Advances in Magnetic Reconnection with Magnetospheric Multiscale

*Burch L James[1]

1. Southwest Research Institute

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 (J dot 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 J dot 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

*Barbara L Giles[1], James L Burch[2], Tai Duc Phan[4], James Webster[13], Levon A Avanov[1,5], Roy B Torbert[2,3], Scott A Boardsen[1,5], Michael O Chandler[6], Li-Jen Chen[1,5], Victoria N Coffey[6], John C Dorelli[1], Robert E Ergun[7], Stephen Fuselier[2], Kevin Genestreti[2], Daniel Gershman[1,5], Benoit Lavraud[8], David A Mackler[1,10], Thomas E Moore[1], William R Paterson[1], Craig J Pollock[9], Amy C Rager[1,10], Christopher T Russell[11], Yoshifumi Saito[12], Conrad Schiff[1], Jason R Shuster[1,5], Susanne E Smith[1,10], Robert J Strangeway[11], Adolfo Figueroa-Viñas[1], Shan Wang[5], Frederick Wilder[7], Eftyhia Zesta[1]

1. NASA Goddard Space Flight Center, 2. Southwest Research Institute, 3. Univ of New Hampshire, 4. Univ of California, Berkeley, 5. Univ of Maryland, College Park, 6. NASA Marshall Space Flight Center, 7. LASP, Univ of Colorado, 8. Research Inst in Astrophysics and Planetology, Toulouse, France, 9. Denali Scientific, 10. Catholic Univ of America, 11. Univ of California, Los Angeles, 12. Institute for Space Science, Sagamihara, Japan, 13. Rice Univ

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

*Sergio Toledo Redondo[1], Mats Andre[2], Yuri Khotyaintsev[2], Benoit Lavraud[3,4], Wenya Li[2], Denise Perrone[1], Daniel Gershman[5], Barbara Giles[5], Craig J Pollock[5], Stephen Fuselier[6], Per-Arne Lindqvist[7], Roy torbert[8], Christopher T Russell[9]

1. European Space Agengy (ESA), Spain, 2. Swedish Institute of Space Physics, Uppsala, Sweden, 3. Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, Toulouse, France, 4. Centre National de la Recherche Scientifique, Toulouse, France, 5. NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, 6. Southwest Research Institute, San Antonio, Texas, USA, 7. Department of Space and Plasma Physics, Royal Institute of Technology, Stockholm, Sweden, 8. Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA, 9. Department of Earth and Space Sciences, University of California, Los Angeles, California, USA

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

Issaad Mahmoud kacem[1,2], *V. genot[1,2], C. Jacquey[1,2], B. Lavraud[1,2], Y. Vernisse[1,2], A. Marchaudon[1,2], O. Le Contel[3], T. Phan[4], M. Oka[4], H. Hasegawa[5], J. L Burch[6], C. Farrugia[7], C. Russel[8], M. Oieroset[4], D. Gershman[9,10], J. Dorelli[9], C. J Pollock[9], B. Giles[9], J. Eastwood[11], F. Wilder [12], T. Moore[9], Y. Saito[5], T. Mukai[5], J.-A. Sauvaud[1,2], E. Penou[1,2], R. Torbert[7], R. Ergun[12], B. Mauk[13], S.A. Fuselier[6], R. Nakamura[14], L. Avanov[9,7], A. Barrie[9,15], M. Chandler[16], L.J. Chen[9], V. Coffey[16], E. MacDonald[9], A. Rager[9,17], S. Smith[9,17], S. Wang[15], S. Yokota[5]

1. Institut de Recherche en Astrophysique et Planétologie, Université de Toulouse, France, 2. Centre National de la Recherche Scientifique, UMR 5277, Toulouse, France, 3. Laboratoire de Physique des Plasmas, Palaiseau, France, 4. Space Sciences Laboratory, Berkeley, CA, 5. Institute for Space and Astronautical Science, Sagamihara, Japan, 6. Southwest Research Institute, San Antonio, TX, 7. University of New Hampshire, Durham, NH, 8. University of California, Los Angeles, CA , 9. NASA Goddard Space Flight Center, Greenbelt, MD, 10. Oak Ridge Associated Universities, Washington, DC, 11. The Blackett Laboratory, Imperial College, London, UK, 12. University of Colorado / Laboratory for Atmospheric & Space Physics, Boulder, CO, 13. Johns Hopkins University Applied Physics Laboratory, Laurel, MD, 14. Space Research Institute, Austrian Academy of Sciences, Graz, Austria, 15. University of Maryland, College Park, MD, 16. NASA Marshall Space Flight Center, Huntsville, AL, 17. Catholic University of America, Washington, DC

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

*Daniel Bruce Graham[1], Yuri Khotyaintsev[1], Andris Vaivads[1], Cecilia Norgren[1], Mats Andre[1], James Webster[2], James L Burch[3], Per-Arne Lindqvist[4], Göran Marklund[4], Olivier Le Contel[5], Robert Ergun[6], Roy Torbert[7], William Paterson[8], Daniel Gershman[8], Barbara Giles[8], Craig J Pollock[8], John Dorelli[8], Levon Avanov[8], Benoit Lavraud[9], Yoshifumi Saito[10], Werner Magnus[11], Christopher T Russell[12], Robert Strangeway[12]

1. IRF Swedish Institute of Space Physics, Uppsala, Sweden, 2. Rice University, Houston, TX, USA, 3. Southwest Research Institute, San Antonio, TX, USA, 4. KTH Royal Institute of Technology, Stockholm, Sweden, 5. LPP, CNRS, Palaiseau, France, 6. LASP, University of Colorado, Boulder, CO, USA, 7. University of New Hampshire, Durham, NH, USA, 8. NASA Goddard Space Flight Center, Greenbelt, MD, USA, 9. IRAP, CNRS, Toulouse, France, 10. JAXA, Chofu, Japan, 11. Space Research Institute, Austrian Academy of Sciences, Graz, Austria, 12. Department of Earth and Space Sciences, University of California, Los Angeles, California, USA

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

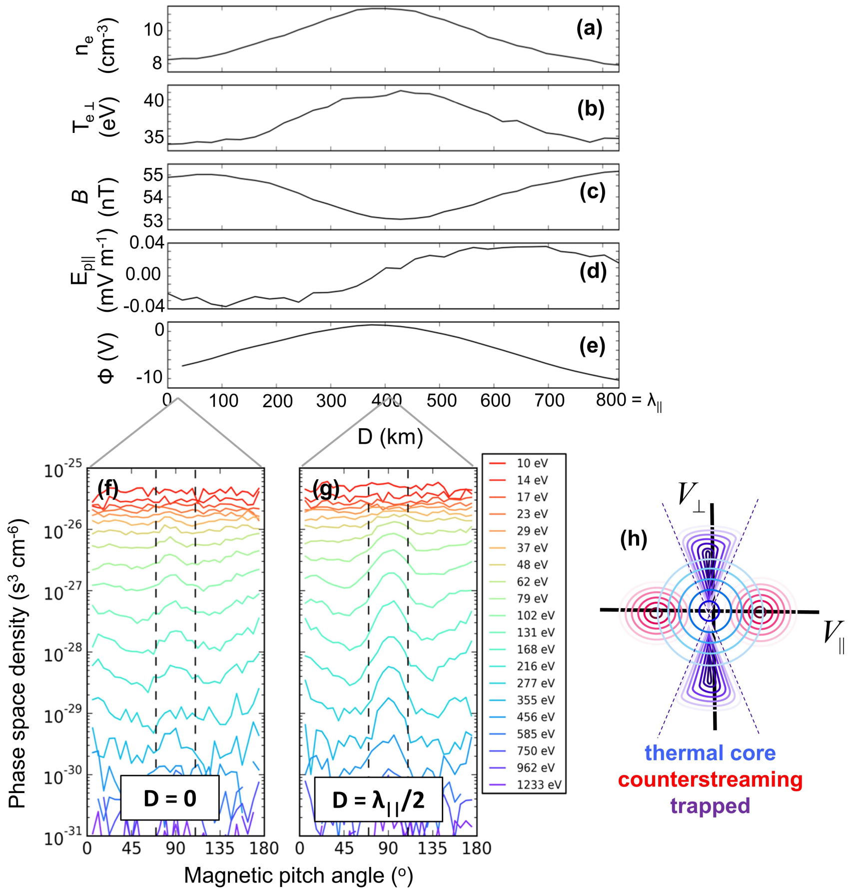
*Daniel J Gershman[1,2], Adolfo Viñas[2], John Dorelli[2], Scott Boardsen[2], Levon Avanov[1,2], Paul Bellan[3], Steven Schwartz[4], Benoit Lavraud[5], Victoria Coffey[6], Michael Chandler[6], Yoshifumi Saito [7], William Paterson[2], Stephen Fuselier[8], Robert Ergun[9], Robert Strangeway[10], Christopher Russell [10], Barbara Giles[2], Craig Pollock[2], Roy Torbert[11], James Burch[8]

1. University of Maryland, College Park, 2. NASA Goddard Space Flight Center, 3. California Institute of Technology, 4. Imperial College London, 5. Université de Toulouse, 6. NASA Marshall Space Flight Center, 7. JAXA Institute of Space and Astronautical Science, 8. Southwest Research Institute, 9. University of Colorado, Boulder, CO, 10. University of California, Los Angeles, 11. University of New Hampshire, Durham

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 alfven wave, plasma physics, plasma wave


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
D (km)
800 = λ||
D = 0
D = λ||/2
Phase space density (s³ cm⁻⁶)
Magnetic pitch angle (°)
10 eV
14 eV
17 eV
23 eV
29 eV
37 eV
48 eV
62 eV
79 eV
102 eV
131 eV
168 eV
216 eV
277 eV
355 eV
456 eV
585 eV
750 eV
962 eV
1233 eV
V⊥
V||
thermal core
counterstreaming
trapped

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

*Jan Egedal[1]

1. University of Wisconsin - Madison, USA

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

*Steven M Petrinec[1], James L Burch[2], Charles J Farrugia[3], Stephen A Fuselier[2], Barbara L Giles[4], Roman G Gomez[2], William S Lewis[2], Joseph Mukherjee[2], Christopher T Russell[5], Robert J Strangeway[5], Roy B Torbert[3], Karlheinz J Trattner[6], Sarah K Vines[7], Cong Zhao[5]

1. Lockheed Martin ATC, 2. SwRI, 3. UNH, 4. NASA/GSFC, 5. UCLA, 6. LASP, 7. JHU-APL

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

*Naritoshi Kitamura[1], Masahiro Kitahara[2], Masafumi Shoji[3], Yoshizumi Miyoshi[3], Yuto Katoh[2], Satoko Nakamura[4], Hiroshi Hasegawa[1], Yoshifumi Saito[1], Shoichiro Yokota[1], Barbara L Giles[5], Thomas E Moore[5], Daniel J Gershman[5,6], Craig J Pollock[7], Adolfo F Vinas[5], Christopher T Russell[8], Robert J Strangeway[8], Stephen A Fuselier[9], James L Burch[9]

1. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 2. Department of Geophysics, Graduate school of Science, Tohoku University, 3. Institute for Space-Earth Environmental Research, Nagoya University, 4. Research Institute for Sustainable Humanosphere, Kyoto University, 5. NASA Goddard Space Flight Center, 6. University of Maryland, 7. Denali Scientific, 8. Institute of Geophysics and Planetary Physics, University of California, Los Angeles, 9. Southwest Research Institute

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 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/m^3 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

*Guan Le[1], Peter Chi[2], Robert J Strangeway[2], Christopher T Russell[2], James Slavin[3], Kazue Takahashi[4], Howard Singer[5], Vassilis Angelopoulos[2], Brain Anderson[4], Kenneth Bromund[1], David Fischer[6], Emil Kepko[1], Werner Magnes[6], Rumi Nakamura[6], Ferdinand Plaschke[6], Roy Torbert[7]

1. NASA Goddard Space Flight Center, USA, 2. University of California, Los Angeles, USA, 3. University of Michigan, USA, 4. The Johns Hopkins University Applied Physics Laboratory, USA, 5. National Oceanic and Atmospheric Administration/SEC, USA, 6. Space Reserach Institute, Austrian Academy of Sciences, Austria, 7. University of New Hampshire, USA

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

*Ali Varsani[1], Rumi Nakamura[1], Victor A Sergeev[2], Wolfgang Baumjohann[1], Anatoli A Petrukovich [3], Christopher J Owen[4], Zhonghua Yao[5], Thomas Sotirelis[6], Ferdinand Plaschke[1], Werner Magnes [1], Christopher T Russell[7], Yuri V Khotyaintsev[8], Barbara L Giles[9], John Dorelli[9], Daniel J Gershman [10], Robert J Strangeway[7], Victoria N Coffey[11], Roy B Torbert[12], Per-Arne Lindqvist[13], Robert Ergun [14]

1. Austrian Academy of Sciences, Space Research Institute, Graz, Austria, 2. St Petersburg State University, St Petersburg, Russia, 3. Space Research Institute RAS, Moscow, Russia, 4. Mullard Space Science Laboratory/UCL, Dorking, UK, 5. Space science, Technologies and Astrophysics Research (STAR) Institute, Liège, Belgium, 6. Johns Hopkins University Applied Physics Laboratory, Laurel, MD, United States, 7. University of California Los Angeles, IGPP/EPSS, Los Angeles, CA, United States, 8. IRF Swedish Institute of Space Physics Uppsala, Uppsala, Sweden, 9. NASA Goddard Space Flight Center, Heliophysics Science Division, Greenbelt, MD, United States, 10. University of Maryland College Park, Department of Astronomy, College Park, MD, United States, 11. NASA Marshall Space Flight Center, Huntsville, AL, United States, 12. University of New Hampshire Main Campus, Durham, NH, United States, 13. KTH Royal Institute of Technology, Stockholm, Sweden, 14. University of Colorado, Laboratory for Atmospheric and Space Physics, Boulder, CO, United States

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 ~4mV/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

*Akira Kadokura[1], Naritoshi Kitamura[2], Yoshifumi Saito[2], Barbara L Giles[4], Christopher T Russell[3]

1. National Institute of Polar Research, 2. Institute of Space and Astronautical Science, 3. University of California, Los Angeles, 4. National Aeronautics and Space Administration, Goddard Space Flight Center

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

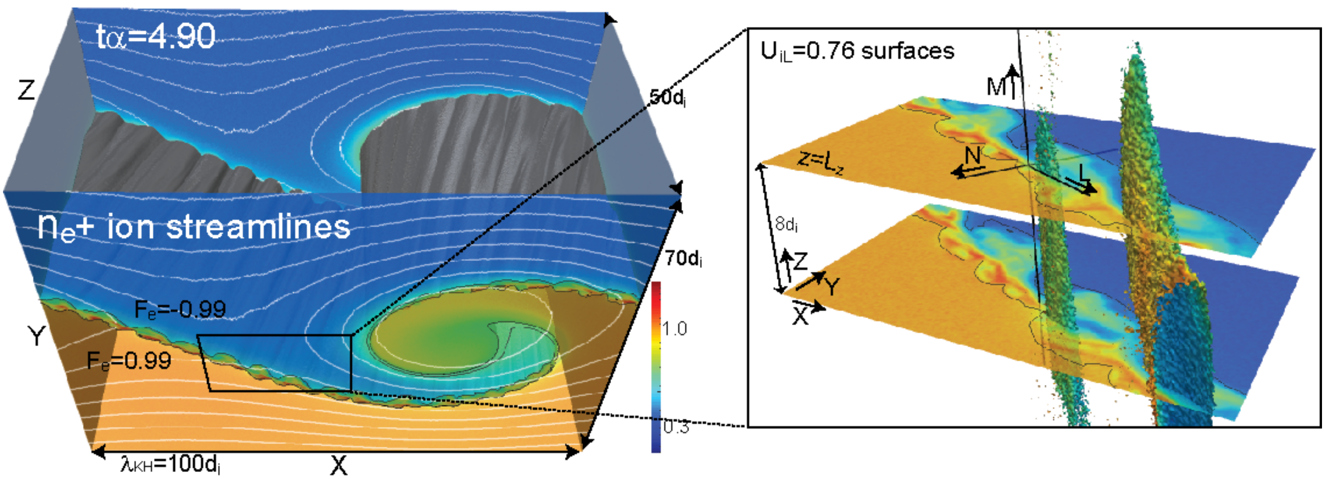
Event study of vortex-induced reconnection at the magnetopause using MMS observations and fully kinetic simulations

*Takuma Nakamura[1], Hiroshi Hasegawa[2], Stefan Eriksson[3], William Daughton[4], Wenya Li[5], Rumi Nakamura[1]

1. Space Research Institute, Austrian Academy of Sciences, 2. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 3. Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, 4. Los Alamos National Laboratory, 5. Swedish Institute of Space Physics

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

*Yoann Vernisse[1,2], Benoit Lavraud[1,2], Stefan Eriksson[3], Matteo Faganello[4], Daniel J. Gershman[5,6], John Dorelli[5], Craig J Pollock[5], Barbara Giles[5], Nicolas Aunai[7], Levon Avanov[5,6], Jim Burch[8], Michael Chandler[9], Victoria Coffey[9], Jérémy Dargent[1,7], Robert Ergun[3], Charlie Farrugia[10], vincent genot[1,2], Daniel Graham[11], Hiroshi Hasegawa[12], Christian Jacquey[1,2], Issaad Kacem[1,2], Yuri Khotyaintsev[11], Wenya Li[11], Werner Magnes[13], Aurélie Marchaudon[1,2], Thomas earle Moore[5], William r Paterson[5], Emmanuel Penou[2,1], Tai Phan[14], Alessandro Retino[7], Christopher t Russell[15], Yoshifumi Saito[12], Jean-André Sauvaud[1,2], Conrad Schiff[5], Roy Torbert[10], Frederick Wilder[3], Shoichiro Yokota[12]

1. Institut de Recherche en Astrophysique et Planétologie, Université Paul Sabatier, Toulouse, France, 2. Centre National de la Recherche Scientifique, France, 3. Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, Colorado, USA, 4. Laboratoire de Physique des Interactions Ioniques et Moléculaires, Université Aix-Marseille, Marseille, France, 5. NASA Goddard Space Flight Center, Greenbelt, Maryland, USA, 6. Department of Astronomy, University of Maryland, College Park, Maryland, USA, 7. Laboratoire de Physique des Plasmas, Palaiseau, France, 8. Southwest Research Institute, San Antonio, Texas, USA, 9. NASA Marshall Space Flight Center, Huntsville, Alabama, USA, 10. Physics Department and Space Science Center, University of New Hampshire, Durham, New Hampshire, USA, 11. Swedish institute of Space Physics, Uppsala, Sweden, 12. Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan, 13. Space Research Institute, Austrian Academy of Sciences, Graz, Austria, 14. Space Sciences Laboratory, Berkeley, California, USA, 15. Institute of Geophysics and Planetary Physics, and Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA

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

*Hiroshi Hasegawa[1], Takuma Nakamura[2], Naritoshi Kitamura[1], Barbara L. Giles[3], Christopher T Russell[4], Yuri V. Khotyaintsev[5], Robert E. Ergun[6], Yoshifumi Saito[1]

1. Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, 2. Space Research Institute, Austrian Academy of Science, 3. NASA Goddard Space Flight Center, 4. Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, 5. Swedish Institute of Space Physics, 6. Department of Astrophysical and Planetary Sciences, University of Colorado

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

*Mitsuo Oka[1], Arthur J Hull[1], Masahiro Hoshino[2], Tai Phan[1], Takanobu Amano[2], the MMS Team

1. University of California Berkeley, 2. The University of Tokyo

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 accel- eration’ 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

*Sun Hee Lee[1], David G. Sibeck[1], Kyoung-Joo Hwang[1,2], Yongfu Wang[3], Marcos V. D. Silveira[1], Christina Chu[4], Barry Mauk[5], Ian J. Cohen[5], George C. Ho[5], Glenn M. Mason[5], Robert E. Gold[5], Jim L. Burch[6], Barbara L. Giles[1], Roy B. Tobert[7], Christopher T. Russell[8], Hanying Wei[8]

1. NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA., 2. Goddard Planetary and Heliophysics Institute, University of Maryland, Baltimore County, Baltimore, MD 21228, USA., 3. Institute of Space Physics and Applied Technology School of Earth and Space Sciences, Peking University, Beijing 100871, China., 4. University of Alaska Fairbanks, Fairbanks, AK 99775, USA., 5. The Johns Hopkins University Applied Physics Laboratory, 11100 Johns Hopkins Rd., Laurel, MD 20723, USA., 6. Southwest Research Institute, San Antonio, TX, USA., 7. University of New Hampshire, Durham, NH, USA., 8. University of California, Los Angeles, CA, USA.

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

*William R Paterson[1], Mostafa El-Alaoui[2], Barbara L Giles[1], Alex C Barrie[1], Scott A Boardsen[1], Levon A Avanov[1], John C Dorelli[1], Daniel J Gershman[1], David A Mackler[1], Melvyn L Goldstein[1], Craig J Pollock[3], Thomas E Moore[1], James L Burch[5], Christopher T Russell[2], Robert J Strangeway[2], Roy B Torbert[4]

1. NASA GSFC, 2. UCLA, 3. Denali Scientific, 4. Univ. New Hampshire, 5. Southwest Research Inst.

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.

