plasma and investigate the heating mechanisms as well as their implications for the global energy budget. It is found that cold ions are pre-heated already inside the magnetospheric separatrix region before entering the exhaust, in the vicinity of the Hall electric field. The temperature increases one order of magnitude and the heating is mainly perpendicular to the magnetic field.

Keywords: Magnetic reconnection, cold ions, magnetosphere

Thin current sheet and plasma jet observed within a FTE by MMS

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Bursty magnetic reconnection may lead to the formation of flux transfer events (FTEs) on the dayside magnetopause. FTEs are characterized by a peak in magnetic field intensity and a bipolar signature in the magnetic field component normal to the magnetopause surface. Many features of FTEs have not been precisely identified owing to the limited resolution of plasma instruments on past missions. Thanks to unprecedented high resolution and accuracy, measurements made by the recent MMS mission reveal the fine structure of FTEs in full detail. The work presented here consists in the study of an FTE that was detected by MMS on November 7th, 2015. Burst data were available from all four spacecraft, in good tetrahedral configuration, allowing us to use multi-spacecraft data analysis methods. The event shares several features with FTEs but our interest lies in a very localized current system and an ion jet observed in the center of the structure. There is evidence of multiple sub-structures inside the FTE. We discuss the presence of a current sheet inside the event as a result of colliding jets leading to the possible formation of magnetic islands or coalescence of multiple magnetic islands.

Waves and wave-particle interactions in magnetopause reconnection

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The role of waves in magnetic reconnection remains an outstanding question. Waves can produce particle heating and acceleration, particle diffusion, and anomalous resistivity, all of which can impact ongoing reconnection. Therefore, it is crucial to characterize the waves associated with magnetic reconnection. We investigate the waves that develop near the electron and ion diffusion regions of asymmetric reconnection at Earth's magnetopause using the Magnetospheric Multiscale spacecraft. In particular, we show that near the stagnation point intense lower hybrid drift waves are produced, which result in cross-field particle diffusion, broadening the density gradient in ion diffusion region and magnetospheric separatrices. We also show that agyrotropic beams generated in EDRs can become unstable to high-frequency electrostatic waves. These waves are sufficiently large to thermalize the beam, potentially modifying the electron dynamics near or within EDRs. We discuss the role these waves play in ongoing magnetic reconnection.

Keywords: Magnetic reconnection, Plasma waves, Wave-particle interactions

Energy transfer and electron dynamics in a kinetic Alfvén wave

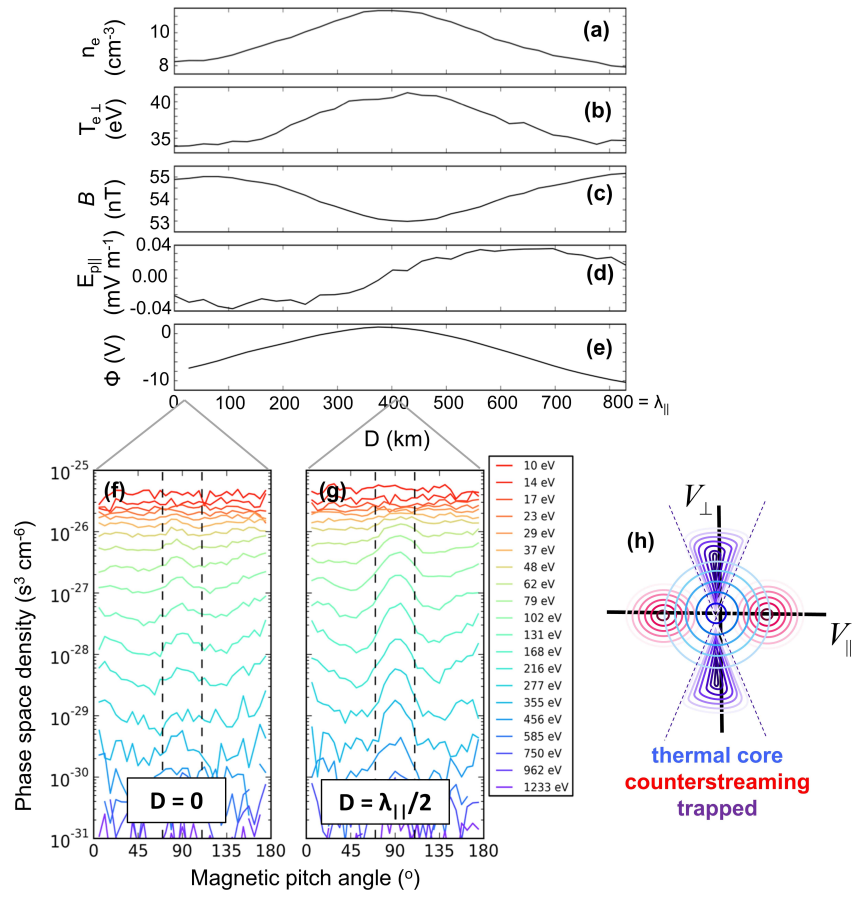
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Kinetic Alfvén waves (KAW) provide a mechanism for the transfer of energy in plasmas throughout the universe. The detailed properties of these waves have been elusive due to limits on plasma instrumentation. However, NASA's Magnetospheric Multiscale (MMS) mission provides high resolution particle and fields instrumentation suitable to resolve kinetic-scale physics. On 30 December 2015, MMS resolved a monochromatic KAW in a magnetopause reconnection exhaust. Through determination of the three-dimensional wavevector, particle currents, and pressure-gradient driven electric fields, we are able to observe the conservative energy transfer between the wave field and plasma particles for the first time.

In addition to resolving wave fluctuations, we identify a dynamically significant population of non-linearly trapped electrons. These electrons are trapped within a kinetic scale magnetic mirror formed by the parallel magnetic field fluctuations of the KAW. This population, which accounted for ~50% of the density fluctuations within the wave, may have inhibited Landau and transit-time damping of the KAW, enabling its stable propagation and transport of energy away from the reconnection X-line.

Keywords: kinetic alfvén wave, plasma physics, plasma wave



Spacecraft observations of a Maxwell Demon coating the separatrix of asymmetric magnetic reconnection with crescent-shaped electron distributions

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During asymmetric magnetic reconnection in the dayside magnetopause in situ spacecraft measurements show that electrons from the high density inflow penetrate some distance into the low density inflow. Supported by a kinetic simulation, we present a general derivation of an exclusion energy parameter, which provides a lower kinetic energy bound for an electron to jump across the reconnection region from one inflow region to the other. As by a Maxwell Demon, only high energy electrons are permitted to cross the inner reconnection region, strongly impacting the form of the electron distribution function observed along the low density side separatrix. The dynamics produce two distinct flavors of crescent-shaped electron distributions in a thin boundary layer along the separatrix between the magnetospheric inflow and the reconnection exhaust. The analytical model presented relates these salient details of the distribution function to the electron dynamics in the inner reconnection region.

Keywords: MMS, reconnection, plasma

Magnetosheath flux transfer events –minor ion populations as observed by MMS/HPCA

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The NASA Magnetospheric Multiscale (MMS) mission has completed two sweeps of the dayside magnetopause, successfully sampling with high temporal and spatial resolution the microphysics controlling the asymmetric magnetic reconnection of collisionless plasmas. During these sweeps, several flux transfer events (FTEs) associated with localized magnetopause reconnection were observed by the MMS instrumentation at high temporal resolution. This work examines in detail the characteristics of minor ions associated with some of the longer-sampled FTEs in the upstream magnetosheath region by the MMS Hot Plasma Composition Analyzer (HPCA). The influence of associated variables such as season, local time, and solar wind conditions on the minor ion populations within FTEs are also investigated as part of this effort.

Keywords: Magnetic reconnection, Flux transfer events, Magnetosheath

Direct measurements of energy exchange between EMIC waves and ions observed by the MMS spacecraft in the magnetosphere

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Wave particle interactions, which cause particle acceleration and pitch-angle scattering, are a fundamental energy exchange process in collisionless space plasma. The four MMS (Magnetospheric Multiscale) spacecraft traversing the duskside magnetosphere measured electromagnetic ion cyclotron (EMIC) waves from ~12:18 to 12:22 UT on 1 September 2015. In this period, the burst ion data from Fast Plasma Investigation Dual Ion Spectrometer (FPI-DIS) with a time resolution of 150 ms are available. Although electric field data from probes were not usable to analyze the wave electric field due to the fluctuation with a frequency of ~0.1 Hz likely caused by ion beams from Active Spacecraft Potential Control (ASPOC) neutralizes, cold ions with energies less than 300 eV are detected by FPI-DIS due to the large magnitude of the electric field drift caused by the wave electric fields under weak background magnetic fields (~22-40 nT). Since the frequency of the EMIC waves were lower than ~1/5 of the proton gyro frequency, perpendicular electric fields were derived from the cross product of the negative cold ion velocity and the magnetic field. Using these data, we investigate energy exchange rates between EMIC waves and ions. To directly detect energy exchange between EMIC waves and energetic ions, we apply the method of Wave-Particle Interaction Analyzer (WPIA) that is to calculate the Joule heat from dot product between the wave electric field (perpendicular component in the frequency range of 0.05-0.15 Hz in the present case) and ion resonant currents [Fukuhara *et al.*, 2009; Katoh *et al.*, 2013]. Near the beginning of the wave event, 15-second averages of the dot product reached -0.4 pW/m³ for ions with pitch angles of 33.25-78.75 degrees and energies of 14-30 keV. The negative value of the power in this pitch angle range indicates that the perpendicular energy of ions was being transferred to the EMIC waves propagating toward higher latitudes at the MMS location by cyclotron resonance. Ion data show non-gyrotropic distributions around the resonance velocity, and that is consistent with the nonlinear trapping of protons by the wave and formation of an electromagnetic proton hole [e.g., Omura *et al.*, 2010]. Near the beginning of the same wave event, strongly phase bunched He⁺ ions up to ~2 keV with pitch angles slightly larger than 90 degrees were also detected. The dot product of the wave electric fields and He⁺ ion currents showed a positive value. This indicates that the He⁺ ions were being accelerated by the electric field of the EMIC waves. The observed feature of He⁺ ions is consistent with non-resonant interaction with the wave but is inconsistent with cyclotron resonance. In this event, we could measure energy transfer from hot ions to the EMIC wave and from the wave to He⁺ ions for the first time.

Keywords: wave particle interaction, EMIC wave, MMS spacecraft, WPIA, heavy ion, particle acceleration

Global observations of high-m poloidal waves in the magnetosphere during the recovery phase of the June 2015 magnetic storm

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In this paper, we report global observations of high-m poloidal waves occurred during the recovery phase of the magnetic storm starting on 22 June 2015. The long lasting waves are observed by a constellation of widely spaced satellites from 5 missions including MMS, Van Allen Probes, THEMIS, Cluster, and GOES, covering L-values between 4 and 12 in a large range of local times. These observations have demonstrated that storm-time high-m poloidal waves can occur globally. High-resolution data from four MMS satellites enable us to detect the azimuthal phase shifts and determine the m number to be ~ 100 . The mode identification suggests that the observed poloidal waves are associated with the second harmonic of the field line resonance. The wave frequencies range from 8 to 22 mHz and decrease as the L-value increases. Detailed examinations of instantaneous wave frequency show discrete spatial structures with step-like changes along the radial direction. In each discrete structure the wave has a steady frequency and spans about 1 Re in the radial direction. Our observations suggest that storm-time high-m poloidal waves are different from the single-frequency global poloidal mode waves that are common during periods of low-level of geomagnetic activities.

Keywords: Magnetospheric ULF Waves, High-m Poloidal Waves, Magnetospheric Multiscale Mission, Magnetic Storms

Simultaneous Remote Observations of Intense Reconnection Effects by MMS and DMSP Spacecraft During Storm-time Substorms

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During a magnetic storm on 23 June 2015, several very intense substorm took place whose signatures were observed by various spacecraft including MMS and DMSP. At the time of interest, MMS was located duskward of 22h MLT, during an inward crossing of the expanding plasma sheet boundary. A poleward-expanding auroral bulge boundary was crossed inwards by DMSP F18 at 23.5h MLT. Both spacecraft consistently observed a set of signatures as they simultaneously crossed the reconnection separatrix layer during this very intense reconnection event, including: 1) Energy dispersion of the energetic electrons travelling earthwards, accompanied with unusually high (10keV) electron energies in the vicinity of the separatrix, 2) Intense inward convection of the magnetic field lines $\sim 4\text{mV/m}$ at MMS location, and 3) Energy dispersion of polar rain electrons, with high-energy cutoff. The high temporal resolution measurements by MMS provide unprecedented observations of the low-energy cutoff in the earthward moving electrons. We discuss the relevance of the energy dispersion of the electrons and the evolution in pitch angle distribution, to the spatial and temporal evolution of plasma sheet, resulting from this magnetic reconnection.

Keywords: Plasma sheet boundary layer, Magnetic reconnection, Magnetospheric Multiscale (MMS) mission

Detail evolution of nightside auroral and magnetospheric phenomena after SC observed by ground and MMS simultaneous observations

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Detail evolution of nightside auroral and magnetospheric phenomena after an SC were analyzed by using the ground-based data at Syowa Station, Antarctica and the data observed by the MMS satellites for the event on June 22, 2015.

SSC occurred at 18:33 UT due to the arrival of an interplanetary shockwave. At that time, the MMS satellites were located in a pre-midnight region around $(X, Y, Z) = (-5.6, 7.5, 1.5)$ Re in GSM coordinate, and their footprints were located about 6 degree north and 19 degree east from Syowa Station (69.0S, 39.6E) in geographic coordinate.

During the magnetic PI (Preliminary Impulse) period after the SSC, a diffuse proton auroral appeared at lowest latitudes in the FOV at Syowa and started to expand poleward. At MMS, tailward and dawnward plasma motion was observed.

During the magnetic MI (Main Impulse) period, the lower latitude proton auroral was further enhanced, and diffuse electron auroral was bifurcated into two in the FOV. Around the peak of the MI variation, a discrete auroral arc appeared around the higher latitude edge of the electron diffuse auroral region. At MMS, plasma motion changed to duskward, and the tailward velocity started to decrease. Around the time of the MI peak, magnetic configuration at MMS showed an acceleration of the taillike change.

At 18:38 UT, the higher latitude discrete arc became multiple arcs, and a gap between the discrete auroras and the lower latitude diffuse aurora became clear. At MMS, earthward flow appeared at 18:38:30 UT.

At 18:39:05 UT, the earthward flow velocity increased, became maximum (400km/s) at 18:39:15 UT, and then decreased to zero at 18:40:15 UT. During that period, a clear dipolarization occurred. At ground, an intense discrete arc appeared in the gap region and moved poleward with an overall poleward expansion of the whole auroral activity.

At 18:40:45 - 41:00 UT, a clear spiral form, moving westward, appeared in the discrete aurora and its size became larger. At MMS, tailward flow started at 18:40:35 UT.

At 18:41:30 - 42:40 UT, another larger spiral appeared from eastern side, extended to the lower latitudes. At MMS, tailward flow speed reached maximum (300km/s).

In our presentation, we will discuss about a possible scenario to understand those correspondence between the ground-based and magnetospheric phenomena.

Keywords: SC, shock aurora, magnetospheric compression

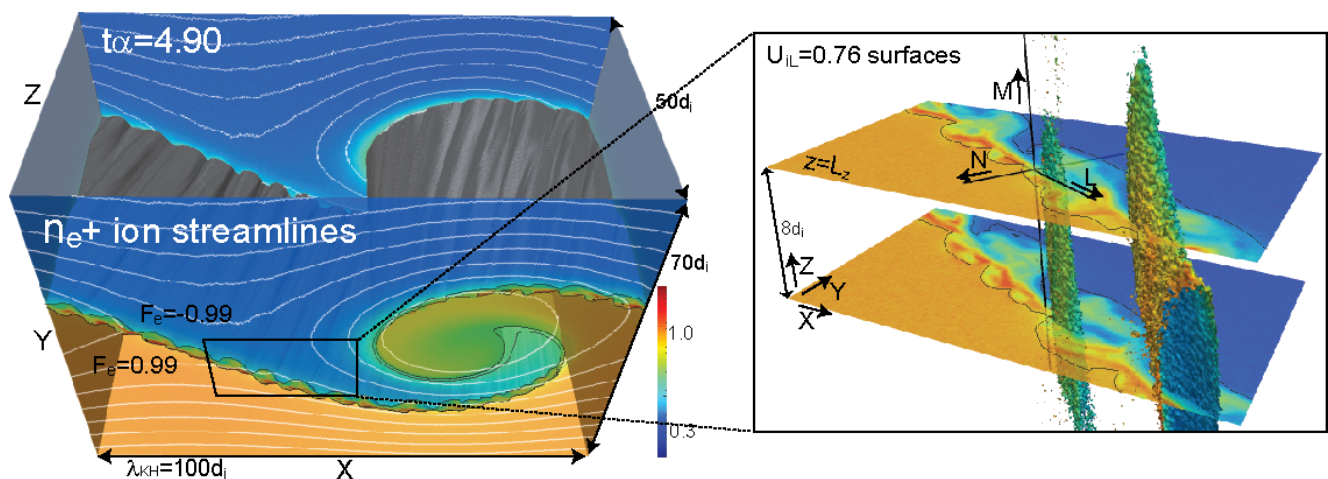
Event study of vortex-induced reconnection at the magnetopause using MMS observations and fully kinetic simulations

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A large-scale three-dimensional fully kinetic simulation is performed for a Kelvin-Helmholtz (KH) vortex event recently observed by the Magnetospheric Multiscale Mission (MMS) at the duskside magnetopause. In this event, kinetic-scale reconnection signatures are observed within the flow patterns of the MHD-scale KH vortices. The simulation was performed with realistic density and magnetic field structures for this event and with a sufficiently large system size to separate the scales between the reconnection region and the vortex. The results show the clear development of the ion and electron reconnection jets within the large-scale vortex flows for the first time, which are in quantitative agreement with the observed reconnection signatures. The simulation also demonstrates an efficient, large-scale plasma transport across the magnetopause resulting from the vortex-induced reconnection. In this presentation, we will show the detailed comparisons between the simulation and the MMS observation, and discuss how largely the KH vortex and the resulting vortex-induced reconnection process contribute to the solar wind entry into the magnetosphere.

Keywords: Kelvin-Helmholtz instability, Magnetic reconnection, MMS, Particle-in-cell simulation



Asymmetry in mid-latitude reconnection site locations associated with the Kelvin-Helmholtz instability

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On 08 September 2015, MMS observed a long duration Kelvin-Helmholtz instability at the dayside magnetopause near the terminator. Kinetic signatures of local reconnection have been observed, showing evidences of Type I reconnection associated with the Kelvin-Helmholtz waves. Remote observations, i.e., streaming hot electrons in the magnetosheath boundary layer, suggested that reconnection occurred at higher latitudes both above and below the KH development plane. A revised analysis shows that the electron signatures have a preferred directionality, suggesting a preference for mid-latitude reconnection occurring mostly southward of the KH development plane. We investigate this preference by means of the high resolution instruments of the MMS mission combined with MHD simulations and show potential relation between the magnetic field line tension and reconnection.

Keywords: Kelvin-Helmholtz instability, mid-latitude reconnection, magnetospheric multiscale mission

Large-scale context of a magnetopause Kelvin-Helmholtz event observed by the MMS spacecraft on 8 September 2015

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The Kelvin-Helmholtz (KH) instability is known to grow along the Earth's magnetopause, but its role in transporting solar wind mass and energy into the magnetosphere is not fully understood. On 8 September 2015, the Magnetospheric Multiscale (MMS) spacecraft, located at the postnoon magnetopause, encountered thin low-shear current sheets at the trailing edge of the KH waves, where KH-induced reconnection, one of the plasma transport processes, was occurring [Eriksson et al., 2016; Li et al., 2016]. The event occurred during a prolonged period of northward interplanetary magnetic field, and was characterized by an extended region of the low-latitude boundary layer (LLBL) immediately earthward of the KH unstable magnetopause, which appeared to have been formed through magnetopause reconnection poleward of the cusp. In this LLBL, MMS observed plasma turbulence, another agent for the plasma transport [Stawarz et al., 2016], and cold electrons possibly of ionosphere origin [Wilder et al., 2016], despite that magnetic field lines threading the LLBL would have been detached from the ionosphere a few tens of minute before the observation. In the present study, we revisit this KH-wave event and address the questions of how the KH instability got excited, how the current sheets at the KH wave trailing edges were generated, what is the origin of the turbulence seen within the KH vortices, and how the cold plasma populations got access to and reached the LLBL. Our analysis suggests that MMS was not at most KH-unstable latitudes but on their southern side, and the observed current sheets with a systematic pattern of magnetic field variations result from three-dimensional development of the KH instability.

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Keywords: magnetopause, Kelvin-Helmholtz instability, magnetic reconnection, plasma transport, plasma turbulence, ionospheric plasma

Stochastic Electron Acceleration by Whistler Waves within Earth's Bow Shock Layer

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High-energy electrons with relativistic velocities are produced at high Mach number astrophysical shocks, as have been indicated by emissions such as synchrotron X-rays and radio waves. In the standard 'diffusive shock acceleration' scenario, electrons are accelerated stochastically by receiving 'energization' 'kicks' multiple times while being scattered back and forth across the shock front. A challenge is that electrons need to be sufficiently energetic before being injected into the standard process for further energization. The lack of such a seed population is termed "injection problem" and has been a subject of theoretical debate. In interplanetary space where in-situ measurements are available, non-thermal electrons have been detected, but the precise location and mechanism of electron acceleration have remained unclear. Here we show that electrons are energized through bursts of whistler waves within the transition layer of Earth's bow shock. We further found evidence of the diffusive shock acceleration although, unlike the standard scenario, electrons were accelerated even in a low energy range (>0.1 keV) and were confined within the shock layer. The new observation at Earth suggests a need for revisiting current models of electron injection and subsequent acceleration to high energies at astrophysical shocks.

Keywords: electron acceleration, shock, whistler waves

MMS Observation of Inverse Energy Dispersion in Shock Drift Accelerated Ions

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The four Magnetospheric Multiscale (MMS) spacecraft observed a ~1 min burst of energetic ions (50-1000 keV) in the region upstream from the subsolar quasi-perpendicular bow shock on December 6, 2015.

The composition, flux levels, and spectral indices of these energetic protons, helium, and oxygen ions greatly resemble those seen in the outer magnetosphere earlier while MMS crossed the magnetopause and differ significantly from those simultaneously observed far upstream by ACE.

However, the event cannot be explained solely in terms of leakage from the magnetosphere. The strongly southward orientation of the interplanetary magnetic field (IMF) lines at the time of the event precludes any connection to the magnetosphere. This point is confirmed by the presence of energetic electrons, known to occur on magnetic field lines that graze the bow shock rather than connect to the magnetosphere.

We suggest that the ions gradient drifted out of the nearby quasi-parallel foreshock and into the quasi-perpendicular bow shock. Each of the ion species exhibited an inverse energy dispersion. As predicted by models for shock drift acceleration, the energies of the ions increased as Θ_{Bn} , the angle between the IMF and the shock normal, increased. Finally, we note that a similar event was observed a few minutes later in the subsolar magnetosheath, indicating that such events can be swept downstream of the bow shock.

Investigation of turbulence in the magnetosheath with observations from Magnetospheric Multiscale's Fast Plasma Instrumentation

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The Fast Plasma Instrumentation for the Magnetospheric Multiscale mission measures the velocity distributions of electrons and ions with energies several eV to 30 keV. In its fast survey mode of operation, velocity distributions are acquired every 30 ms for the electrons and every 150 ms for the ions. Due to telemetry limitations, only a small subset of these high time resolution distributions can be transmitted to the ground, and priority is given to potential observations of reconnection. However, a continuous and compact set of approximate plasma moments is computed onboard the spacecraft and sent to the ground at the full temporal resolution of the instrumentation. Thus it is possible to examine the power spectral densities of plasma parameters in the magnetosheath for hours at a time. Additionally, the 4-spacecraft tetrahedron provides a capability for direct observation of vorticity. In this presentation we report on the study of magnetosheath turbulence based on analysis of these measurements.

Observations of strong plasma enhancement at the dawn terminator by the MMS

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At the dawn terminator (~ 6 am MLT) the four MMS spacecraft detected several significant plasma enhancements accompanied by strong plasma acceleration. The strongest event was captured by MMS in burst mode (30 ms for electron and 150 ms for ions). The number density abruptly increased from typical magnetospheric background values, $\sim 1 \text{ cm}^{-3}$, up to 50-60 cm^{-3} . The solar wind parameters corresponding to these observations are quite stable without any sharp changes, therefore there is no apparent solar wind driver that is responsible for these injections. The estimated distance from the nominal magnetopause to the spacecraft was $\sim 3 R_E$ and the data does not show characteristics of multiple magnetopause crossings. We combine the MMS observations with results of global MHD simulations to understand which one of several possible scenarios might explain MMS observations: either set of the Flux Transfer Events (FTE) resulting from the dayside reconnection or earthward-propagating dipolarization fronts caused by the tail reconnection.

Keywords: Reconnection, FTE

CLUSTER and MMS missions : Estimation of the gradient of a field with a flattening tetrahedron

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The ESA mission CLUSTER, successfully launched in 2000 has been the first one to involve four identical spacecraft orbiting simultaneously around the Earth in order to provide a three dimensional view of plasma processes with inter-spacecraft distances varying from a few tens to a few thousands of kilometers. CLUSTER is going on and has already demonstrated the impressive benefit of simultaneous multipoint observations; its success has triggered new projects like the NASA MMS mission, launched in 2014, which is currently investing shorter scales than CLUSTER. For not too large inter-spacecraft distances, multi-spacecraft data analysis methods have been developed to estimate gradients of fields : see the detailed presentations in two ISSI books [1,2]. It has been demonstrated by Chanteur [3] that estimated gradients are spoiled by large errors when the tetrahedron of spacecraft flattens, which occurs twice per orbit and sometimes during “interesting” time intervals. Shen et al. [4] proposed to estimate gradients under such difficult configurations by making use of the principal axes of the inertia tensor of the configuration of the cluster : that solves the problem only partially, but the divergence remains along the normal to the plane of the singular “flat” tetrahedron. We have designed a rigorous analysis of the flattening tetrahedron by making use of a frame of reference attached to the tetrahedron which allows to estimate all components of the gradient, avoiding any divergence but nonetheless the estimated gradient is affected by the geometrical amplification of errors due to the flattening.

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Keywords: magnetospheric physics, multi-spacecraft data analysis, reciprocal vectors of a tetrahedron

Investigation of the magnetic neutral line region with the frame of two-fluid equations: A possibility of anomalous resistivity inferred from MMS observations

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Magnetic reconnection is a basic physical process by which energy of magnetic field is converted into the kinetic energy of plasmas. In recent years, MMS mission consisting of four spacecraft has been conducted aiming at elucidating the physical mechanism of merging the magnetic fields in the vicinity of the magnetic neutral line that exists in the central part of the structure. In this paper, we examine the magnetic field frozen-in relation near the magnetic neutral line as well as the causal relationship between electron and ion dynamics in the frame of two fluid equations.

It is thought that the electron dissipation region with the thickness of about the electron inertial length surrounds the magnetic neutral line, and the ion dissipation region with the thickness of about the ion inertia length further surrounds them. Theoretically, it is shown that electrons are frozen-in to the magnetic fields while ion's frozen-in relation is broken in the ion dissipation region. However, when we examined the observational data around 1307 UT on October 16, 2015 when MMS spacecraft passed through the vicinity of the magnetic neutral line [Burch et al., Science 2016], it was confirmed that the frozen-ion relation was not established for electrons in the ion dissipation region. In addition, we found that intense wave electric fields in this region. From the spectral analysis of the waves, it turned out that their characteristic frequencies are the lower-hybrid and electron cyclotron frequencies.

In the framework of the two-fluid equation, we can evaluate the values of each term of the equations of motion for both ions and electrons except for the collision term from MMS spacecraft data. Therefore, it is possible to obtain collision terms for both species. Since magnetospheric plasma is basically collisionless, it is considered that the collision term is due to anomalous resistivity associated with the excited waves. On the other hand, in the usual two-fluid equation system, the two vectors corresponding to the collision terms of ions and electrons have the same absolute value. Because the force exerted between the two is the internal force, they should face exactly in the opposite direction. However, the vectors corresponding to the collision terms obtained by using the actual data did not satisfy such a condition. One of the possible reasons is that the momentum carried by the waves cannot be neglected. Another possibility is that, such a discrepancy is caused by measurement error of each physical quantity.

After careful examination, we conclude that the effect of the anomalous resistivity in the ion dissipation region acts to some degree that cannot be ignored in the equation of motion of the two-fluid system.

Keywords: MMS mission, two fluid equation, magnetic reconnection, plasma waves, anomalous resistivity

Currents and associated electron scattering and bouncing near the diffusion region at Earth's magnetopause

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Based on high-resolution measurements from NASA's Magnetospheric Multiscale mission, we present the dynamics of electrons associated with current systems observed near the diffusion region of magnetic reconnection at Earth's magnetopause. Using pitch angle distributions (PAD) and magnetic curvature analysis we demonstrate the occurrence of electron scattering in the curved magnetic field of the diffusion region down to energies of 20 eV. We show that scattering occurs closer to the current sheet as the electron energy decreases. The scattering of inflowing electrons, associated with field-aligned electrostatic potentials and Hall currents, produces a new population of scattered electrons with broader PAD which bounce back and forth in the exhaust. Except at the center of the diffusion region the two populations are collocated and behave adiabatically: the PAD of inflowing electrons focuses inward (towards lower magnetic field), while the bouncing population gradually peaks at 90° away from the center (where it mirrors owing to higher magnetic field and probable field-aligned potentials).

Keywords: Reconnection, Electrons, Plasma

Inverse Energy Dispersion of Energetic Ions Observed in the Magnetosheath

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We present a case study of energetic ions observed by the Energetic Particle Detector (EPD) on the Magnetospheric Multiscale (MMS) spacecraft in the magnetosheath just outside the subsolar magnetopause that occurred at 1000 UT on December 8, 2015. As the magnetopause receded inward, the EPD observed a burst of energetic (~50-1000 keV) proton, helium, and oxygen ions that exhibited an inverse dispersion, with the lowest energy ions appearing first.

The prolonged interval of fast antisunward flow observed in the magnetosheath and transient increases in the H components of global ground magnetograms demonstrate that the burst appeared at a time when the magnetosphere was rapidly compressed.

We attribute the inverse energy dispersion to the leakage along reconnected magnetic field lines of betatron-accelerated energetic ions in the magnetosheath and a burst of reconnection has an extent of about $1.5 R_E$ using combined Super Dual Auroral Radar Network (SuperDARN) radar and EPD observations.

Electron crescent distributions as a manifestation of diamagnetic drift in an electron scale current sheet: Magnetospheric Multiscale observations using new 7.5 ms Fast Plasma Investigation moments

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We report Magnetospheric Multiscale spacecraft observations of electron pressure gradient electric fields near a magnetic reconnection diffusion region using a new technique for extracting 7.5 ms electron and 37.5 ms ion moments from the Fast Plasma Investigation (FPI) data. Comparing our results to previously reported 30 ms electron and 150 ms ion FPI moments (e.g., Burch et al. Science 2016, Torbert et al. GRL 2016), we find a significant improvement in the agreement between the FPI perpendicular electron bulk velocity and the ExB drift as measured by the Electric Field Double Probes (EDP) and Flux Gate Magnetometer (FGM) instruments (averaged to the FPI data). While the 7.5 ms moments recover significant additional structure in the electron bulk velocity, no significant additional structure is observed in the 7.5 ms electron parallel or perpendicular pressure. The violation of the electron frozen flux constraint in the vicinity of the stagnation point (where electron crescent shaped velocity distributions have been previously reported by Burch et al. Science 2016) can be explained largely by the gradient of the perpendicular electron pressure perpendicular to the magnetic field. These results suggest that the electron crescent distributions are a manifestation of the electron diamagnetic drift and do not in themselves contribute to the dissipation of magnetic energy.

Keywords: diamagnetic drift, plasma moments, crescent distributions

Calibration of wave vector analysis techniques for low frequency waves detected by MMS in the terrestrial magnetosphere and magnetosheath regions

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There are certain difficulties in determining wavelengths using in-situ single-spacecraft data without assuming the dispersion relation of the waves. Wave vector analysis techniques using multi-spacecraft data have been developed after the 1990s in space science [Neubauer and Glassmeier, 1990; Narita et al., 2011]. Recent MMS mission enables us to resolve smaller wavelength in the ion kinetic range [Narita et al., 2016]. While the developed techniques provide the wave energy distribution in the frequency-wave vector domain with high resolution, some parameters can affect significantly on the distribution. We perform the wave vector analyses using synthetic multi-spacecraft data and investigate two parameters: the noise tolerance parameter n and degree of freedom for ensemble averaging m . The synthetic data are constructed assuming low frequency waves detected by MMS in the terrestrial magnetosphere and magnetosheath regions. We compare the results obtained by beam former projection, Capon's minimum variance projection, extended MUSIC, and MSR technique quantitatively to identify adequate parameters n and m for the target waves.

Walen and Slow-mode shock analysis of magnetopause crossings by MMS

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Magnetic reconnection is the main driving process behind phenomena like solar flares, magnetic storms and astrophysical plasma jets. The fast rate of reconnection as seen in observations was explained by Petschek's model [1964] in MHD regime. In this model, X-line geometry with a narrow diffusion region and two pairs of slow-mode shocks helps to achieve faster reconnection than Sweet-Parker's model [Sweet, 1958 and Parker, 1957]. On one hand, resistive Hall MHD simulations show that the quadrupole magnetic fields formed by inclusion of the Hall term achieve the X-line geometry in scale of the ion inertial length and thus fast reconnection [e.g., Drake et al., 2008].

Laboratory experiments support the importance of the Hall physics, while they have not observed the slow-mode shocks till date [Zweibel and Yamada, 2016]. However, in-situ observations in space show the existence of slow shocks on MHD scale [Feldman et al., 1987, Saito et al., 1995]. Recent studies on presence of slow-mode shocks in Earth's magnetotail have been carried out extensively using THEMIS and Cluster data [e.g., Erikson et al., 2004]. Also, in the asymmetric reconnection at the Earth's magnetopause, the combination of slow-mode shock and other discontinuity such as the rotational discontinuity is theoretically predicted [Levy et al., 1965, Hau and Wang, 2016] and observed [Walthour et al., 1994]. Thus, the structure and presence of slow-mode shocks seems to be established on MHD scale but on ion inertial scale, it still remains controversial.

We aim to study the inside structure (on ion inertial length scale) of the slow-mode shocks. As a first step towards our final aim, we investigated the presence of slow-mode shocks and other discontinuities in Earth's magnetopause by using Magnetospheric Multiscale (MMS) data. High time resolution of MMS data enables us to observe reconnection structure from the ion diffusion to MHD scales. The results of the Walen test and slow-mode shock analysis (Rankine-Hugoniot conditions) of magnetopause crossings by MMS are presented.

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(2016).

Keywords: MMS, Slow shock, Reconnection, Magnetopause

MMS observations of sub-ion scale magnetic holes in the magnetosheath

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Magnetic holes (MHs), structure of an observable magnetic field magnitude decrease, have been widely observed in space plasma. Spatial size of the MHs ranged from tens to thousands of proton gyroradius (ρ_i). In previous studies, these large magnetohydrodynamics (MHD) MHs were associated with mirror instabilities. In this study, we report a series of sub-ion scale magnetic holes in the terrestrial magnetosheath. The main characteristics are summarized below. 1. These structures have been observed in a scale of $10 \sim 20 \rho_e$ (electron gyroradii) and lasted $0.1 \sim 0.3$ s. 2. The magnetic field magnitude decreases along the background direction; distinctive electron dynamics features are observed, while no substantial deviations in ion data are seen. 3. An electron flow vortex is found perpendicular to the background magnetic field. 4. Electron diamagnetic drift contributes the calculated current density. 5. For the 90° pitch angle electrons, the flux is decreases between 34 eV to 66 eV and significantly increases between 109 eV to 1024 eV. 6. Electron magnetohydrodynamics (EMHD) soliton theory is considered as a possible generation mechanism.

Keywords: magnetic hole, sub-ion scale, vortex, diamagnetic drift, MMS, soliton