Fundamental Physical Processes in Solar-Terrestrial Research and Their Relevance to Planetary Physics 2018

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ABSTRACT BOOK

TABLE OF CONTENTS

SOLAR WIND, BOW SHOCK, and DAYSIDE MAGNETOSPHERE

Recent Results from a Three-dimensional MHD Simulation of the Solar Corona and Solar Wind

Melvyn L Goldstein (1,2), Arcadi Usmanov (3), William H Matthaeus (3), and Rohit Chhiber (3)
(1) University of Maryland Baltimore County
(2) Space Flight Center
(3) University of Delaware

I will present recent results from a three-dimensional MHD model of the solar corona and solar wind that includes effects of turbulence. Turbulence transport equations for turbulence energy, cross helicity, and correlation length are coupled and solved concurrently with Reynolds-averaged solar wind equations in the region extending the coronal base to the outer heliosphere beyond the termination shock. The results are applied to study the heating, acceleration and three-dimensional properties of the corona and solar wind and are compared with data from Ulysses during its first and third fast latitude transits.

Interplanetary flux ropes of a low twist

Marek Vandas (1) and Eugene Romashets (2)
(1) Astronomical Institute, CAS, Prague, Czech Republic
(2) LSC, Houston, Texas, USA

Recent investigations indicate that interplanetary flux ropes are low twisted. It is in contrast with common magnetic field models which are used to fit them, namely constant-alpha force-free fields, the twist of which increases without limits toward the flux-rope boundary. We present analytical magnetic field configurations with low twists in cylindrical as well as in toroidal geometries. They are compared with in situ observations of magnetic clouds. Average levels of twist and its change across the flux ropes are inferred from these comparisons.

Solar Wind Interactions and Soft X-rays

David Sibeck (1)
(1) Space Weather Laboratory, NASA/GSFC

High charge state solar wind ions (O6+, O7+, C6+, etc) emit soft X-rays isotropically when they capture electrons from neutral atoms. Narrow field-of-view imagers have observed the resulting line emissions coming from comets, Mars, Venus, the heliospheric focussing cone, and the Earth's cusps, dayside and flank magnetosheath. Results from simulations employing global magnetohydrodynamic and exospheric models indicate that the locations of the bow shock, magnetopause, and cusps should be readily identifiable in the images obtained by wide field-of-

view soft X-ray telescopes. We describe both the prospects and the scientific objectives for such telescopes in near-Earth orbit. These include studies of the bow shock location and motion as a function of solar wind conditions, dawn/dusk asymmetries in magnetosheath properties, the nature and extent of reconnection on the dayside magnetopause, and the response of the cusps to varying solar wind conditions.

Planetary Foreshocks: Common & Uncommon Features

Nick Omidi and David Sibeck
(1) Solana Scientific Inc. (2) NASA/GSFC

Planetary foreshocks form upstream of quasi-parallel shocks due to ion reflection and leakage at the shock and formation of backstreaming ion beams. The interaction between these beams and the solar wind result in the generation of ULF waves and the associated nonlinear structures. In particular, recent hybrid (kinetic ions, fluid electrons) simulations and spacecraft observations at the Earth's foreshock have shown the presence of structures termed foreshock cavitons that form as a result of the nonlinear evolution of parallel and obliquely propagating fast magnetosonic waves. Both simulations and observations at Earth show that foreshock cavitons are carried by the solar wind towards the bow shock resulting in the formation of a related nonlinear structure named spontaneous hot flow anomalies (SHFAs). Simulations show that SHFAs form for shock Alfvén Mach numbers of ~3 and larger regardless of the IMF direction with significant impacts on the magnetosheath such as the formation of magnetosheath filamentary structures (MFS), cavities and high speed jets. This suggests that cavitons and SHFAs are common features of planetary bow shocks. Spacecraft observations at Venus, Mars and Saturn confirm this expectation by demonstrating the formation of SHFAs in their foreshocks. Because the size of foreshock cavitons and SHFAs scales with the ion inertial length, their dimensions change with the solar wind density such that at the rocky planets they are of the order of 1 RE while at Saturn they are ~5-6 RE. As for uncommon features, recent simulations and Cassini observations show a highly unique foreshock associated with the formation of a single, deformed bow shock for the Titan-Saturn system during periods of high solar wind pressure. For example, the foreshock associated with Saturn's portion of the bow shock may fall upstream of the quasi-perpendicular portion of Titan's bow shock. As a result, ions can undergo acceleration through a combination of Fermi and shock drift acceleration processes not considered in the past. Similarly, the deformed bow shock may be associated with regions of space that fall in the foreshocks associated with both Titan and Saturn's portions of the shock leading to the highly unusual situation with two overlapping foreshocks.

Solar wind Magnetosphere Ionosphere Link Explorer (SMILE)

C. P. Escoubet (1), C. Wang (2), G. Branduardi-Raymont (3), S. Sembay (4), L. Dai (2), L. Li (2), E. Donovan (5), E. L. Spanswick (5), D. Sibeck (6), H. Laakso (7), A. Read (4), D. Agnolon (1), W. Raab (1), C. Runciman (1), A. Wielders (1), A. P. Dimmock (8), J. Li (2), J. Zheng (2)
(1) ESA/ESTEC (Netherlands), (2) NSSC/CAS (China), (3) MSSL - UCL (UK), (4) Leicester U. (UK), (5) Calgary U. (Canada), (6) GSFC (USA), (7) ESA/ESAC (Spain), (8) Aalto University (Finland)

The interaction between the solar wind and the Earth's magnetosphere, and the geospace dynamics that result, is a fundamental process in plasma physics. Understanding how this vast system works requires knowledge of energy and mass transport, and coupling between regions and between plasma and neutral populations. In situ instruments on a fleet of solar wind and magnetospheric observatories now provide unprecedented observations of Sun-Earth connection. However, we are still unable to quantify the global effects of those drivers, including the conditions that prevail throughout geospace. This information is the key missing link for developing a complete understanding of how the Sun gives rise to and controls Earth's plasma environment and space weather. Solar wind Magnetosphere Ionosphere Link Explorer (SMILE) is a novel selfstanding mission dedicated to observing the solar wind-magnetosphere coupling via simultaneous in situ solar wind/magnetosheath plasma and magnetic field measurements, X-Ray images of the magnetosheath and polar cusps, and UV images of global auroral distributions. Remote sensing of the magnetosheath and cusps with X-ray imaging is now possible thanks to the relatively recent discovery of solar wind charge exchange (SWCX) X-ray emission, first observed at comets, and subsequently found to occur in the vicinity of the Earth's magnetosphere. SMILE is a collaborative mission between ESA and the Chinese Academy of Sciences (CAS) that was selected in November 2015 and is due for launch at the end of 2021. The SMILE science as well as the results of the on-going study undertaken jointly by ESA and CAS will be presented.

The Upstream Energetic Particle Debate at Earth and Beyond

Ian Cohen(1), Barry Mauk(1), Joe Westlake(1), Sasha Ukhorskiy(1), David Sibeck(2), Joe Fennell(3), Bern Blake(3), Drew Turner(3), Dan Baker(4), Trevor Leonard(4), Allison Jaynes(5), Harlan Spence(6), and Geoff Reeves(7)
(1) JHU/APL, (2) NASA GSFC, (3) Aerospace Corp., (4) CU/LASP, (5) Univ. of Iowa, (6) UNH, (7) LANL

The observation of energetic (greater than tens of keV) particles outside of planetary magnetospheres is common. In fact, the discovery of such particles beyond the Earth's magnetopause were made early on in the space age, spawning a rich legacy of investigation. A debate arose in the literature as to whether these energetic particles are sourced by the solar wind and accelerated near the bow shock (e.g., shock drift or Fermi acceleration) or whether these are particles from the magnetosphere that have escaped beyond the magnetopause (e.g., through either magnetic reconnection or "leakage" due to finite gyroradius effects). This talk will review some of the history of this debate, including observations at other magnetized and unmagnetized planetary bodies, and review new insights afforded by recent measurements from the Energetic Particle Detector (EPD) investigation aboard MMS.

The structure of low Mach number, low beta, quasi-perpendicular collisionless shocks

Lynn B. Wilson III (1) and A. Koval (1) and A. Szabo (1) and M.L. Stevens (2) and J.C. Kasper (3) and C.A. Cattell (4) and V.V. Krasnoselskikh (5)
(1) NASA Goddard Space Flight Center, Heliophysics Division, Greenbelt, MD 20771, USA
(2) Harvard-Smithsonian Center for Astrophysics, Harvard University, Cambridge, MA 02138, USA
(3) University of Michigan, Ann Arbor, School of Climate and Space Sciences and Engineering, Ann Arbor, MI 48109, USA
(4) University of Minnesota, School of Physics and Astronomy, Minneapolis, MN 55455, USA
(5) University of Orleans, LPC2E/CNRS, Orleans, France

We present results from a recent study [Wilson et al., 2017] of the structure of 145 low Mach number (M ≤ 3), low beta (beta ≤ 1), quasi-perpendicular interplanetary collisionless shock waves observed by the <i>Wind</i> spacecraft has provided strong evidence that these shocks have large amplitude whistler precursors. The common occurrence and large amplitudes of the precursors raise doubts about the standard assumption that such shocks can be classified as laminar structures. This directly contradicts standard models. In 113 of the 145 shocks (~78%), we observe clear evidence of magnetosonic-whistler precursor fluctuations with frequencies ~0.1--7 Hz. The presence or absence of precursors showed no dependence on any shock parameter. The majority (~66%) of the precursors propagate at ≤45° with respect to the upstream average magnetic field, most (~87%) propagate ≥30° from the shock normal vector, and most (~79%) propagate at least 20° from the coplanarity plane. The peak-to-peak wave amplitudes are large with a range of maximum values of ~0.2--13 nT with an average of ~3 nT. When we normalize the wave amplitudes to the upstream averaged magnetic field and the shock ramp amplitude, we find average values of ~50% and ~80%, respectively.

Plasma Heating of Nonlinear Structures Upstream of Earth's Bow Shock

George Parks, E. Lee, S. Y. Fu, N. Lin, Y. Liu, Z. W. Yang
(1) Space Sciences Laboratory, UC Berkeley, Berkeley, CA
(2) Astronomy and Space Science Department, Kyung Hee University, Suwon, Korea
(3) Department of Geophysics, Peking University, Beijing, China
(4) NSSC, CAS, Spaceweather, Beijing, China

Nonlinear structures upstream of Earth's bow shock are often heated to ten times that of the SW beam. Wave-particle interaction has been suggested but a specific mechanism has not been identified. SW plasma is treated as collisionless and the Vlasov theory is used to interpret the observations. However, the Vlasov equation is time symmetric and can only describe reversible processes. Heating involves irreversible process, which requires particles to diffuse in velocity space. Bernstein and Tehran (1960) first studied the perturbed Vlasov equation and showed that there are growing solutions whose amplitudes can become nonlinear. They suggest that the nonlinear waves can break like steepened water waves releasing energy to heat the particles. Schmidt (1966) discussed a beam distribution that somehow gets scattered into a narrow shape spiral, conserving entropy as the temperature increases because the plasma us spread over larger velocity space. There is also a dilemma that PIC codes can produce heating. The particles in PIC codes move obeying the Lorentz force and therefore cannot produce heating by design. One speculative idea about resolving this dilemma is to consider phase mixing of various waves with inhomogeneous plasmas, creating small-scale structures that occupy a larger velocity space. Future work will need to verify that phase mixing indeed occurs in PIC codes resulting in higher temperatures.

MMS Observations of Hot Flow Anomalies

Hui Zhang
University of Alaska Fairbanks

Hot flow anomalies (HFAs) are events observed near planetary bow shocks that are characterized by greatly heated solar wind plasmas and substantial flow deflection. HFAs are universal phenomena that have been observed near the bow shock of Earth, Venus, Mars, and Saturn. The dynamic pressure inside HFAs is lower than the ambient solar wind due to the density depletion and flow deflection. The passage of HFAs will therefore result in local negative pressure impulses, which lead to a local sunward expansion of the magnetopause. HFAs can also transmit compressional waves into the magnetosphere that can excite resonant ULF waves and cause particles to scatter into the loss cone and precipitate into the ionosphere, generate field-aligned currents in the magnetosphere that drive magnetic impulse events in the high-latitude ionosphere, and trigger transient auroral brightenings. NASA's MMS mission produce unprecedented high resolution data, which enable the observations of HFA structures in great details.

Particle Acceleration in a Hot Flow Anomaly

Sun Lee (1) and David Sibeck (1)
(1) NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

We present multi-point observations of foreshock transient events and their impact on the Earth's magnetosphere. The four Magnetospheric Multiscale (MMS) spacecraft observed a hot flow anomaly (HFA) at the boundary of the quasi-parallel and quasi-perpendicular bow shock on 28 December 2015. The HFA is identified by a greatly decelerated and deflected antisunward flow, a significant increase in temperature, and depressed plasma densities and magnetic field strengths flanked by enhanced plasma densities and magnetic field strengths. Energetic particles (E > 50 keV) within the event appear to have escaped from the outer magnetosphere rather than energization of solar wind particles within the foreshock. The escaping energetic ions may be further energized within the quasi-parallel foreshock. We will compare the observations with the predictions of various particle energization mechanisms to determine the relationship between

the foreshock transient and ion energization. Observed magnetospheric responses to this transient phenomenon include transient magnetic field variations in ground magnetograms and ionospheric flow enhancements. We will also inspect the magnetospheric response to this transient event with simultaneous in-situ observations of inner magnetosphere by Cluster and Geotail.

Comparing and contrasting transient ion foreshock phenomena observed by MMS and their effectiveness for particle acceleration

Drew Turner (1)
(1) The Aerospace Corp.

On the dayside of Earth's system, NASA's Magnetospheric Multiscale (MMS) mission, consisting of four identically instrumented spacecraft, often spends time in the ion foreshock region upstream of the bow shock. From those periods, multiple foreshock transient events were captured in burst mode by the MMS Scientists in the Loop, offering unprecedented multipoint observations and resolution of plasma, energetic particles, and electric and magnetic fields and waves. In this presentation, we compare and contrast details of multiple transient ion foreshock phenomena (e.g., hot flow anomalies, foreshock bubbles) observed by MMS. In particular, we focus on which foreshock transients are effective at accelerating energetic particles (> a few keV electrons and >10s of keV ions) and which are not. We compare and contrast key characteristics of each type of event to investigate the nature of the particle acceleration. We also discuss how such acceleration methods may be important at collisionless plasma shocks throughout the Universe.

Fermi acceleration of electrons inside foreshock transient cores

Terry Z. Liu (1), San Lu (1), Vassilis Angelopoulos (1), Heli Hietala (1), and Lynn B. Wilson III (2)
(1) Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA,
(2) NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Foreshock transients upstream of Earth's bow shock have been recently observed to accelerate electrons to many times their thermal energy. How such acceleration occurs is unknown, however. Using THEMIS case studies, we examine a subset of acceleration events (31 of 247 events) in foreshock transients with cores that exhibit gradual electron energy increases accompanied by low background magnetic field strength and large-amplitude magnetic fluctuations. Using the evolution of electron distributions and the energy increase rates at multiple spacecraft, we suggest that Fermi acceleration between a converging foreshock transient's compressional boundary and the bow shock is responsible for the observed electron acceleration. We then show that a one-dimensional test particle simulation of an ideal Fermi acceleration model in fluctuating fields prescribed by the observations can reproduce the observed evolution of electron distributions, energy increase rate, and pitch-angle isotropy, providing further support for our hypothesis. Additionally, using THEMIS observations and 3-D global hybrid simulations, we show that similar acceleration processes can also operate on ions.

Dayside magnetosphere and ionosphere responses to transient upstream disturbances measured by satellite-imager coordination

Boyi Wang (1); Yukitoshi Nishimura (2); Heli Hietala (3); Xiaochen Shen (4); Quanqi Shi (5); Hui Zhang (6); Larry Lyons (7); Vassilis Angelopoulos (8); Yusuke Ebihara (9); Allan Weatherwax (10)
(1) University of California, Los Angeles; (2) Boston University

Localized upstream disturbances, such as foreshock transients and magnetosheath high speed jets (HSJs), which can occur in absence of interplanetary shocks, could be geo-effective. In this study, coordinated observations between the THEMIS satellites and the all-sky imager at South

Pole during 2008-2010 are used to investigate magnetosphere and ionosphere responses to localized upstream disturbances. 2-d measurements by imaging allow to find a structure and propagation of magnetosphere-ionosphere responses much more in detail than possible by other means of observations. The THEMIS satellites observed magnetopause compression and localized ULF waves in the dayside magnetosphere in most cases, and sometimes, travelling convection vortices (TCVs) can be identified by the ground-based magnetometers. The all-sky imager at South Pole observed that both diffuse and discrete aurora brightened locally soon after the occurrence of the upstream disturbances. The auroral size mapped to the equator was few Re in GSM-Y and mostly propagated azimuthally, in a consistence with the Vy of the corresponding magnetosheath flows. This reveals the azimuthal geo-effective scale of the upstream disturbances, and the propagation is suggested to follow the background magnetosheath flows. This study presents that the localized upstream disturbances can have substantial impacts on the magnetosphere-ionosphere coupling system, causing magnetospheric compression and aurora brightening, in a similar manner to responses during interplanetary shocks except for a smaller scale-size.

Average and extreme locations and shapes of the magnetopause boundary and associated characteristics at Earth and at other solar system bodies

Steven Petrinec
Lockheed Martin ATC

It has long been understood that planetary bodies possessing significant intrinsic magnetic field stand off and deflect the incident solar wind flow. The internal space plasma environment (the magnetosphere) is thus separated from the plasma of the heliosphere along a three-dimensional surface discontinuity (the magnetopause). This boundary acts as an obstacle to the super-magnetosonic solar wind, but can vary in shape and location relative to the planet in response to changes in internal and external pressures and the magnetic dipole tilt of the planet. The shape and location is also influenced by dynamic processes such as magnetic reconnection. The current understanding of the average and extreme locations of this boundary and associated characteristics at the magnetized planets of the solar system are described, compared, and contrasted.

Variations of plasma parameters in the magnetopause region

Harri Laakso and Helen Middleton
ESA/ESAC, Madrid, Spain

We use multi-point observations from the Cluster spacecraft to investigate the variations of plasma parameters in the magnetopause region, in particular with respect to the location of the magnetopause current layer. With help of the curlometer technique we determine the location of the magnetopause current layer and its variability in the cases where the magnetopause is moving back and forth. The Cluster spacecraft carry a complete set of plasma and field instruments that allow us to observe the variations of the plasma and field parameters in the magnetopause and boundary layer region. We are particularly interested in seeing how and where other parameters such as the plasma density and the electron and ion drift velocities vary with respect to the main current layer. It appears that the main current sheet exists in the outer edge of the magnetopause region, and for instance the main density gradient in the magnetopause region occurs earthward of the current layer.

An MHD simulation of magnetospheric dynamics for the weak solar wind and small-scale magnetic flux rope

Kyung Sun Park (1), Dae-Young Lee (1)
(1) Dep. Astronomy and Space Science, Chungbuk National University, Korea

Topology of magnetic field lines in the earth's magnetosphere is determined by magnetic reconnection between the IMF and geomagnetic field. For understanding where the magnetic reconnection occur, how the reconnected field lines move to tail, and how many energy transported from the solar wind, we have performed a three-dimensional global MHD simulation to examine effect of the weak solar wind and small-scale magnetic flux rope conditions. The simulation results show that the magnetic reconnection favorably occur in anti-parallel field region at the dayside magnetopause with a slower shear velocity in magnetosheath to dominantly control successive magnetospheric dynamics. Also, the dayside magnetopause reconnection occur at dusk/dawn sector and high latitude in both hemisphere with a finite IMF By component. The cross polar cap potential usually increase over 20 kV and it is mainly governed by IMF Bz as well as By and magnitude of B. It suggest the possibility that the magnetospheric disturbance can result by even though small-scale solar wind and IMF condition.

The dayside magnetopause reconnection location: predictions and open questions

K.J. Trattner(1), J.L. Burch(2), R. Ergun(1), S. Eriksson(1), S.A. Fuselier(2), B. Giles(4), S.M. Petrinec(3), R.J. Strangeway(5) and F.D. Wilder(1)
(1) University of Colorado, Boulder, CO 80303, USA
(2) Southwest Research Institute, San Antonio, TX 78253, USA
(3) Lockheed Martin Advanced Technology Center, Palo Alto, CA 94304 USA
(4) NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA
(5) University of California, Los Angeles, CA 90095, USA

Magnetic reconnection at the Earth's magnetopause is discussed and has been observed as anti-parallel and 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) predicts the location of the reconnection line to be anchored at the sub-solar point and extend continuously along the dayside magnetopause, while the ratio of the IMF By/Bz component 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 model predicts that during dominant IMF By conditions, magnetic reconnection occurs along an extended line across the dayside magnetopause but generally not through the sub-solar point (as predicted in the original tilted X-line model). Rather, the line follows the ridge of maximum magnetic shear across the dayside magnetopause. In contrast, for dominant IMF Bz (155° < tan-1(By/Bz) < 205°) or dominant Bx (|Bx|/B > 0.7) conditions, the reconnection location bifurcates and traces to high-latitudes, in close agreement with the anti-parallel reconnection scenario, and does not cross the dayside magnetopause as a single tilted reconnection line. This presentation will revisit the predictions for the magnetopause reconnection location and discuss open issues with our ability to determine the reconnection location.

Variability at Earth's dayside magnetopause

Jean Berchem (1), Robert L. Richard (1), Giovanni Lapenta (2), C. Philippe Escoubet (3), William R. Paterson (4)
(1) UCLA (2) KU Leuven (3) ESTEC ESA (4) GSFC NASA

There are numerous sources for the variability of the Earth's dayside magnetopause. Some of these are related to the global interaction between the solar wind and the magnetosphere-ionosphere system such as the impact of solar wind discontinuities with the magnetospheric boundary, while others are related to local microprocesses such as variations in magnetic reconnection. They all can significantly affect the dayside magnetosphere. Examples include the development of unexpected global magnetospheric asymmetries in particle precipitation and the generation of magnetic flux ropes that lead to flux transfer events. Understanding the nature of the variability and predicting its consequences is challenging because of the local-global duality of its sources. It necessitates resolving both the global evolution of the dayside magnetosphere resulting from large-scale stresses and the local dynamics of kinetic processes. To this end we have carried out numerical studies that combine global magnetohydrodynamic (MHD) simulations with implicit particle-in-cell (iPIC3D) and large-scale kinetic (LSK) simulations. We present the results of simulations that focus on relatively simple solar wind conditions and examine variability at the dayside magnetopause and its impacts. In these studies, we first use the low dissipation, high resolution UCLA global MHD code to determine the large-scale stresses imposed on the dayside magnetosphere by the solar wind. Then, kinetic models using global plasma parameters and fields from the MHD simulations are used to follow the local evolution of kinetic processes and predict observable signatures that can be compared with spacecraft observations.

Magnetic Reconnection Variability

Stephen A. Fuselier, Karlheinz J. Trattner, Steven M. Petrinec, Sarah K. Vines, Craig A. Kletzing
Southwest Research Institute, Laboratory for Astrophysics and Space Physics, Lockheed Martin Advanced Technology Center, Applied Physics Laboratory, University of Iowa

Magnetic reconnection at the Earth's magnetopause is a fundamental physical process and is the dominant mechanism for transfer of mass and energy into the magnetosphere. The variability of this process has been debated since the first observations that confirmed the presence of reconnection at the magnetopause. Observations during northward IMF conditions show that reconnection can be quasi-steady and quasi-stationary for hours. Observations of Flux Transfer Events during southward IMF conditions suggest variability in reconnection in both time and space. This talk focuses on the investigation of reconnection variability at the dayside magnetopause and in the magnetospheric cusps.

Electron dynamics surrounding the X line in asymmetric magnetic reconnection

Seiji Zenitani (1), Hiroshi Hasegawa (2), and Tsugunobu Nagai (3)
Kyoto U (1), JAXA/ISAS (2), Tokyo Tech (3)

Electron dynamics surrounding the X line in magnetopause-type asymmetric reconnection is investigated using a two-dimensional particle-in-cell simulation. We study electron properties of three characteristic regions in the vicinity of the X line. The fluid properties, velocity distribution functions (VDFs), and orbits are studied and cross-compared. On the magnetospheric side of the X line, the normal electric field enhances the electron meandering motion from the magnetosheath side. The motion leads to a crescent-shaped component in the electron VDF, in agreement with recent studies. On the magnetosheath side of the X line, the magnetic field line is so stretched in the third dimension that its curvature radius is comparable with typical electron Larmor radius. The electron motion becomes nonadiabatic, and therefore the electron idealness is no longer expected to hold. Around the middle of the outflow regions, the electron nonidealness is coincident with the region of the nonadiabatic motion. Finally, we introduce a finite-time mixing fraction (FTMF) to evaluate electron mixing. The FTMF marks the magnetospheric side of the X line, where the nonideal energy dissipation occurs.

Reconnection and Turbulence: A Timely Nexus of Collisionless Space Plasma Phenomena

Craig Pollock
Denali Scientific

Both magnetic reconnection and plasma turbulence are multi-scale fundamental processes for which required energy dissipation mechanisms have thus far eluded our understanding. In the case of reconnection, the length scales over which the reconnection-enabling energy dissipation typically occurs are comparable to the local electron inertial length, near one km in the on the sheath side of Earth's magnetopause and several km at reconnection sites in Earth's geomagnetic tail. Turbulent dissipation is thought to occur on very short scales, at the small-scale

end of some Kolmogorov-like cascade. Again, electron scales are implicated. In both cases, one process gives rise to the other. Reconnection induces turbulence in super-alfvenic ion and electron outflows. Turbulent fields of magnetized plasma flows and their dragged-along magnetic fields spawn local reconnection within the field. Space plasma diagnostics at small scales requires high time resolution measurements owing to the short length scales and substantial convection velocities involved. In this paper we explore these issues, expose relevant recent results from NASA's Magnetospheric Multiscale (MMS) mission, and address potential future progress in these areas.

MMS Observations of Magnetic Reconnection in Turbulent Magnetosheath Current Sheets

Tai Phan, and the MMS team
UC Berkeley

The magnetosheath region downstream of quasi-parallel bow shocks is an ideal region to investigate the possible occurrence of reconnection in plasma turbulence. This region often contains hundreds of small-scale current sheets in which reconnection could potentially occur. These current sheets are thin, and they convect past spacecraft typically in a few seconds or less. MMS is the first mission that can resolve such current sheets with plasma measurements to reveal the presence or absence of reconnection plasma jettings. Here we will show the unprecedented multi-spacecraft observations of bi-directional super-Alfvenic electron jets, parallel electric fields, and enhanced magnetic-to-particle energy conversion, providing direct evidence for reconnection in a turbulent current sheet. We will discuss the implications of this finding for the understanding of the role of reconnection in turbulent plasmas.

The Role of Parallel Electric Fields in Magnetic Reconnection As Observed by MMS

Frederick Wilder (1), Robert Ergun (1), Narges Ahmadi (1), Katherine Goodrich (1), Stefan Eriksson (1), James Burch (2), Tai Phan (3), Roy Torbert (4), Barbara Giles (5), Per-Arne Lindqvist (6), Yuri Khotyaintsev (7)
(1) University of Colorado Boulder (2) Southwest Research Institute (3) University of California, Berkeley (4) University of New Hampshire (5) NASA GSFC (6) Royal Institute of Technology (7) Uppsala University

In 2015, NASA launched the Magnetospheric Multiscale (MMS) mission to study phenomena of magnetic reconnection down to the electron scale. One advantage of the MMS is a 20s spin period, and long axial booms, which together allow for measurement of 3-D electric fields with accuracy down to 1 mV/m. During the two dayside phases of the prime mission, MMS has observed multiple electron and ion diffusion region events at the Earth's subsolar and flank magnetopause, as well as in the magnetosheath, providing an option to study both symmetric and asymmetric reconnection at a variety of guide field strengths. We present a review of parallel electric fields observed by MMS crossings near the diffusion region, and discuss their role in the dissipation process in magnetic reconnection. We find that as the guide field increases, the dissipation in the diffusion region transitions from being due to currents and fields perpendicular to the background magnetic field, to being associated with parallel electric fields and currents sooner than expected. Additionally, the observed parallel electric fields are significantly larger than what are predicted in simulations under strong guide field conditions.

Energy partition during asymmetric reconnection

Shan Wang 1,2, Li-Jen, Chen 1,2, Naoki Bessho 1,2, Michael Hesse 3, Masaaki Yamada 4, Jongsoo Yoo 4 and MMS team
(1) University of Maryland College Park, USA (2) NASA Goddard Space Flight Center, USA
(3) University of Bergen, Norway, (4) Princeton Plasma Physics Laboratory, USA

The energy conversion in the diffusion region during asymmetric reconnection is studied using particle-in-cell (PIC) simulations and measurements from the Magnetospheric Multiscale (MMS) spacecraft. The simulation result shows that the energy partition is region-dependent and vary with the guide field strength. Without a guide field, within the central electron diffusion region, the input magnetic energy is mostly converted to the electron thermal energies; over the entire ion diffusion region, about half of the energy goes to ions, and 20% goes to electrons. Electrons obtain energies mainly from the reconnection electric field (Er), and in-plane electric field (Ein) does negative work to electrons. For the ion total energy gain in the diffusion region, Er and Ein have comparable contribution. Adding a guide field tends to reduce the plasma energy gain through reducing the contribution from Ein, even though the reconnection rates are similar. The energy partition in the diffusion region observed by MMS is estimated and compared with the results from PIC simulations.

On the Ubiquity of Electron Phase Space Holes Deep within Dayside Asymmetric Magnetic Reconnection Exhausts

S. Eriksson (1), D. L. Newman (2), L. Andersson (1), N. Ahmadi (1), S. J. Schwartz (1), R. E. Ergun (1), K. J. Trattner (1), F. D. Wilder (1), G. Lapenta (3), J. L. Burch (4), B. L. Giles (5), R. J. Strangeway (6), and R. B. Torbert (7)
(1) Laboratory for Atmospheric and Space Physics, University of Colorado Boulder
(2) Center for Integrated Plasma Studies, University of Colorado Boulder
(3) Center for Mathematical Plasma Astrophysics, Department of Mathematics, University of Leuven, Leuven, Belgium
(4) Southwest Research Institute, San Antonio, Texas, USA
(5) NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
(6) Institute of Geophysics and Planetary Physics, and Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, California, USA
(7) Physics Department and Space Science Center, University of New Hampshire, Durham, New Hampshire, USA

New MMS observations show a ubiquitous presence of electron phase space holes deep within dayside asymmetric exhaust regions. There is no clear evidence of any double layers in the vicinity of the observed electron holes. The predominantly negative-then-positive bipolar parallel electric fields in a positive Bzgsm magnetic field suggest a source region in the direction of the magnetic reconnection X-line that generated these southward ion jets.

Electron scale magnetic hole formation and implication

H. Liu (1), Q.-G. Zong (1), X.-Z. Zhou (1)
(1) Peking University
Institute of Space Physics and Applied Technology, Peking University, Beijing, China

It has been tens of years since the first study of magnetic holes in space plasma physics. Recently, small scale magnetic holes have attracted attentions after the launch of the MMS spacecraft. In this paper, we re-analyze an electron scale magnetic hole event in the dayside magnetosheath on 23 Oct 2015, using an energetic particle sounding technique. By this technique we are able to directly detect the boundary of the hole, and obtain the shape and the size quantitatively. Our analyses show that the shape of the boundary is a circle, and the radius is only about 9.3 km, which would be even smaller than the gyro-radius of a 3 keV electron, and the spacecraft motion relative to the magnetic hole is also obtained.

Multi-scale Investigations of Dayside Dynamics

Kyoung-Joo Hwang (1), Eunjin Choi (2,3), D. G. Sibeck (2), J. L. Burch (1), B. L. Giles (2), D. Gershman (2), C. J. Pollock (4), R. E. Ergun (5), Y. Khotyaintsev (6), J. C. Dorelli (2), L. Avanov

(2,3), W. R. Paterson (2), C. T. Russell (7), R. J. Strangeway (7), and R. B. Torbert (8)
(1) Southwest Research Institute, San Antonio, TX
(2) NASA Goddard Space Flight Center, Greenbelt, MD
(3) The Goddard Planetary Heliophysics Institute, University of Maryland, Baltimore County, Baltimore, MD
(4) Denali Scientific, LLC, Alaska, AK
(5) Laboratory for Atmospheric and Space Physics, University of Colorado at Boulder, Boulder, CO
(6) Swedish Institute of Space Physics, Uppsala, Sweden
(7) Institute of Geophysics and Planetary Physics, University of California, Los Angeles, Los Angeles, CA
(8) Space Science Center, University of New Hampshire, Durham, NH
Both observations and simulations indicate the frequent occurrence, often simultaneously, of current-driven magnetic reconnection and velocity shear driven flow vortices on the Earth's dayside magnetopause. The MMS spacecraft have emphasized multi-scale processes occurring throughout the Earth's magnetosphere, helping unravel the mysteries of magnetic reconnection and flux transfer events with unprecedented time-resolution measurements of particles and fields. MMS spacecraft observations not only enable the quantitative testing of micro and meso-scale reconnection physics but also permit the calculation of flow vorticities. Here we inspect MMS observations of magnetic reconnection, flux transfer events, and Kelvin-Helmholtz vortices to investigate multi-scale phenomena occurring on the magnetopause boundary and quantitative testing of micro and meso-scale physics. These dayside dynamics are key to the solar wind-magnetosphere coupling and Earth's global current system, which will ultimately improve our ability in space weather forecasts under a variety of external interplanetary conditions and structures.

Generation of turbulence observed in magnetopause Kelvin-Helmholtz vortices: Revisiting Magnetospheric Multiscale observations on 8 September 2015

Hiroshi Hasegawa (1), Takuma Nakamura (2), Dan J. Gershman (3), Naritoshi Kitamura (1), Yasuto Hoshi (1), Yoshifumi Saito (1), Adolfo F.-Vinas (3), Barbara L. Giles (3), Christopher T. Russell (4), Benoit Lavraud (5), Yuri V. Khotyaintsev (6), and Robert E. Ergun (7)
(1) Institute of Space and Astronautical Science, JAXA
(2) Space Research Institute, Austrian Academy of Science
(3) NASA Goddard Space Flight Center
(4) University of California, Los Angeles
(5) IRAP, University of Toulouse
(6) Swedish Institute of Space Physics
(7) University of Colorado Boulder
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, southern-hemisphere 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., GRL, 2016; Li et al., GRL, 2016]. The event was observed 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., JGR, 2016]. Key features are that (i) significant magnetic shears were seen only at the trailing edges of the KH surface waves, (ii) for both the leading and trailing edge traversals, both field-aligned and anti-field-aligned streaming D-shaped

ion populations, which are consistent with reconnection on the southward and northward sides, respectively, of MMS, were observed on either the magnetosheath or LLBL side of the magnetopause, though not always simultaneously, and (iii) the field-aligned Poynting flux was positive in some parts of the LLBL but was negative in other parts. Based on these observations and further wave analysis, we address the questions of how the current sheets at the KH wave trailing edges were generated, and what could have been the driver of the turbulent fluctuations observed within the KH vortices.

Three-dimensional Nonlinear Interaction Between Kelvin–Helmholtz Instability and Magnetic Reconnection

Ma Xuanye
Embry-Riddle Aeronautical University

It has been well demonstrated that the nonlinear Kelvin-Helmholtz (KH) instability plays a critical role for the solar wind interaction with the Earth's magnetosphere. Recently, more and more studies demonstrated the fundamental difference between the two- and three-dimensional (3-D) KH instability. For northward interplanetary magnetic field (IMF) conditions, the low-latitude nonlinear KH wave can dramatically bend the magnetic field lines and form strong anti-parallel magnetic field components at high latitudes, which triggers high-latitude magnetic reconnection in both north and south hemispheres. This high-latitude double reconnection process can exchange the portion of magnetosheath and magnetospheric flux tubes between those two reconnection sites, consequently transporting plasmas at the transport rate about 10^10 m^2/s for typical magnetopause conditions at Earth. For southward IMF conditions, both KH instability and magnetic reconnection can operate simultaneously. The well developed KH vorticity forms multiple thin current layers at low latitudes, which can cause patchy reconnection and complex flux rope structure. The overall reconnection rate is close to a fast Petschek reconnection rate, however, the total open flux is limited.

On the Heating of Plasma due to Kelvin-Helmholtz Instability

K. Nykyri (1), T. W. Moore (1), A. Dimmock (2), X. Ma (1)
(1) Embry-Riddle Aeronautical University, USA (2) Aalto University, Finland

Kelvin-Helmholtz instability (KHI) is a universal shear flow instability taking place in many plasma systems such as magnetospheres of magnetized and non-magnetized planets, solar corona, Coronal Mass Ejectas, astrophysical accretion disks, as well as in laboratory plasmas. During recent years it has been shown that KHI can produce significant plasma transport via reconnection in the vortices as well as via secondary mechanisms such as kinetic wave activity and diffusion through thin boundaries created by the KHI. Likely associated with this transport, statistical studies have shown that cold-component ions are about 30-40 percent hotter on the dawn side of the Earth's plasma sheet, where KHI more frequently occurs. In this talk we discuss the origin of plasma heating during Kelvin-Helmholtz Instability via various physical mechanisms associated with the KHI such as kinetic plasma waves and magnetic reconnection, by using data from ESAs Cluster mission, NASAs THEMIS and MMS missions, as well as high-resolution numerical simulations. Our statistical and case study results clearly demonstrate that the dawn-flank favored asymmetric evolution of the KHI and associated enhanced ion heating due to secondary mechanisms in KH vortices can explain the origin of dawn-favored plasma sheet temperature asymmetry of the cold-component ions.

Solar Energetic Electrons detected in the Earth’s cusp region by the BD-IES instrument

Linghua Wang(1)1, Q. -G. Zong(1), Quanqi Shi(2), R F Wimmer-Schweingruber(3), Jiansen He(1), Chuanyi Tu(1), Hui Tian(1) and Stuart D Bale(4)
(1)Institute of space physics and applied technology, Peking University, Beijing, China

(2)Shandong University at Weihai, Weihai, China (3)IEAP, University of Kiel, Kiel, Germany
(4)University of California Berkeley, Berkeley, CA, United States
Here we present a comprehensive study of three solar energetic electron events observed in the Earth's cusp region by the BeiDa Image Electron Spectrometer (BD-IES) instrument onboard an inclined (55°) geosynchronous orbit (IGSO) satellite, respectively, in 2015 October, 2015 November and 2016 January. In all the three events at ~50-200 keV, the omnidirectional differential fluxes from the BD-IES show a strong (~0.7-0.9) correlation with the electron fluxes measured by the WIND 3DP instrument in the solar wind, but with a generally smaller intensity (especially at lower energies). Compared to the WIND 3DP electron flux versus energy spectra, the BD-IES electron spectra also fit well to a power-law function, J ~ E-γ, but the observed spectral index γ appears to be smaller and decrease with time, for all the three events. These results suggest that solar energetic electrons can continuously enter the planets' cusp and get trapped there, probably leading to a contribution to the energetic electrons in the magnetosphere, e.g., in the radiation belts.

On Turbulence and Intermittency in the Polar Ionosphere

G. Consolini (1), P. De Michelis (2), F. Giannattasio (2), R. Tozzi (2), V. Quattrociocchi (1), I. Coco (2) and M.F. Marcucci (1)
(1) INAF-Istituto di Astrofisica e Planetologia Spaziali, Roma, Italy
(2) Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy
Turbulence is an ubiquitous phenomenon occurring in space plasmas, which plays a relevant role in plasma heating and acceleration. Recent studies [De Michelis et al, 2015, 2017] have evidenced how magnetic field fluctuations in the high latitude polar ionosphere are characterized by scaling features, which are compatible with the occurrence of turbulence. This is particularly true for magnetic fluctuations during disturbed periods in the regions which are interested by particle precipitation and heating and where FACs flow. Here, using data from the ESA-Swarm constellation we study the nature of magnetic field fluctuations and its relationship with the occurrence of turbulence and intermittency in the regions interested by FACs. The relationship with electronic heating is also investigated.

INNER MAGNETOSPHERIC PHYSICS

Solar Wind-Driven Enhancements and Losses of Radiation Belt Particles: Van Allen Probes Observations

Daniel N. Baker
Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO, USA.

The dual-spacecraft Van Allen Probes mission has provided a new window into megaelectron Volt (MeV) particle dynamics in the Earth's radiation belts. Observations (up to E ~10 MeV) show clearly the behavior of the outer electron radiation belt at different time scales: months-long periods of gradual inward radial diffusive transport and weak loss being punctuated by dramatic flux changes driven by strong solar wind transient events. Analysis of multi-MeV electron flux and phase space density (PSD) changes during key intervals from March 2012 into 2017 are presented in the context of the first several years of Van Allen Probes operation. These key periods demonstrate the classic signatures both of inward radial diffusive energization as well as abrupt localized acceleration deep within the outer Van Allen zone (L ~,4.0±0.5). Such results reveal graphically that both "competing" mechanisms of multi-MeV electron energization are at play in the radiation belts, often acting almost concurrently or at least in very rapid succession. They also show in remarkable ways how the coldest plasmas in the magnetosphere intimately control the most highly energetic particles.

The Sources for the Inner Radiation Belt – Revisited

Xinlin Li, Richard Selesnick, Quintin Schiller, Kun Zhang, Hong Zhao, Daniel Baker, and Michael Temerin
University of Colorado

Measurements from the Relativistic Electron-Proton Telescope integrated little experiment (REPTile) on board Colorado Student Space Weather Experiment (CSSWE) CubeSat, in a highly inclined low Earth orbit, showed that CRAND is the main electron source for the radiation belt near its inner edge, and also contributes to the inner belt (L<2) elsewhere. Furthermore, this direct measurement of the CRAND electron intensity provides the first experimental determination of the neutron density in near-Earth space, confirming earlier theoretical estimates. Comprehensive measurements of energetic protons (10s of MeV) in the inner belt and slot region (2<L<3) from the Relativistic Electron-Proton Telescope (REPT) onboard Van Allen Probes, in a geo-transfer-like orbit, revealed various features of these energetic protons in terms of their spectrum distribution, spatial distribution, pitch angle distribution, and their different dynamic variations associated with their different source populations. These are part of a summary of the most recent measurements and analysis of the dynamics of energetic particles in the inner zone and slot region to be exhibited and discussed in this presentation.

MMS FEEPS Energetic Electron Microinjection Observations During 2016-2017

J. F. Fennell(1), D. L. Turner(1), C. L. Lemon(1), S. Kavosi(2), H. E. Spence(2), T. Leonard(3), A. Jaynes(4), J. B. Blake(1), J. H. Clemmons(1), D. N. Baker(3), B. H. Mauk(5)
(1) Aerospace Corp., (2) University of New Hampshire, (3) University of Colorado,
(4) University of Iowa, (5) Johns Hopkins Applied Physics Laboratory

During MMS traversals of the midnight to dusk local time regions energetic electron data often show clusters of electron injections we call microinjections because of their short duration signatures. These microinjections of 50 to >400 keV electrons have energy dispersion signatures indicating that they gradient and curvature drifted from earlier local times. We show detailed results from some microinjections taken with burst mode data. We will also show a case where the microinjections were observed simultaneous with and superimposed upon a classic substorm electron injection profile at 10-11 Re altitude near local midnight. These data show that the energy of the electrons in the microinjections exceed those of the classic injection and were trapped with predominantly field-aligned angular distributions. Drift calculations constrained by the observed electron dispersion times indicate the electrons had drifted from near the magnetopause hours

earlier in local time. The 2016 observations were limited to altitudes of ~9 to 12 Re because the MMS apogee was 12 Re then. The MMS apogee was raised to 25 Re in March 2017 and we will show how these later microinjection observations compare to the earlier ones. These microinjection clusters are a new phenomenon in this region of the magnetosphere and with the higher orbit we will observe how close to the magnetopause they exist and possibly traverse the source regions. We will provide some statistics on the occurrence of the injections and discuss possible sources and implications.

The Radial Propagation Characteristics of the Injection Front: A Statistical Study Based on BD-IES and Van Allen Probes Observations

Q. -G. Zong, Z.Y. Liu, Y. X. Hao
Institute of Space Physics and Applied Technology, Peking University, Beijing, China.

By analyzing electron flux measurements outside geosynchronous orbit (GSO) returned from BeiDa Imaging Electron Spectrometer instrument onboard a 55°-inclined GSO satellite and measurements inside GSO returned from Van Allen Probes, temporal-spatial evolution of the substorm electron injection region is investigated. First, our study shows that in one injection event, the particle injection signatures can be detected in a large radial extent, for example, from L ~ 4.1 to L ~ 9.3. Then, injection onset times are derived from the energy dispersion of particle injection signatures with a method applicable to both dispersionless and dispersive injections. Analysis of them reveals the injection boundaries, which in turn, is termed as “injection front”, can propagate both earthward and tailward with a speed varying from a few km/s to ~100 km/s. Evolutions of the upper-cutoff magnetic moments (μ_{uc}) of injected electrons are also analyzed. The result indicates injection events studied in this paper can be classified into two categories: in one category μ_{uc} observed by the two radially separated satellites are approximately equal taking into account the error caused by the finite width of energy channels, whereas in the other category, μ_{uc} at lower L shells are smaller than that at higher L shells. Lastly, implication of the results is discussed.

Detection of ions injection in RBSPICE data

German Farinas Perez (1)   David Sibeck (2)   Alexa Halford(3)
NASA-Goddard Space Flight Center

We use data from the RBSPICE instrument aboard the Van Allen Probes spacecraft to identify particle injection events, specifically ion drift echoes and dispersive injection. An automatic routine was developed to detect the dispersive protons injections.124 protons injections events were observed for Van Allen Probes from Feb 2013- June 2017 (almost the entire mission). We calculated the origin of the injections by tracing back the ions drift echoes. We will present some statistical results about the origin and composition of the ion injections detected by the routine.

2D full-wave simulations of EMIC waves in the magnetosphere

Eun-Hwa Kim (1), Jay R. Johnson (2), and Ernest Valeo (1)
(1) Princeton Plasma Physics Laboratory, Princeton University, USA (2) Department of Engineering and Computer Science, Andrews University, USA

Simulation results using a 2D full-wave code (FW2D) for magnetospheric EMIC waves are presented. The FW2D code solves the cold plasma wave equations using the finite element method and the wave code has been successfully applied to describe low frequency waves in Earth and Mercury’s multi-ion magnetospheres. The results include generation and propagation of externally driven ultra-low frequency (ULF) waves via mode conversion at Mercury and mode coupling, refraction and reflection of internally driven field-aligned propagating left-handed waves (i.e., electromagnetic ion cyclotron waves) at Earth. We explore the dependence of EMIC waves on plasma conditions using FW2D code by adopting empirical plasma density models, such as the global core plasma model. Recent 2D full-wave calculations showed that left-hand polarized

EMIC waves cannot propagate to the ionospheric altitude in 5% He plasmas, but unguided right-hand polarized waves propagate to the inner magnetosphere. We discuss how EMIC wave propagation varies along plasma density spatial structures, wave frequency, and L-shell, as well as heavy ion density ratio.

Relationship between EMIC wave occurrence and cold plasma density distribution in the outer magnetosphere: THEMIS observations

Khan-Hyuk Kim (1), Gi-Jeong Kim (1), Dong-Hun Lee (1)
(1) School of Space Research, Kyung Hee University, South Korea

The relationship between EMIC wave occurrence and cold plasma density (Nsp) distribution in the outer magnetosphere (L = 6-12) are statistically examined using the THEMIS data for 2008–2011. The hydrogen (H) band EMIC waves mainly appear in the early morning sector (0600–0900 MLT) at the outermost region (L = 10–12) under quiet geomagnetic conditions (Kp ≤ 1). However, the high-occurrence region of the helium (He) band EMIC waves under quiet conditions varies from L = 7 to 12 along the local time (i.e., at L ~ 7 near noon and at L = 8–12 near late afternoon). Under moderate and disturbed conditions (Kp ≥ 2), the H-band occurrence rate is higher in the morning-to-early-afternoon sector for L > 10, while the He-band waves are mainly localized between 1200 and 1800 MLT with a peak around 1500–1600 MLT at L = 8–10. For the He-band intervals, Nsp is much higher than for the H-band intervals by a factor of 10 or more. The He-band high occurrence appears at a steep Nsp gradient region. There is a morning-afternoon asymmetry of the normalized frequency both in H-band and He-band. This is similar to the asymmetric distribution of Nsp along the local time. These observations indicate that the cold plasma density plays a significant role in determining the spectral properties of EMIC waves. We discuss whether the morning-afternoon asymmetry of the EMIC wave properties can be explained by the spatial distribution of cold plasmaspheric plasma.

The role of heavy ions in the ring current dynamics

Raluca Ilie
University of Illinois at Urbana-Champaign

Changes in the ion composition throughout the Earth’s magnetosphere can have profound implications on plasma structures and dynamics, since it can modify the temperature and the magnetic field configuration, altering the convection patterns inside the magnetosphere. The ratio of hydrogen to oxygen ions has been shown to be highly dependent of geomagnetic activity, with the O+ content increasing with increasing activity. This suggest that ions of ionospheric origin can become the dominant species in the inner magnetosphere during disturbed times. Therefore, numerous studies focused on the transport and energization of O+ through the ionosphere-magnetosphere system; however, relatively few have considered the contribution of N+, in addition to that of O+ to the near-Earth plasma dynamics, even though past observations have established that N+ is a significant ion species in the ionosphere and its presence in the magnetosphere is significant. Ring current observations from the Active Magnetospheric Particle Tracer Explorer (AMPTE) spacecraft show that high energy N+ fluxes are comparable to those of O+ during disturbed times, confirming the substantial presence of N+ ions in the inner magnetosphere. In spite of only 12% mass difference, N+ and O+ have different ionization potentials, scale heights and charge exchange cross sections. The latter, together with the geocoronal density distribution, plays a key role in the formation of ENAs, which in turn controls the energy budget of the inner magnetosphere and the decay of the ring current. Numerical simulations using the Hot Electron and Ion Drift Integrator (HEIDI) model suggest that the contribution of N+ to the ring current dynamics is significant, as the presence of N+, in addition to that of O+, alters the development and the decay rate of the ring current. These findings suggest that differentiating the N+ transport from that of O+ in the near-Earth environment has a profound impact on global magnetosphere dynamics, as plasma composition affect both the local and the global properties of the plasma.

A Theoretical and Simulation Study of the Expansion of Chorus Waves from a Localized Broadband Chorus Disturbances

Yu-Chun Huang (1) and Ling-Hsiao Lyu (1)
(1) Institute of Space Science, National Central University, Taoyuan, Taiwan, R.O.C.

The chorus waves observed in the inner magnetosphere are closely associated with the pulsating aurora observed in the post-midnight region. The frequency gap appeared in the observed dynamic spectra of the chorus waves has brought our attention. We examine the group-velocity distribution of the chorus waves and found that the observed frequency gap in the dynamic spectra of the chorus wave can be easily explained based on the group velocity distribution of chorus waves of given frequencies. But the explanation based on group velocity distribution is valid only if the source region of the chorus waves is extremely localized. In this study, a two-fluid simulation model is developed to examine the expansion of a broadband localized chorus disturbances. The dynamic spectra of the chorus waves obtained in our simulations are in good agreement with our theoretical prediction. Our theoretical and simulation results indicate that the frequency gap shown in the dynamic spectra of the chorus waves might be a pure wave propagation effect. Namely, no Landau damping process is required for the formation of the frequency gap. Our theoretical results also predict that the frequency gap will appear at different frequency range if the electron plasma frequency is below the electron cyclotron frequency.

The Generation of Chorus Waves due to Injection of Energetic Electrons from the Near-Earth Plasma Sheet

Ling-Hsiao Lyu (1) and Yu-Chun Huang (1)
(1) Institute of Space Science, National Central University, Taoyuan, Taiwan, R.O.C.

The chorus waves observed in the inner magnetosphere are closely associated with the pulsating aurora observed in the post-midnight region. Based on the group-velocity distribution of the chorus waves, we can easily explain the observed frequency gap in the dynamic spectra of the chorus wave. But the explanation based on group velocity distribution is valid only if the source region of the chorus waves is extremely localized. In this study, we explore possible sources that can produce quasi-periodic localized broadband chorus waves in the inner magnetosphere. Our results indicate that the bounce motion of energetic electrons injected from the plasma sheet can produce the observed quasi-periodic chorus waves in the inner L-shell. Our test particle simulation results indicate that, to inject energetic electrons from the near-Earth plasma sheet to the inner L-shell ($L < 5$) within 10 minutes after onset of a substorm, it requires an enhanced convection electric field with average strength more than four times of the background convection electric field. As a result, the presence of chorus waves might indicate that the convection electric field has been enhanced somewhere in the midnight sector of the magnetosphere between L=8 to L=5. The particle injections associated with the magnetic reconfiguration at other space environments will also be discussed.

Chorus scale size estimation during Van Allen Probes lapping events

Aryan Homayon, Sibeck David
NASA Goddard Space Flight Center

The physical processes controlling the acceleration and loss of trapped relativistic electrons in the radiation belts are complex. Whistler mode chorus waves have attracted significant attention in recent decades for their crucial role in the acceleration and loss of energetic electrons that ultimately change the dynamics of the radiation belts. We study chorus scale size during lapping events between the two Van Allen Probes. The current study takes advantage of the unique equatorial orbit of the Van Allen Probes to estimate the average scale size of chorus wave packets

as functions of various parameters including magnetic local time (MLT). Results show that the scale size of chorus wave packets is dependent on various parameters.

Determining Plasma Densities from Observations of Whistler-Mode Waves

David Hartley (1), Craig Kletzing (1), Sebastian DePascuale (1), Bill Kurth (1), George Hospodarsky (1), and Scott Bounds (1)
(1) University of Iowa, Iowa City, Iowa, USA.

A new method of inferring electron plasma densities from observations of whistler-mode waves is presented. Utilizing the electric and magnetic field wave power associated with these waves, coupled with the cold plasma dispersion relation, permits calculation of the plasma density. For plasmaspheric hiss, these calculated densities are shown to yield sensible results that are generally in agreement with densities determined via other methods. A statistical calibration is performed against the density from the upper hybrid line, accounting for both systematic offsets and distribution scatter in the hiss-inferred densities. The calculation and calibration methodology is demonstrated to be able to provide accurate density estimates inside of the plasmasphere, both statistically and for individual case study events. These calibrated calculated densities are not subject to the same upper limit as densities inferred via other methodologies, thus permitting density estimates to be extended to lower L shells. Since hiss is almost always observable inside of the plasmasphere, obtaining a plasma density estimate from hiss observations is attainable for the vast majority of time periods. For $L < 4$, these hiss-inferred density estimates provide a substantial increase in data coverage compared to other methods of inferring the plasma density. Due to the high-accuracy of these hiss-inferred densities and their plentiful availability, this methodology provides a viable alternative of self-calculating plasmaspheric densities for periods when the density from other sources is not available. The feasibility of applying this same technique to whistler-mode chorus waves in order to obtain density estimates in the lower density region outside of the plasmasphere is also explored.

Investigating Magnetospheric Wave-Particle Dynamics with Ground based Observations

Poorya Hosseini, Mark Golkowski, Vijay Harid
Department of Electrical Engineering, University of Colorado Denver

Solar driven phenomenon causes relativistic particles that form the Earth's radiation belts. The distribution of this energetic particles is extremely variable, with the trapped flux changing by several orders of magnitude on timescales of a few hours to days. These energetic particles pose a significant hazard to satellites and astronauts in the near-Earth space environment. Additionally, the Earth's magnetosphere hosts a large number of wave modes, which interact with the high energy particles of the Earth's radiation belts. One of the most dominant players is believed to be magnetospheric whistler mode waves. These interactions can lead to pitch-angle scattering of these energetic particles where a portion of the particles would fall into the loss cone lowering the altitude of their mirror point to a level where they are absorbed by the atmosphere. The exact generation processes of these wave-particle interactions are not well understood but are known to be coupled to the energy dynamics behind space weather. Although the availability of spacecraft observations has improved rapidly in recent years, providing higher resolution data of magnetospheric emissions or energetic particles in the radiation belts, ground based observation of these emissions are still an important tool. Ground based receivers let researchers investigate a specific L shell of the magnetosphere over a long duration with the capability of higher storage capacity essential for certain long-term and statistical studies of wave properties. We show recent theoretical and numerical results for concurrent observation of whistler mode and triggered emissions.

The characteristic response of whistler mode waves to interplanetary shocks

Chao Yue (1) and Lunjin Chen(2) and Jacob Bortnik (3)

(1)Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA
(2) Physics Department, University of Texas at Dallas, Richardson, TX
(3)Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, California, USA
Magnetospheric whistler mode waves play a key role in regulating the dynamics of the electron radiation belts. Recent satellite observations indicate a significant influence of interplanetary (IP) shocks on whistler mode wave power in the inner magnetosphere. In this study, we statistically investigate the response of whistler mode chorus and plasmaspheric hiss to IP shocks based on Van Allen Probes and THEMIS satellite observations. Immediately after the IP shock arrival, chorus wave power is usually intensified, often at post-midnight to pre-noon sector, while plasmaspheric hiss wave power predominantly decreases near the dayside but intensifies near the nightside. We conclude that chorus wave intensification outside the plasmasphere is probably associated with the suprathermal electron flux enhancement caused by the IP shock. Through a simple ray tracing modeling assuming the scenario that plasmaspheric hiss is originated from chorus, we find that the solar wind dynamic pressure increase changes the magnetic field configuration to favor ray penetration in the nightside and promote ray refraction away from the dayside, potentially explaining the magnetic local time (MLT) dependent responses of plasmaspheric hiss waves following IP shock arrivals.

Equatorial magnetosonic emission generation and spectral features

David R. Shklyar (1,2), Michael A. Balikhin (3)
(1) Space Research Institute, Russian Academy of Sciences, Moscow, Russia
(2) Problems of Physics and Energetics Department, Moscow Institute of Physics and Technology, Moscow, Russia
(3) Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield, UK
Equatorial magnetosonic emission that possesses a discrete harmonic spectrum is regularly observed in the vicinity magnetic equator. We present a model for the dynamics of this emission. In accordance with previous studies it is assumed that these waves arise from the loss-cone instability of the energetic ion population. It is argued that the observed wave field is the result of the superposition of constant frequency wave packets that propagate in a highly oblique mode. The growth rate of these wave packets changes both in sign and magnitude as they propagate along the ray path. Therefore, it is the overall wave amplification, rather than the local growth rate that determines the observed characteristics of the emission. The qualitative correspondence between the proposed model and Cluster observations is demonstrated.

Low energy electrons in the inner Earth's magnetosphere

Natalia Ganushkina (1, 2)
(1) University of Michigan, Ann Arbor, MI, USA
(2) Finnish Meteorological Institute, Helsinki, Finland
The fluxes of electrons with energies < 100 keV are not usually analyzed and modeled in details when studying the electron radiation belts. These fluxes constitute the low energy part of the seed population, which is critically important for radiation belt dynamics. Moreover, energetic electrons with energies less than about 100 keV are responsible for hazardous space-weather phenomena such as surface charging. The electron flux at these energies varies highly with geomagnetic activity and even during quiet-time periods. Significant variations in the low-energy electrons can be seen during isolated substorms, not related to any storm periods. Moreover, electron flux variations depend on the electron energy. Statistical analysis of AMC 12 CEASE II ESA instrument data (5-50 keV) and GOES MAGED data (40, 75, 150 keV) have revealed that electron fluxes increase by the same order of magnitude during isolated substorms with 200 nT of AE

index and storm-time substorms with 1200 nT of AE index. If substorms are represented as electromagnetic pulses which transport and accelerate electrons additionally, how are their amplitudes determined, if not related directly to a substorm's strength? Another factor of crucial importance is the specification of boundary conditions in the electron plasma sheet. We developed a new model for electron number density and temperature in the plasma sheet as dependent on solar wind and IMF conditions based on THEMIS data analysis. We present observational and modeling results on low energy electrons in the inner magnetosphere with newly-developed, time-dependent boundary conditions with a special focus on the role of substorms for electron transport and acceleration.

Electron dropout echoes induced by interplanetary shocks: test particle simulations

Ying Liu (1), Qiugang Zong (1), Xuzhi Zhou (1), Yixin Hao (1) and Zhiyang Liu (1)
(1) Institute of Space Physics and Applied Technology, Peking University, Beijing, China.

"Electron dropout echoes" are defined as repeated flux dropout and recovery signals of energetic electrons in the outer radiation belt. Previous studies have shown that electron dropout echoes are usually found for higher-energy (>300 keV) electrons after the arrivals of interplanetary shocks. Further, statistical work have shown that the dropout mainly originated from dusk magnetosphere, and shock parameters show little effect on the occurrence of dropout echo events. To understand these unexpected characteristics, we model the electron dropout echoes by considering the interaction of an earthward propagating electromagnetic pulse with the preexisting electron population. Such simulations have been performed previously to model the shock-related injections and substorm injections [e.g., Li et al., 1993, 1998]. We follow the electrons using a relativistic guiding center code. The backward tracing Liouville approach is used to simulate electron fluxes in the outer radiation belt during the shock arrival. For higher-energy electrons, simulation results show that energy-dispersionless flux dropout appear in the duskside firstly, then energy-dispersive flux dropout appear in other local time after a short time. Initial dropout regions derived from energy-dispersive signals with the time-of-flight technique are also located at the duskside. These results are consistent with observation characteristics. By comparing electrons' trajectories in the dawnside and duskside during the pulse arrival, two reasons which cause the apparent dawn-dusk asymmetry are found: (1) opposite radial component of magnetic gradient drift of electrons and (2) different interaction time between electrons and electromagnetic pulse in the dawnside and duskside. Our work suggest that the response of magnetosphere to symmetric interplanetary shocks can be strongly asymmetric due to the directed drift motion of charged particles.

Poloidal and Toroidal Mode Field Line Resonances Observed by MMS

G. Le(1), P. J. Chi(2), R. J. Strangeway(2), C. T. Russell(2), J. A. Slavin(3), B. Anderson(4), L. Kepko(1), R. Nakamura(5), F. Plaschke(5), R. Torbert(6)
(1) NASA Goddard Space Flight Center, (2) UCLA, (3) University of Michigan, (4) Johns Hopkins University Applied Physics Laboratory, (5) The Space Research Institute, Austria, (6) University of New Hampshire

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.

Radiation belt dynamics during large scale, monochromatic ULF wave events

Michael Hartinger (1) and Colin Komar (2) and Alex Glocer (2) and Zhonghua Xu (1)
(1) Virginia Tech (2) NASA Goddard Space Flight Center

In the Earth's magnetosphere, Ultra Low Frequency (ULF) waves interact with relativistic electrons and cause radial transport and enhancements/depletions in the radiation belts. These interactions are often represented using a radial diffusion approximation. However, several models predict non-diffusive particle dynamics in the presence of large scale, monochromatic (LSM) ULF waves driven by the solar wind. Until recently there were few observational constraints to test these predictions. We combine multi-point observations from the Van Allen Probes and other satellites, as well as simulations from the Comprehensive Inner Magnetosphere Ionosphere model, to examine three non-diffusive behaviors during LSM ULF wave events: drift resonance, bulk radial transport on timescales faster than expected for radial diffusion, and radially localized phase space density peaks. We discuss the relevance of these non-diffusive behaviors to models of the Earth's radiation belts and radiation belts in other magnetospheres.

Alteration of ULF Wave Power Accessibility and Radiation Belt Energization by Storm-time Convection and Plasma Transport

A. W. Degeling (1) and I. J. Rae (2) and C. E. J. Watt (3) and Q. Q. Shi (1) and R. Rankin (4) and Q. G. Zong (5)
(1) Institute of Space Science, Shandong University, Weihai, China
(2) Department of Space and Climate Physics, University College London, United Kingdom
(3) Department of Meteorology, University of Reading, United Kingdom
(4) Department of Physics, University of Alberta, Edmonton Canada
(5) Institute of Space Physics and Applied Technology, Peking University, Beijing, China

In order for ULF waves to effectively energize radiation belt electrons by drift-resonance, wave power must be available in regions within the magnetosphere where the ULF wave phase propagation and electron drift trajectories are roughly aligned. For ULF waves launched along the dayside magnetopause, such a region is usually located in the afternoon - dusk sector of the inner magnetosphere. However, during periods of geomagnetic storms and of enhanced convection, the plasma density in this region is highly dynamic due to the development of plasmaspheric drainage plume (PDP) structure. This plume significantly affects the local Alfvén speed, and drastically alters the propagation of ULF waves launched from the magnetopause. It can therefore be expected that the accessibility of ULF wave power for radiation belt energization is sensitively dependent on the recent history of magnetospheric convection, and on the stage of development of the PDP. Using a 3D model for ULF waves within the magnetosphere, we investigate the effects of storm-time dynamics on the penetration and characteristics of ULF waves. In this model, the plasma density distribution is evolved using an advection model for cold plasma, driven by a (Volland – Stern) convection electrostatic field (resulting in PDP structure). The wave model includes magnetic-field day/night asymmetry, and extends to a paraboloid dayside magnetopause, from which ULF waves can be launched at various stages during the PDP development. We find that the plume structure significantly alters both field line resonance (FLR) locations, and the turning point for MHD fast waves, introducing a strong asymmetry in the ULF wave distribution

across the noon meridian. We show that this structuring may result in drift-resonance with electron trajectories in regions typically not considered to be important for ULF wave driven electron acceleration. Using test-kinetic simulations, we study both the effects of the external driver, such as the arrival of a pulse in dynamic pressure or shock front along the magnetopause boundary, and the time history of the PDP on the energisaiton of radiation belt electrons occurring at different stages during the evolution of a PDP and quantify how the distribution of plasma density alters the effectiveness of the ULF wave pulse in energizing radiation belt electrons. In so doing, we seek to investigate how the previous state of the magnetosphere, may enhance or suppress the geo-effectiveness of a following storm.

ULF Waves and Radiation Belt Ion Dynamics

Robert Rankin (1) and Chengrui Wang (2) and Yongfu Wang (3) and Quigang Zong (4) and Xuzhi Zhou (5)
(1) University of Alberta (2) University of Alberta (3) Peking University (4) Peking University (5) Peking University

ULF waves have been shown to play an important role in the energization and transport of charged particles in Earth's outer radiation belt. While much attention has been devoted to electron dynamics, the effect of ULF waves on ions has been investigated to a lesser extent. In this paper we present simulations of the phase space density response of hydrogen and oxygen ions to ULF waves, and compare the results with observations. It is demonstrated using relatively simple ULF wave and test particle models that it is possible to explain the observed amplitude of modulations in ion differential flux and their pitch angle dependence. The simulations are also used to verify the drift-bounce resonance theory first introduced by Southwood and Kivelson, and recent extensions of it by Zhou.

Charged particle behavior in localized ultralow frequency waves: Theory and observations

Xuzhi Zhou (1), Li Li (1), Qiugang Zong (1), Robert Rankin (2), Hong Zou (1), and Yixin Hao (1)
(1) School of Earth and Space Sciences, Peking University, Beijing, China
(2) Department of Physics, University of Alberta, Edmonton, Alberta, Canada

The formation and variability of the Van Allen radiation belts are highly influenced by charged particles accelerated via drift-resonant interactions with ultralow frequency (ULF) waves. In the prevailing theory of drift resonance, the ULF wave amplitude is assumed independent of magnetic longitude. This assumption is not generally valid in Earth’s magnetosphere, as supported by numerous observations that point to the localized nature of ULF waves. Here we introduce a longitude dependence of the ULF wave amplitude, achieved via a von Mises function, into the theoretical framework of ULF wave-particle drift resonance. To validate the revised theory, the predicted particle signatures are compared with observational data through a best fit procedure. It is demonstrated that incorporation of nonlocal effects in drift-resonance theory provides an improved understanding of charged particle behavior in the inner magnetosphere through the intermediary of ULF waves.

Nonlinear behavior of charged particles in ultralow frequency waves

Li Li (1) and Xu-Zhi Zhou (1) and Zi-Han Wang (1,2) and Qiu-Gang Zong (1) and Robert Rankin (3)
(1) School of Earth and Space Sciences, Peking University (2) University of Michigan, Ann Arbor (3) University of Alberta

Ultra Low frequency (ULF) transverse electromagnetic waves in Pc 4-5 frequency range can significantly accelerate charged particles via drift resonance in the Earth’s magnetosphere. However, the conventional drift resonance theory cannot be directly applied when the energy changes of particles can be comparable with their initial energies due to large electric fields or

long durations. Therefore, a nonlinear theory of charged particle behavior in ULF waves is required. In this paper, we introduce a nonlinear theory by taking into account the energy changes of particles from the ULF waves. Then a nonlinear phenomenon, the rolled-up structure in the time-varying energy spectra, is presented and interpreted. Finally we predict modulations of particle flux with a frequency twice of that of the ULF waves, which is observable by a particle detector with a finite energy resolution. These signatures are compared with Van Allen Probes observations to validate our theory, which provides new insights into ULF wave-particle interactions in the magnetosphere.

The intense substorm incidence and influence on Energetic electron in response to interplanetary shock impacts

X.-H. MA and Q.-G. ZONG
Peking University

The interaction between interplanetary (IP) shocks and the Earth's magnetosphere would generate/excite various types of geomagnetic phenomena. In order to analyze what kind of IP shock is more likely to trigger intense substorms(SME/AE>1000nT) and how the energetic electrons(50 keV–1.5 MeV) at geosynchronous orbit response to intense substorms, we have systematically analyzed 184 IP shock events based on SuperMAG, and LANL observations during 2001–2013. The statistical analysis shows that the maximum auroral electrojet (SME) indices are significantly increased when the IMF is southward prior to the shock arrival, the median value of which is 700 nT and the 3rd quartile is over 1100 nT. Besides, the intense substorms are much more likely to occur around spring (autumn) equinox when the direction of IMF is toward (away from) the Sun, which can be attributed to the Russell-McPherron (R-M) effect. Thus, the IMF Bs pre-condition of an IP shock and the R-M effect can be considered as a precursor of an intense substorm. Furthermore, after the shock arrival associated with intense substorms, low-energy electron fluxes increase significantly at geosynchronous orbit, especially when the IMF is southward. While, in higher energy channels fluxes show smaller increases and eventually become unchanged or even decrease. However, the fluxes of MeV electron also show distinct increases, especially when the IMF is northward.

Multipoint observations of the electric and magnetic fields and particle response to interplanetary shocks

Galina Korotova (1,2), David Sibeck (3), Scott Thaller (4), Vassilis Angelopoulos (5)
(1) IPST, University of Maryland, College Park, MD,
(2) IZMIRAN, Russian Academy of Sciences, Moscow,
(3) Code 674, NASA/GSFC, Greenbelt, MD,
(4) Department of Physics, Augsburg College, Minneapolis, MN,
(5) Department of Earth, Planetary and Space sciences, UCLA, Los Angeles, CA

We studied multipoint observations of the electric and magnetic fields and particle response to the IP shock on January 9, 2014. Particles from low to high energies showed an increase of energy and enhanced fluxes after the passage of the IP shock. The particle response to the compression was more pronounced for Van Allen Probe B (nearer local noon). We found that the initial encounter of the IP shock with the magnetopause occurred in the interval between 13:00 and 14:00 LT consistent with spiral orientation of the shock. The launched fast mode wave propagated from GOES 13 to GOES 15 at the velocity of 650 km/s and from Van Allen Probe B to A at the velocity of 700 km/s. We performed statistical study of more than 90 signatures of the electric field associated with IP shocks and classified them into four groups that are strongly local time dependent. The direction of Vx component of plasma flow is antisunward at all local times except the nightside magnetosphere, where it is sunward near the Sun-Earth line. The Vx amplitudes are much larger in the dayside magnetosphere.

Magnetospheric Particles and Field Response to a Fast Reverse Shock

Ankush Bhaskar (1,2), David Sibeck(1), Shrikanth Kanekal(1), Howard Singer(3), Geoff Reeves(4), Vassilis Angelopoulos (5)
(1)NASA/Goddard Space Flight Center, (2) University Corporation for Atmospheric Research, (3)NOAA Space Weather Prediction Center (4)Los Alamos National Lab,
(5)Institute of Geophysics and Planetary Physics, University of California

Numerous studies show that fast forward interplanetary shocks cause sudden compressions of the magnetosphere that abruptly accelerate charged particles and inject them deep into the radiation belts. The response of magnetospheric particles and fields to fast reverse shocks (FR) remains a much less studied topic. We present a multi-spacecraft investigation of the magnetospheric response to a FR shock which struck the magnetosphere at ~21:55 UT on December 06, 2014. Spacecraft on the dayside (GOES-15, GOES-13, LANL 97A, LANL 1991-80, LANL 1994-84, THEMIS-A) observed decreases in the energetic particle fluxes. The magnetometers on GOES-13, 15, and THEMIS-A recorded decreases in the magnetic field strength. There was a corresponding decrease in SYM-H. Particles with different energies respond simultaneously, a local response to the fast mode wave front transmitted by the shock into the magnetosphere. On the nightside, the Van Allen Probes saw no corresponding signatures. The observations indicate a local time dependence of the response, with the clearest signatures being observed near noon. The observed decrease in the particle fluxes appeared to be a combination of radial gradient and adiabatic effect.

Untangling the drivers of nonlinear systems with information theory

Simon Wing (1) and Jay R. Johnson (2)
(1) Johns Hopkins University (2) Andrews University

Many systems found in nature are nonlinear. The drivers of the system are often nonlinearly correlated with one another, which makes it a challenge to understand the effects of an individual driver. For example, solar wind velocity (Vsw) and density (nsw) are both found to correlate well with radiation belt fluxes and are thought to be drivers of the magnetospheric dynamics; however, the Vsw is anti-correlated with nsw, which can potentially confuse interpretation of these relationships as causal or coincidental. Information theory can untangle the drivers of these systems, describe the underlying dynamics, and offer constraints to modelers and theorists, leading to better understanding of the systems. Two examples are presented. In the first example, the solar wind drivers of geosynchronous electrons with energy range of 1.8–3.5 MeV are investigated using mutual information (MI), conditional mutual information (CMI), and transfer entropy (TE). The information transfer from Vsw to geosynchronous MeV electron flux (Je) peaks with a lag time (τ) of 2 days. As previously reported, Je is anticorrelated with nsw with a lag of 1 day. However, this lag time and anticorrelation can be attributed mainly to the Je(t + 2 days) correlation with Vsw(t) and nsw(t + 1 day) anticorrelation with Vsw(t). Analyses of solar wind driving of the magnetosphere need to consider the large lag times, up to 3 days, in the (Vsw, nsw) anticorrelation. Using CMI to remove the effects of Vsw, the response of Je to nsw is 30% smaller and has a lag time < 24 hr, suggesting that the loss mechanism due to nsw or solar wind dynamic pressure has to start operating in < 24 hr. nsw transfers about 36% as much information as Vsw (the primary driver) to Je. Nonstationarity in the system dynamics are investigated using windowed TE. When the data is ordered according to high or low transfer entropy it is possible to understand details of the triangle distribution that has been identified between Je(t + 2 days) vs. Vsw(t). In the second example, the previously identified causal parameters of the solar cycle such as the solar polar field, meridional flow, polar faculae (proxy for polar field), dipole axis strength, are investigated. We discuss the response lag times of the sunspot numbers and information transferred to the sunspot numbers from the dynamic time series of these parameters.

Space weather forecasts via PROGRESS

S. N. Walker
Department of Automatic Control and Systems Engineering, University of Sheffield, Sheffield, UK

PROGRESS, an EU Horizon 2020 funded space weather project, aims to provide accurate and reliable forecasts of geomagnetic indices and electron flux levels in the radiation belts utilising methodologies based on systems science techniques. This presentation provides an overview of project PROGRESS, outlining the use of these methodologies within the project. The results from models developed for geomagnetic indices and electron flux forecasts are discussed and compared to those obtained using conventional methods. It is shown that systems science methodologies are capable of generating superior results. The application of these models to the forecast of major historical storms will be discussed.

Sun to Earth Geomagnetic Storm Predictions with EUHFORIA and OpenGGCM

Joachim Raeder (1) Camilla Scolini (2,3) William D. Cramer (1) Stefan Poedts (2) Emmanuael Chane (2)
(1) Space Science Center, University of New Hampshire, Durham, NH 03824 USA, (2) Centre for mathematical Plasma Astrophysics (CmPA), KU Leuven, 3001 Leuven, Belgium (3) Solar-Terrestrial Centre of Excellence, SIDC, Royal Observatory of Belgium, 1180 Brussels, Belgium

Geomagnetic storms can be driven by various solar wind drivers,in particular Coronal Mass Ejections (CMEs) and Corotating Interaction Regions (CIRs). In both cases, the solar wind driver is characterized by high solar wind speed, but the IMF stucture is quite different. Present state-of-the-art operational solar wind forecast models have difficulty predicting the IMF, in particular that of CMEs. Recent progress in developing the EUHFORIA model makes solar wind predictions with embedded CMEs possible. In this presentation we present storm effects, as computed using the OpenGGCM magnetosphere-ionosphere-thermosphere model, with solar wind and IMF prtedictions of different sophistication, and show how the resulting geomagnetic storms differ.

The theoretical basis for the Kappa distribution in space physics: Is the Tsallis nonextensive entropy formalism applicable?

Bernie D. Shizgal
Department of Chemistry, University of British Columbia, Vancouver, British Columbia V6T1Z1, Canada

Abstract on next page

The theoretical basis for the Kappa distribution in space physics: Is the Tsallis nonextensive entropy formalism applicable?

Bernie D. Shizgal
Department of Chemistry
University of British Columbia
Vancouver, British Columbia V6T1Z1, Canada

There have been numerous measurements of the nonequilibrium energy spectra of charged particles in space physics that have been fitted to the Kappa distribution (1) given by

$$f_\kappa(x) = C(\kappa)\Big[\frac{1}{1+\frac{x^2}{\kappa+1}}\Big]^{(\kappa+1)}, \tag{1}$$

where $x = v\sqrt{m/2k_BT}$ is the reduced speed of the particles. There have been numerous theoretical models proposed to explain the origin of the Kappa distribution (2,3,4) including the use of the non-extensive entropy formalism (5). The present paper is based on a general isotropic Fokker-Planck equation for energetic electrons of the form

$$\frac{\partial f(x,t)}{\partial t} = \frac{1}{x^2}\frac{\partial}{\partial x}\Big[2x^4\sigma(x) + x^2 B(x)\frac{\partial}{\partial x}\Big]f(x,t), \tag{2}$$

where $\sigma(x)$ is a dimensionless electron moderator momentum transfer cross section and $B(x) = x\sigma(x) + \alpha^2/x\sigma(x)$. The stationary distribution at infinite time is

$$f_{ss}(x) = C\exp\Big[-2\int^x \frac{y^2\sigma(y)}{B(y)}dy\Big]. \tag{3}$$

The steady distribution for a power law cross section $\sigma(x) = x^{-p}$ versus p and an electric field parameter, α, is found to be a Kappa distribution for $p = 2$ and $\alpha < \sqrt{2/5}$ with $\kappa = (1-\alpha^2)/\alpha^2$. Different steady state distributions are obtained for different values of p and α that are not Kappa distributions and are not within the Tsallis nonextensive formalism. The Kappa distribution function arises from particular choices of the drift and diffusion coefficients in the Fokker-Planck equation including the situations with wave-particle interactions (4,6-8).

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MAGNETOTAIL DYNAMICS

Driving of Strong, stormtime Nightside Reconnection and Geomagnetic Activity by meso-scale Polar Cap Flow enhancement

Larry Lyons (1), Bea Gallardo-Lacourt (1,5), Ying. Zou (2), Toshi Nishimura (1,3), Jiang Liu (1,4), E. Donovan (5), J. M. Ruohoniemi (6)
(1) Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, CA 90095-1565, USA, (2) Center for Space Physics and Department of Astronomy, Boston University, Boston MA 0221 , (3) Center for Space Physics and Department of Electrical and Computer Engineering, Boston University, Boston, MA 02215, USA, (4), Department of Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA 90095-1567, USA, (5) Department of Physics and Astronomy, University of Calgary, 2500 University Drive, Calgary, Alberta, Canada T2N 1N4, (6) Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061, USA

It is now known that enhanced meso-scale flows within the polar cap often cross the separatrix leading to plasma sheet flow bursts, poleward boundary intensifications (PBIs), streamers, and poleward motion of the polar cap boundary from reconnection. Here we apply this to stormtime reconnection and disturbances. Previous studies have shown that dynamic pressure impacts (e.g., shocks initiating CME storms) with southward IMF promptly lead to strong auroral nightside activity and concurrent poleward expansion (indicating strong nightside reconnection), and strong enhancements in convection and currents. Consistent with some previous studies, we find that shock driven auroral activity and poleward expansion resembles a substorm, but starts from an already broad MLT sector without much subsequent azimuthal expansion and without classical brightening of the equatorward-most arc. We furthermore find a large enhancement of meso-scale ionospheric polar cap flows heading towards the nightside separatrix immediately after shock impact. Thus, these flow enhancements, which must extend outward along field lines from the ionosphere, are an attractive candidate as the driver for the almost immediate strong auroral, current, and reconnection activity resulting from shock impact. We discuss and present some evidence that this phenomenon may be more general, leading to similar oval responses without a shock impact, including during and following the expansion phase of some substorms. We will also include evidence that the flow enhancements lead to stormtime substorms and to morning-side omega bands, both of which are major disturbances during storms.

Observation of magnetospheric braking oscillations propagating through geospace

Evgeny Panov (1) and Rumi Nakamura (2) and Wolfgang Baumjohann (3)
(1) Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Braking earthward reconnection outflows in the Earth's magnetotail often overshoot their equilibrium position and oscillate around that position. Such oscillations being a local disturbance, may globally initiate Pi2 pulsations by launching waves throughout the inner magnetosphere and down to the ionosphere. Here we show examples of propagation of these waves based on observations in the near-Earth plasma sheet, in the inner magnetosphere and on the ground.

Alfven Waves and Plasma Transport associated with Magnetotail Fast Flows

Yu Lin (1), Xueyi Wang (1), Joe Perez (1), Lei Cheng (1), Jay Johnson, (2) and Simon Wing (3)
(1) Auburn University (2) Andrews University (3) JHU/APL

Dynamics of the Earth's magnetotail is simulated using the Auburn Global Hybrid Code in 3-D (ANGIE3D). The focus of this talk will be on the electromagnetic structure and propagation of shear Alfven waves/kinetic Alfven waves (KAWs) generated in the tail plasma sheet in association with the reconnection flux ropes and fast flows. The simulation shows that the fast flows and associated Alfvenic waves/field-aligned currents possess a short dawn-dusk extent. The flow braking region in front of the ring current is found to play an important role in the transport of Alfvenic waves into the dipole-like magnetic field of the inner magnetosphere. At the flow braking,

wave turbulence leads to strong perpendicular ion heating. Effects of the waves on the propagation of entropy-depleted bubbles of flux tubes and the global plasma transport are also discussed.

Evaluating the Mechanism of the Substorm Current Circuits

A. T. Y. Lui
JHU/APL, Laurel, MD 20723-6099, USA

There are two main competing mechanisms for the generation of substorm currents in the magnetosphere. These two different mechanisms have different signatures for electric field expected in the ionosphere. One observational feature is that an equatorward-directed electric field in the ionosphere emerges at the equatorward portion of the substorm breakup auroral arc. Another feature is that an independent current system, apparently distinct from that at the substorm onset, appears around the peak of the substorm expansion phase. The ability of these two different generation mechanisms for the substorm current circuits are evaluated based on these two observational features. It is found that the substorm current circuits are consistent with the predictions of the current disruption model and contradict the predictions of the plasma flow braking model based on mid-tail magnetic reconnection.

THEMIS observations on the plasma sheet pressure variations in the near Earth magnetotail during substorm growth phase

Weijie Sun (1, 2, 3), Suiyan Fu (3), Yong Wei (1, 2, 4), Zhonghua Yao (5), Zhaojin Rong (1, 2), Xuzhi Zhou (3), James A. Slavin (6), Weixing Wan (1, 2, 4), Qiugang Zong (3), Zuyin Pu (3), Quanqi Shi (7), Xiaochen Shen (7)
(1) Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.
(2) Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China.
(3) School of Earth and Space Sciences, Peking University, Beijing 100871, China.
(4) College of Earth Sciences, University of Chinese Academy of Sciences, Beijing, China.
(5) Laboratoire de Physique Atmosphérique et Planétaire, STAR Institute, Université de Liège, Liège, Belgium.
(6) Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA
(7) Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, School of Space Science and Physics, Shandong University, Weihai, China

This presentation will show a recent investigation on the plasma sheet pressure variations in the near Earth magnetotail during substorm growth phase with THEMIS observations. This study has found that about 40% of the investigated events display a phenomenon of equatorial plasma pressure (Peq) decrease during the substorm growth phase. And the occurrence rates for the Peq decrease cases are higher in the dawn and dusk flanks than in the midnight region. This study has further investigated the percentages of Peq decrease, and the Peq at the end of substorm growth phase comparing with the Peq prior to the substorm growth phase. This study also reveals the importance of electron pressure in the variation of Peq in the substorm growth phase. Among the investigated events, during the growth phase, an enhanced equatorial plasma convection flow, which diverges in the midnight tail region and propagates towards the dayside magnetosphere with velocity of ~ 20 km/s, is observed. It is proposed that the Peq decreases in the near Earth plasma sheet during the substorm growth phase may be due to the transport of closed magnetic flux towards dayside magnetosphere driven by the dayside magnetopause reconnection.The possible influences from the distributions of occurrence rates for Peq decrease events and the Peq increase percentages are discussed.

Kinetic features of explosive energy conversion and dissipation in magnetotail dipolarizations

Mikhail Sitnov (1) and Tetsuo Motoba (1) and Vyacheslav Merkin (1) and Ian Cohen (1) and Barry Mauk (1)
(1) Johns Hopkins University Applied Physics Laboratory

Magnetotails of the Earth and other planets are the main reservoirs where the energy of the solar wind/magnetosphere interaction is accumulated and then explosively released in the form of substorms, preudobreakups, bursty bulk flows and dipolarization fronts. Since magnetotail plasmas are practically collisionless, the description of these bursty phenomena cannot be limited by ideal or resistive MHD models and it requires kinetic approaches. Here we discuss one of the regimes of magnetotail dipolarizations, which becomes possible when a region of accumulated magnetic flux forms in the tail. It starts as an ideal MHD instability coined as the Magnetic Flux Release Instability or MFRI. The ideal MFRI then transforms into the ion tearing instability, which may still preserve the original tail topology even in the nonlinear phase due to the formation of dipolarization fronts. The dissipation at fronts can be provided by the ion Landau resonance. The subsequent flux starvation behind the front may cause the formation of a new X-line and the corresponding electron diffusion region, another dissipation area in the tail. We provide both standard MHD and new kinetic measures of the energy conversion and dissipation for the ion and electron Landau dissipation regions and compare them with recent tail season MMS observations.

Ground Magnetic Perturbations Associated with Substorms, Pseudo-Breakups, Auroral Streamers and Omega Bands

Michale G. Henderson
Los Alamos National Laboratory

Strong magnetic perturbations on the ground are a prime cause of Geomagnetically-Induced Currents (GICs) that can have catastrophic effects on a number of engineered technological systems like power grids, communication lines, railways, and pipelines. In recent years we have learned that the strongest dB/dt signals may be confined to relatively localized regions. A number of localized auroral phenomena are known to occur during highly disturbed intervals including substorms, pseudo-breakups, auroral streamers, torches and omega bands. Here we examine whether any of these types of disturbances can be responsible for the localized dB/dt signals associated with harmful GIC events.

The FAC in geo-magnetotail and its response to IMF variation

Jiankui Shi and Zhengwei Cheng
National Space Science Center, Chinese Academy of Sciences, Beijing, China

The properties of the FACs (field-aligned currents) in the Plasma Sheet Boundary Layer (PSBL) in the Earth's magnetotail are studied with data from the Cluster four-point measurements. The FAC distribution in the magetotail had not only Earth-tailward asymmetry and dawn-dusk asymmetry, but also north-south hemispheric asymmetry. Mapping along the field line to the polar region, the FAC footprints also had north-south hemispheric asymmetry. The FAC distribution function consisted of a Gauss distribution and an exponent distribution. In non-storm times, the FAC variation seemed well correlated with the Kp index but not with AE index. During the storm times, in sudden commencement phase, the FAC density variation inversed to the AE variation; in main phase, the FAC variation correlated with the AE, in recovery phase, it seemed that the two phenomena had no correlation. In general, the FAC was mainly carried by high energized electrons. However, in substorm times, energetic ions also were the main carriers of the FACs and the ions were probably originated from the ionosphere. The IMF had a controlling role on the FACs in PSBLs. In the northern hemisphere, the influence of the positive (negative) IMF By was on earthward (tailward) FACs. In the southern hemisphere, the effects were just opposite. There was a clear north–south asymmetry in the FAC polarity. Only the lager IMF By had influence in

the FAC density. There was also a dusk–dawn asymmetry in the FAC densities, with the dawn density appearing larger than the dusk. The FAC occurrence increased monotonically with IMF cone angle and had two peaks at -90° and +110° clock angle, respectively. The FAC occurrence was closely associated with duskward IMF and southward IMF. In the polar region, the equatorward boundary of the FAC footprints expended to low latitude clearly with increasing IMF cone angle θ, especially for θ>60º, while the poleward boundary showed almost no change. Overall, we can see that the IMF influence on the FACs is from all IMF components, and not only a single component. The FAC is associated to the particle motion in the space plasma and the physical mechanisms of the FAC properties are also discussed.

Mesoscale Perturbations in the Earth's Mid-Tail

Chih-Ping Wang (1) Xiaoyan Xing (2) T.K.M. Nakamura (3) V.G. Merkin (4) Yi-Hsin Liu (5) Andrei Runov (6) Larry Lyons (7) and Vassilis Angelopoulos (8)
(1) UCLA (2) XS Research (3) Space Research Institute (4) APL (5) Dartmouth College (6) UCLA (7) UCLA (8) UCLA

The Earth's magnetotail plays an essential role in regulating energy and particle flows from the solar wind to the magnetosphere. New results from ARTEMIS observations and global simulations have indicated that the structures and dynamics of the mid-tail (X ~40-100 Re) are quite different from the tail inside 30 Re. I will present our recent investigations of mesoscale (< 15 min) perturbations observed by the two ARTEMIS probes in three mid-tail regions: (1) Bursty enhancements of hot electrons (a few keV) in the magnetosheath likely associated with bow shock perturbations. (2) Plasma pressure enhancement in the mantle/lobe caused by tailward propagating Kelvin-Helmholtz vortices. (3) An earthward moving midtail plasma bubble and its connection with ground equatorward propagating magnetic bays and Pi2 pulsations.

Mini-magnetosphere on the Moon: Influence of ion-scale magnetic field to solar wind plasma

Yoshifumi Futaana (1)
(1) Swedish Institute of Space Physics, Box 812, Kiruna SE 98128, Sweden.

This talk reviews the physics of mini-magnetosphere of the Moon, with a particular focus of observations conducted by lunar missions in this two decades. It has been well-known that a part of the lunar crust is magnetized, up to a few hundred nano tesla at the surface, influencing the plasma environment near the Moon. Because of its rather small spatial scale (similar to or smaller than that of the upstream ions), the influence of the magnetization had been thought limited; but it is not true. Nowadays, the lunar plasma environment is known to be very dynamic, and a lot of fundamental plasma phenomena are ongoing. For example, a significant fraction of the solar wind protons is reflected back due to the sub-ion scale structure, due to the electric potential formed in the vicinity of mini-magnetosphere. Such electric potential has been measured indirectly. Strong wave activities due to the existence of mini-magnetosphere have also been observed. More enthusiastic aspect of mini-magnetospheres is that the mini-magnetosphere couples significantly with other environment, for example, volatile cycle, surface albedo feature, and potentially water / hydroxyl production at the lunar surface (via proton implantation followed by chemical reactions). In the last part of the presentation, I will introduce a next-generation lunar mission, SELMA, proposed to European Space Agency, as a candidate of EsA's medium class mission (M5). The SELMA mission investigate the interaction of the lunar environment; One out of four mission sciences devotes the investigation of the mini-magnetosphere.

IONOSPHERIC PHYSICS

Coordinated studies of magnetosphere-ionosphere coupling using e-POP and Swarm

A.W. Yau (1), G.A. Enno (1), H.G. James (1,2), and R. Floberghagen (3)
(1) University of Calgary (2) Natural Resources Canada (3) ESRIN

The CASSIOPE small satellite and the fleet of Swarm satellites (Swarm A, B, and C) were both launched in late 2013 into polar orbits. The science operation of the Enhanced Polar Outflow Probe (e-POP) on CASSIOPE was recently integrated to the Swarm science operation, as an added component to the Swarm satellite constellation. The integrated e-POP and Swarm operation has enabled or enhanced a host of coordinated studies of magnetosphere-ionosphere coupling (MIC), including the Earth's magnetic field and related current systems, upper atmospheric dynamics, auroral dynamics, and related magnetosphere-ionosphere-thermosphere coupling, for example. These coordinated studies take advantage of the complementary nature of the orbital (altitude and local time) coverage and unique measurement capabilities between e-POP and Swarm. In this talk, we illustrate the diversity of such studies, including (a) small-scale structures of magnetic field perturbations at high latitudes, (b) thermospheric density variations and plasma density irregularities, (c) electrodynamics of the auroral arcs, and (d) wave-particle interactions and related trans-ionospheric radio propagation processes.

FAC's: The fundamental M-I coupling parameter that remains a puzzle.

Jesper W Gjerloev (1), Shin Ohtani (1), Matthew Friel (2)
(1) Applied Physics Laboratory, Johns Hopkins University, Laurel, MD
(2) Georgetown Day School, Washington DC, United States

Field-aligned currents are the main coupling mechanism between the Earth and near-space. Despite this well-known fact it remains a considerable observational challenge to obtain reliable quantitative measurements of these currents. ESA's Swarm mission provide multi-point measurements that allow a glimpse of the dynamics and structure of the FAC's. This glimpse has taught us that the crippling assumptions single satellites use to calculate FAC density can lead to results with even the wrong polarity. We show results from the Swarm mission to illustrate the technical difficulties as well as utilize the observational advantages of the multi-point mission to gain an understanding of the dynamics and structure of the M-I coupling.

Case Study of Dayside Cusp Field-Aligned Current

Y. X. Sun, Q.-G. Zong, J. Ren
Institute of Space Science and Applied Technology, Peking University, China

Cusp field-aligned current (FAC) is highly affected by IMF. On 23rd September 2004, the fleet of Cluster spacecraft penetrated Energetic Electron Wall(EEW) at noon and after that they observed cusp FAC indicated by a bipolar structure of By component. The amplitude of the bipolar structure kept increasing and existing region also enhanced consecutively as observed by the spacecraft one by one. While the enhancement of bipolar structure happened, IMF Bz turned from southward to northward and By from around zero to dawnward. After IMF change, more and hotter electrons showed up within FAC region, and a new group of electron outflow came up poleward of FAC region. The outflow then moved close to the original FAC and finally next to it. Calculation presents that these electrons contributed to the FAC and its enhancement. Anti-sunward and sunward flow and proton dispersion indicated change of reconnection site which is supposed to be responsible for the evolvement of FAC.

Comparative Ionospheric Variability: Inner versus Outer Solar System Planets

Michael Mendillo and Luke Moore
Boston University

Observations of the Earth's ionosphere started in the 1930s, with subsequent discovery-mode studies of the ionospheres at Mars and Venus in the 1960s, at Jupiter in the 1970s, followed by

Saturn (1979-1981), Uranus (1986), and Neptune (1989). Today, millions of observations of the terrestrial ionosphere are made daily. The totality of ionospheric profiles [Ne(h)] measured at other planets are far less: ~thousands at Mars, ~hundreds at Venus, sixty-four at Saturn, ~dozen at Jupiter, and two each at Uranus and Neptune. With the enormous ionospheric data bases available for Earth, it is possible to have "same-day" observations to compare with every one of the Ne(h) profiles obtained at the other planets. In this paper, we describe an approach to compare Earth-Mars and Earth-Saturn ionospheres in quantitative ways for electron density magnitudes and variability over solar-cycle time scales. All of the other planets have most of their ionospheres embedded in dense neutral atmospheres and thus their maximum electron densities [Nmax] are described using photo-chemical-equilibrium (PCE) theory. For Earth, Nmax occurs in the F-layer (h ≥ 300 km) where plasma dynamics competes with PCE processes, and thus it is the lower altitude E-layer's peak electron density (NmE) that has PCE ionospheric-synergy with the other planets. We find that NmE correlates highly with the peak electron density at Mars over solar cycle time scales due to the dominance of the solar irradiance driver of PCE conditions within the inner solar system. Sources of shorter-term, non-photon variability are the topics most in need of study at Mars. For the outer planet with the most data (Saturn), its peak electron density exhibits the opposite trend—a poor correlated with "same day" NmE values at Earth. Severe atmospheric dynamics and/or in-falling material from the magnetosphere are the sources of variability most in need of study for ionospheres in the outer solar system.

Combined contribution of solar illumination, solar activity, and convection to ion upflow above the polar cap

Qing-He Zhang (1), Yu-Zhang Ma (1), Zan-Yang Xing (1), P. T. Jayachandran (2), J. Moen (3), Roderick A. Heelis (4), and Yong Wang (1)
(1) Shandong Provincial Key Laboratory of Optical Astronomy and Solar-Terrestrial Environment, Institute of Space Sciences, Shandong University, Weihai, 264209, China (2) Physics Department, University of New Brunswick, Fredericton, New Brunswick, Canada (3) Department of Physics, University of Oslo, Oslo, Norway (4) William B. Hanson Center for Space Sciences, University of Texas at Dallas, Richardson, Texas, USA

By analyzing DMSP plasma data during a 5-year period (2010-2014), we investigated ion upflow occurrence, speed, density, and flux above the polar cap in the northern hemisphere under different solar zenith angle (SZA), solar activity (F10.7), and convection speed (cross-track drift velocity) conditions. The upflow occurrence rate is higher in the dawn sectors, which is coincided with the region of higher convection speed, while the upflow flux is higher both in dawn and dusk sectors, which is main due to higher upflow speed in the dawn sectors and due to higher upflow density in the dusk sectors. The upflow occurrence increased with convection speed and solar activity, but decreased with SZA, which became very low when SZA>100o in low convection conditions. While, the upflow velocity and flux showed clear seasonal dependence with higher speed in the winter and higher flux in the summer during low convection conditions, however, they are detected for the first time to be both higher in summer during high convection conditions. These results suggest that ion upflow in the polar cap is controlled by the combination of convection, solar activity, and solar illumination.

Atmospheric erosion - the role of ion outflow

Stein Haaland (1,2)
(1) Max-Planck Institute, Goettingen, Germany (2) Birkeland Centre for Space Science, Bergen, Norway

Most planets in the solar system posess a gaseous outer layer - they have an atmosphere. Various accretion and ablation processes cause exchange of material between planetary atmospheres and their space environment over a range of time scales. Outflow of ionized material can also be an important supplier of plasma to the planet's magnetosphere. Since ions of

atmospheric origin typically have much lower energies that the hot magnetospheric plasma, ion outflow can also alter fundamental magnetospheric processes and properties. In this talk, we focus on cold plasma outflow from the terrestrial ionosphere and discuss topics such as modulation of outflow, transport paths, distribution and impact on magnetospheric dynamics. We also point out some outstanding issues in our understanding of ion outflow.

High-latitude Thermosphere Neutral Density Response to Solar Wind Dynamic Pressure Enhancement

Hyunju Connor (1), Yong Shi (2), and Eftyhia Zesta (3)
(1) University of Alaska Fairbanks (2) University of New Mexico (3) NASA GSFC

We examine the response of the thermosphere to the impact of solar wind dynamic pressure enhancements using observations and global magneto-hydrodynamics (MHD) simulations by the OpenGGCM model. Combining neutral density observations from the Challenging Mini-satellite Payload (CHAMP) and the Gravity Recovery and Climate Experiment (GRACE) satellites with simultaneous Poynting flux measurements from the Defense Meteorological Satellite Program (DMSP) F16 we find that thermospheric density as well as downward Poynting flux intensified shortly after a sudden enhancement of the solar wind dynamic pressure. The intensification manifested mostly on the dayside high-latitude region with peak intensity in the vicinity of the noon and pre-noon cusp. OpenGGCM modeling results show that the ionospheric Joule heating increased abruptly in response to the sudden enhancement of the dynamic pressure in the same region as the observed Poynting flux and neutral density enhancements. The modeling results show that the enhanced Joule heating coincides, both in time and location, with the appearance of a pair of high-latitude localized field-aligned currents (FACs) in the cusp region. The FACs intensified and extended azimuthally. Coincidental with the solar wind dynamic pressure enhancement the y-component of the interplanetary magnetic field (IMF) By became strongly positive and, in addition, had some large fluctuations. We explore the separate and combined effects of the dynamic pressure and IMF By perturbations, with specifically designed simulation experiments that isolate the effect of each solar wind parameter. We find that the dynamic pressure enhancement is the primary source for the Joule heating and neutral density enhancements, but the IMF By modulates the level of enhancement.

FUV Remote Sensing of Geospace

Yongliang Zhang (1) and Larry J. Paxton (1)
(1) The Johns Hopkins University Applied Physics Laboratory

The FUV (100-200 nm) emissions from the ionosphere and thermosphere carry rich information of the density and composition of the IT (ionosphere-Thermosphere) system, aurora and solar EUV flux. The key emissions include atomic hydrogen line (121.6nm), atomic oxygen lines (e.g. 130.4, 135.6, 164.1 nm), atomic nitrogen lines (e.g. 120.0, 149.3, 174.3 nm), molecular nitrogen bands (LBH and VK bands) and nitric oxide ε bands. We will show a few TIMED/GUVI products that help to solve some of MIT (Magnetosphere-Ionosphere-Thermosphere) science problems and serve as validation data sources for models.

Shear-Driven Aurora

Jay Johnson (1) and Simon Wing (2)
(1) Andrews University (2) Johns Hopkins University/ Applied Physics Laboratory

Velocity shears serve as effective voltage generators in planetary magnetospheres and drive field-aligned currents, coupling the magnetosphere-ionosphere system and powering auroral emissions. We present a simple quasi-static magnetosphere-ionosphere coupling model model that relates solar wind and ionospheric parameters to the strength and thickness of field-aligned currents in a region of sheared velocity, such as the LLBL. We compare the predictions of the model with DMSP observations and find remarkably good scaling of the currents with solar wind

and ionospheric parameters in the upward region-1 region located at the boundary layer or open-field lines at 1100--1700 MLT. Auroral bright spots have been also observed at Earth, Jupiter, and Saturn in regions that map to the boundary layer. It has been suggested that the bright spots are associated with Kelvin-Helmholtz instability. We utilize our model to determine how the field-aligned current structure depends on ionospheric and boundary layer parameters for a vortex structure. We compare vortex induced currents with shear-flow induced currents. We find that the strength of the maximum currents are comparable, but the structure is significantly different.

Cluster results on auroral particle acceleration and associated auroral density cavities

Göran Marklund (1), Andrew Fazakerley (2), Matthieu Berthomier (3), Per-Arne Lindqvist (1), Nickolay Ivchenko (1), Love Alm (4), Mats André (5)
(1) Space and Plasma Physics, Royal Institute of Technology, KTH, Stockholm, Sweden; (2) Mullard Space Science Laboratory, University College, Holmbury St Mary, Dorking, Surrey RH56NT, UK; (3) Laboratoire de Physique des Plasmas (LPP), Observatoire de St Maur, 4 avenue de Neptune, 94107 Saint-Maur des Fossés Cedex, France; (4) University of New Hampshire, Durham, NH 03824, US; (5) Swedish Institute of Space Physics, Box 537 , SE-751 21 Uppsala, Sweden

Auroral particle acceleration has been studied for more than five decades by a large number of polar or high inclination satellites, traversing auroral field lines at geocentric altitudes between 1.2 RE and 3-4 RE. FAST was first to measure particles at high time resolution and full pitch angle coverage together with high-resolution fields data, in the lower part of the acceleration region, resulting in new findings on the auroral processes. Cluster was first to probe the acceleration region in situ with four spacecraft at geocentric altitudes of 2-4 RE. Results will be presented on the altitude distribution and stability of auroral electric fields, the relative role of quasi-static and wave acceleration producing aurora, and on the auroral density cavity. A candidate for further advances in this area, is the Alfvén+ mission, recently proposed to the ESA M5 call. It comprises two spacecraft with fields and particle instruments of high temporal resolution as well as imagers, capable of monitoring the aurora at the foot point of the magnetic field line traversed by the satellites. If selected, Alfven will be ideally suited to reveal remaining open issues on the aurora and the underlying processes, which are universal in space plasmas.

Spikes to Like or Dislike: Dynamical Processes in Earth's Auroral Zone Revealed

Martin Connors (1), Sébastien Guillon (2), Mark Engebretson (3), Kyle Reiter (4), David Boteler (5)
(1) Athabasca University (2) Hydro-Québec (3) Augsburg University (4) University of Calgary (5) NRCan

Examination of times of voltage distortion events (a GIC proxy) in the Hydro-Québec power grid in northeastern North America suggests that most are associated with auroral electrojets and substorms. Some fraction is instead associated with impulsive changes in the solar wind (SI). In both cases, GIC activity seems to mainly be associated with spikes, mainly in the vertical component, of magnetic fields detected in the nearby AUTUMNX, MACCS, and CANMOS magnetic networks. These spikes can be very large, exceeding 1000 nT, and last of order only one minute, giving rise to large rates of change of a geoeffective component of the field. With emphasis on two large events, one of each type, we will discuss physical processes giving rise to such spikes, with reference to pre-existing models developed by Lanzerotti and Araki.

An Improved Magnetosphere-Ionosphere Coupling Model to Simulate the Brightening of the Aurora Arc in the Midnight Sector at Onset of a Substorm

Pai-Shen Wang (1) and Ling-Hsiao Lyu (1)
(1) Institute of Space Science, National Central University, Taoyuan, Taiwan, R.O.C.

Substorm onset is marked by a sudden brightening of the most equatorward aurora arc in the midnight sector of the auroral oval (Akasofu, 1964). A simplified magnetosphere-ionosphere (M-I) coupling model has been proposed by Kan et al. (1988) to study the evolution of the field-aligned current distribution in the high-latitude ionosphere. In this study, we modify the boundary condition on the magnetospheric side in the M-I coupling model. We include the Hall effect in the near-Earth plasma sheet, which is expected to take place during the explosive thinning period. The Hall effect in the near-Earth plasma sheet can lead to an earthward ambipolar electric field, which can enhance the equatorward upward field-aligned current in the midnight sector so that the distributions of Region-1 and the Region-2 upward field-aligned currents will join each other to form a continuous and uninterrupted aurora arc in the midnight sector. Our results indicate that the sudden brightening of the most equatorward aurora arc in the midnight sector is indeed a manifestation of the explosive thinning process in the near-Earth plasma sheet.

Impact of Flow Bursts in the Auroral Zone on the Ionosphere and Thermosphere

Yue Deng, Roderick Heelis, Lawrence Lyons
(1) University of Texas at Arlington, (2) University of Texas at Dallas,
(3) University of California, Los Angeles

Large-scale ionospheric convection at high latitudes often contains embedded localized enhancements, called flow bursts with associated elevated plasma number density and temperatures. Flow bursts have been observed within the auroral zone with the scale sizes of ~100 km, and typical lifetimes of ~15 minutes. The plasma velocity of a flow burst can reach more than 1000 m/s and enhancements in electron precipitation associated with auroral streamers are often observed within the flow burst. Such localized strong flow is a significant meso-scale momentum and energy source to the thermosphere that is not contained in present empirical models of plasma convection. To evaluate the influence of such a localized strong enhancement of forcing on the global dynamics of the upper atmosphere, the Global Ionosphere-Thermosphere model (GITM) has been run with high resolution. GITM is a non-hydrostatic model with a flexible resolution, which is suitable for studying transient meso-scale phenomena. Specifically, the change of neutral velocity, neutral density, TEC and electron density in the E and F regions has been examined closely by comparing cases with and without a flow burst. Different configurations of flow bursts have also been examined, such as one flow burst with typical size, two typical flow bursts and one flow burst with doubled size. The outcome of this study will illustrate local and non-local responses of the I-T system that result from meso-scale energy and momentum inputs.

Reconstruction of the small-scale electric field in the high latitudes using machine-learning methods

Mingwu Jin, Qingyu Zhu, Yue Deng
(1) University of Texas at Arlington (2) University of Texas at Arlington
(3) University of Texas at Arlington

In the high latitudes, in addition to the large-scale background electric field there is a significant component of the small-scale electric field or electric field variability. Its contribution to the Joule heating can be comparable to or even larger than the background electric field. While the significance of electric field variability to the Joule heating has been recognized, to describe it precisely and to implement it in the GCMs appropriately are still a big challenge. To enhance the capability of specifying the high-latitude electrodynamics, the machine learning methods will be applied to the DE-2 satellite measured electric field data to reconstruct the small-scale electric field. The learned models will be compared with an empirical model and tested using DMSP satellite observations. The influence on the upper atmosphere will be simulated through coupling with Global Ionosphere-Thermosphere Model (GITM).

External and internal driving sources of the ionosphere: an analysis based on the wavelet decomposition method

D. H. Zhang, H. SHI, Y. Q. Hao and Z. Xiao
Department of Geophysics, Peking University, Beijing, China

The ionosphere is influenced by solar, interplanetary, geomagnetic, neutral atmospheric and some other variations. Here, the wavelet decomposition method is applied to obtain the variance distributions of these parameters in 2002 and 2007, and the ionospheric variability in the period intervals of 2-64 days is analyzed. For the ionosphere, nearly half of the variances are concentrated on the 2-4 days period interval, and the variance proportion goes down with the increase of the period. In both 2002 and 2007, the pronounced 2-4-day period variances show some latitudinal trend and local time dependence. The solar parameters show the maximum variance in the 16-32 days period interval. For solar wind speed and geomagnetic activities, most of the variance is about averagely distributed on periods shorter than 32 days. The variance distributions of IMF Bz and lower thermospheric temperature are similar to those of the ionosphere. Their variances of periodic oscillations show the maximum in the 2-4 days period interval and decline with the increase of the period. And the variances of the O/N2 ratio are mainly in the 2-4 and 32-64 days period intervals. The characteristics of the variance distributions of these space environmental parameters are analyzed. And by comparing with those of the ionosphere, the possible qualitative contributions of various sources are discussed.

Solar flare produced traveling ionospheric disturbances on 6 September 2017

Shunrong Zhang, Anthea Coster, and Phil Erickson
MIT Haystack Observatory

Solar flares are known to produce Sudden Ionospheric Disturbances (SIDs). These disturbances are characterized with a sudden increase in absorption of radio-waves that reach the ionosphere and are reflected by ionospheric electrons mostly in the D-region. Solar flares increase not only the D-region electron density, depending on the wavelengths and intensity of EUV enhancements accompanying the solar flare, the ionospheric E region, F region and even the topside can undergo obvious increases. Can they produce traveling ionospheric disturbances (TIDs)? TIDs occur on a regular basis, and they are considered as manifest of gravity waves in the neutral atmosphere with a range of disturbance sources, including lower atmospheric perturbation that eventually reaches the thermosphere/ionosphere altitudes, and high-latitude heating processes which are associated with the geomagnetic activity effect on the ionosphere and thermosphere. To our knowledge, it remains unclear that strong solar flares can serve as a new space weather source to yield TIDs. To be qualified as TIDs, it is important to note that the ionospheric disturbances have to be of propagating nature and therefore atmospheric gravity waves should be involved. The recent X9.7 class solar flare on 6 September 2017 provides an opportunity to examine potential TIDs because it occurred on dayside for 50% of CONUS where very dense GNSS receiver network is available to provide high fidelity and resolution TEC observations. We have also conducted an incoherent scatter radar world-day campaign during the period of the solar flare, providing ionospheric electron density profile information as well as plasma temperatures and plasma drift information. Our study indicates that even though the TID activity is generally visible in the morning hours (perhaps associated with the solar terminator), there are very clear signs of TIDs generated by the solar flare, which are not resulted from the historical evolution of pre-existing TIDs. These TIDs, with various scales (medium and large scales), were propagating southeast, a direction that was known to be unpopular during daytime in the northern hemisphere. We will provide analysis of the GNSS TEC data along with observations by the Millstone Hill incoherent scatter radar.

Data-adaptive harmonic analysis and modeling of solar wind-magnetosphere coupling

Dmitri Kondrashov
Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles

The solar wind-magnetosphere coupling is studied by recently developed data-adaptive harmonic (DAH) decomposition approach for the spectral analysis and inverse modeling of multivariate observations from complex nonlinear dynamical systems. DAH identifies frequency-based modes of interactions in the combined dataset of Auroral Electrojet (AE) index and solar wind forcing. The time evolution of these modes can be very efficiently simulated by using systems of stochastic differential equations (SDEs) that are stacked per frequency and formed by coupled Stuart-Landau oscillators. These SDEs capture the modes' frequencies as well as their amplitude modulations, and yield, in turn, an accurate modeling of the AE index' statistical properties.

References M. D. Chekroun and D. Kondrashov (2017): Data-adaptive harmonic spectra and multilayer Stuart-Landau models, Chaos, 27, 093110: doi:10.1063/1.4989400.

PLANETARY PHYSICS

Variability of Plasmas in the Outer Heliosphere and Interstellar Medium

John Richardson and The Voyager Team
M.I.T.

The variability of space plasma persists throughout the heliosphere and affects the interaction of the heliosphere with the local insterstellar medium. The heliosheath is a very dynamic region with plasma and magnetic fields varying on time scales of tens of minutes. Two sources of this variability at the termination shock and reconnection near the current sheet. Larger scale heliosheath variability is driven by solar wind changes and transients. Months-long pressure pulses propagate through the heliosheath and reach the heliopause, driving shocks and other disturbances in the interstellar medium. This paper describes the observed variability observed by the Voyager spacecraft and discusses the sources and effects of this variability.

Interstellar Boundary Explorer (IBEX) Observations of our Evolving Heliosphere

David McComas
Princeton University

The Interstellar Boundary Explorer (IBEX) returned nearly continuous observations that have led to numerous scientific discoveries and “firsts” over its first nine years of operation in space. These advances have reshaped our entire understanding of the outer heliosphere and its interaction with the local interstellar medium. In this talk we summarize a number of these advances. Observed fluxes of Energetic Neutral Atoms (ENAs) from ~0.2 to 6 keV have evolved significantly over the years from 2009-2017, with an overall reduction in fluxes at all energies over most of this interval. The Ribbon, which is likely generated beyond the heliopause, in the outer heliosheath, has evolved differently from the globally distributed flux (GDF), which is primarily produced in the inner heliosheath, between the termination shock and heliopause. The Ribbon also lost its latitudinal ordering several years after the demise of the solar minimum latitudinal ordering of the 3-D solar wind, consistent with a multi-year recycling time for outflowing solar wind ions into returning Ribbon ENAs. Finally, we show the initial response of the heliosphere to a major increase in the solar wind output that occurred over the second half of 2014. McComas et al. (2017, ApJS) predicted: “that this dramatic increase in solar wind dynamic pressure will soon be reflected in IBEX data as enhanced ENA emissions...” This study will assess the veracity of that prediction and shows exactly how the heliosphere has responded so far.

Dynamics of the giant planet magnetospheres

P. A. Delamere
University of Alaska Fairbanks

Jupiter and Saturn are fundamentally different from Earth, driven primarily by the combination of rapid rotation and internal plasma sources originating from moons embedded deep in the inner magnetosphere. Centrifugal stresses and the resulting outward plasma transport distort the planetary magnetic field into a magnetodisc structure with magnetosphere-ionosphere coupling currents that fuel auroral emissions. Pronounced magnetospheric dawn/dusk asymmetries are observed and are fundamentally linked to the solar wind interaction. The debate regarding the nature of the solar wind interaction was reinvigorated following the New Horizons flyby in 2007. Key aspects of this on-going debate focus on the role of large-scale magnetic reconnection (Dungey, 1961) vs. some unspecified tangential drag at the magnetopause boundary that generates a viscous-like interaction (Axford and Hines, 1961). Recent studies have demonstrated that a viscous-like interaction, mediated by the Kelvin Helmholtz instability, generates intermittent and small-scale reconnection – a key component of mass, momentum, and energy transport at the magnetopause boundary. Burkholder et al., [2017] showed that reduced magnetosheath flows on Saturn’s dawn flank (Cassini CAPS data) are consistent significant momentum transport at the magnetopause boundary, confirming a very active solar wind interaction. In fact, compared with Earth, it has been argued that Jupiter's and Saturn's magnetospheres exhibit a relatively stronger solar wind interaction. This presentation will provide a broad overview of the internal drivers and the fundamental processes associated with the solar wind interaction at Jupiter and Saturn, including different perspectives from data, theory, and modeling.

Properties of Jupiter's magnetospheric turbulence observed by the Galileo spacecraft
Chihiro Tao (1)(2), Fouad Sahraoui (2), Dominique Fontaine (2), Judith de Patoul (2, 3), Thomas Chust (2), Satoshi Kasahara (4), Alessandro Retinò (2), and Elena Kronberg (5)
(1) NICT, Japan, (2) LPP, Ecole Polytechnique/CNRS, France, (3) University of Exeter, UK, (4) ISAS, JAXA, Japan, (5) Max Planck Institute for Solar System Research, Goettingen, Germany/ Ludwig Maximilian University of Munich, Germany
In collisionless plasmas, turbulence is thought to play an important role in mass transport and energy dissipation. Magnetic fluctuations in the Jovian magnetosphere are essentially in a turbulent state. Previous studies discussed the effect of turbulence on heating the expanding plasma from Io and the relationship with the electric potential drop which accelerates electrons and leads to strong Jovian aurora. Previous analyses of the Jovian magnetosphere disturbances have focused mainly on their power spectra and the corresponding slopes in the low frequency range of 10^-4–10^-2 Hz, which is limited by low time resolution (Δt ~ 24 sec.). Here we extend those studies to cover a wider range of scales by combining both low and high-time resolution data of Galileo magnetometer (MAG). We use particles data from the plasma instrument (PLS) and empirical models including energetic particle contributions to estimate the local plasma parameters. We obtain 11 power spectra of magnetic field in the frequency range of 10^-4–1 Hz, which covers both MagnetoHydroDynamics (MHD) and ion kinetic scales. The frequencies of the evidenced spectral breaks are found to be relatively well correlated with the characteristic scales of heavy ion. The spectral indices below and above the spectral breaks are found to be broad and cover the ranges of 0.6–1.9 and 1.7–2.5, respectively. An analysis of higher order statistics shows an intermittent feature of the turbulence, found to be more prominent in the plasma sheet than in the lobe. Furthermore, a statistical survey of the power of the fluctuations using low-time resolution data suggests a radially varying dawn-dusk asymmetry: the total power is larger in the duskside (dawnside) at distances <50 RJ (>80 RJ), which would reflect flow shear and global magnetospheric activity.

Momentum Transfer Processes at Planets and Moons
Jasper S Halekas
Department of Physics and Astronomy, University of Iowa
The environments around planets and moons typically contain multiple ion populations with very different velocity distributions. Many plasma processes can act to transfer momentum between these ion populations, including motional electric field terms (e.g. "ion pickup" or "mass-loading"), magnetic tension forces (e.g. "snowplow" or "slingshot" mechanisms), and plasma instabilities (e.g. two-stream instabilities, magnetic reconnection, Kelvin-Helmholtz, etc.). Each of these momentum transfer processes necessarily involves the formation of electric fields that can accelerate charged particles; however, the mechanism(s) and the resulting fields have very different characteristics. I will discuss the role of momentum transfer processes at planets and moons, utilizing illustrative examples based on observations of charged particles and electromagnetic fields by MAVEN at Mars and by the ARTEMIS probes at the Moon.

Magnetospheres in the Outer solar system: the known (Jupiter, Saturn) and the little known (Uranus, Neptune, Heliosphere)
Stamatios M. Krimigis
Applied Physics Laboratory, Johns Hopkins University, USA and Academy of Athens, Athens, Greece

The exploration of Jupiter's magnetosphere began in 1973 with Pioneer 10, 11, was continued by Voyagers 1,2 in 1979, and by the Galileo orbiter in the 1990s, and Ulysses flybys during the same decade. We now have the first polar orbiter with Juno and observe phenomena that go beyond expectations formulated on the basis of previous missions and Earth analogues. The first intensive study of Saturn's magnetosphere has just been concluded by the Cassini orbiter, following the initial exploration by Pioneer 11 in 1979 and Voyagers 1 and 2 in 1980 and 81, respectively. We now know enough about these two planets that, together with detailed knowledge of Earth, we can examine and perhaps generalize those physical mechanisms that appear to operate in all three environments. The discovery of magnetospheres at Uranus and Neptune by Voyager 2 in 1986 and 1989, respectively, established the fact that all outer planets possess intrinsic magnetic fields and plasma environments of varying composition and sources, plus radiation belts with diverse properties and dynamics. The recent investigation of Pluto by New Horizons revealed little intrinsic plasma activity and minimal interaction with the solar wind. Finally, the in-situ investigation of the heliosheath by the two Voyagers, plus the tool of remote energetic neutral atom (ENA) imaging by Cassini have revealed a bubble-like shape of the heliosphere, thus resolving a 57-year conundrum posed theoretically by Parker in 1961. This talk will examine the plasma properties at each of these environments and highlight the processes that are common and those that are unique to the particular planet.

Plasmoids in the magnetosheaths of Earth and Mercury, and their importance in solar wind-magnetosphere interaction

Tomas Karlsson (1)
(1) KTH Royal Institute of Technology

Recently there has been an increased interest in transient, localized increases in plasma density and flow velocity in Earth’s magnetosheath, often observed behind the quasi-parallel bow shock. Such enhancements have been studied under several different designations, e.g. magnetosheath jets or plasmoids. The latter designation specifically refers to the presence of clear magnetic signatures associated with localized density increases. These transients have been suggested to be universally present downstream of quasi-parallel shocks. As a first check of that hypothesis, we present results from the Mercury magnetosheath and near solar wind, using MESSENGER magnetic field data from the MAG instrument (and ion data from the Fast Imaging Plasma Spectrometer (FIPS) instrument for contextual information). We identify clear, isolated changes in the field magnitude, and study their properties in order to determine if they may be considered as analogues to plasmoids and jets in the terrestrial magnetosheath. Both isolated decreases of the magnetic field absolute value (‘negative structures’) and increases (‘positive structures’) are found in the magnetosheath, whereas only negative structures are found in the solar wind. The similar properties of the solar wind and magnetosheath negative magnetic field structures suggests that they are analogous to diamagnetic plasmoids found in Earth’s magnetosheath and near solar wind. Positive magnetic field structures are only found in the magnetosheath, relatively close to the magnetopause. Their proximity to the magnetopause, their scale sizes, and the association of a majority of the structures with bipolar magnetic field signatures identify them as flux transfer events (which are associated with a decrease of plasma density in the magnetosheath). The positive magnetic field structures are therefore not likely to be analogous to terrestrial paramagnetic plasmoids but possibly to a sub-population of magnetosheath jets. We discuss some consequences of the findings of the present investigation pertaining to the different nature of the quasi-parallel bow shock at Mercury and Earth, and for the solar wind – magnetosphere interaction.

The Fundamental Role of Wave-Particle Interactions in Planetary Magnetospheres

Richard M. Thorne
Department of Atmospheric and Oceanic Sciences, UCLA

Energetic radiation belt particles in planetary magnetospheres are naturally unstable to the excitation of plasma waves. Resulting wave-particle interactions cause scattering loss to the atmosphere and local stochastic acceleration to relativistic energies. Such interactions control the structure of planetary radiation belts and the precipitation of energetic electrons into the atmosphere leading to diffuse auroral emissions. Recent advances in our understanding and modeling of such fundamental processes at Earth and Jupiter will be described.

Ion cyclotron waves in the solar system

Misa Cowee (1), Vania Jordanova (1), Xiangrong Fu (2), Peter Gary (1,3), Hanying Wei (4), Christopher Russell (4), Ravindra Desai (5)
(1) Los Alamos National Laboratory, Group ISR-1, Los Alamos, NM,
(2) New Mexico Consortium, Los Alamos, NM, (3) Space Science Institute, Boulder, CO,
(4) University of California, Los Angeles, CA, (5) University College London, UK

Electromagnetic ion cyclotron waves have been observed in a variety of planetary environments including Venus, Earth, Mars, comets, Jupiter, and Saturn. In some environments, these waves are readily and ubiquitously observed, while at others they are sparse. Identification of such waves indicates a local source of free energy in the ion distribution, and spatial and temporal variability in the wave properties can be used to infer local plasma properties. In environments where these waves are ubiquitously observed, their presence indicates significant (possibly global) energy and momentum transfer. For example, at Earth, ion cyclotron waves arising from a temperature anisotropy instability are believed to play an important role in the energy dynamics of the ring-current and radiation belts while at Mars, ion cyclotron waves arising from either a temperature anisotropy instability or a resonant beam instability are used as an indicator of mass-loading (ion pickup) from the atmosphere. We present an overview of the variable driving conditions, instability behavior, and resultant properties of the ion cyclotron waves in various planetary environments with insights from hybrid (kinetic ion, fluid electron) simulations and linear theory to help inform understanding between environments.

Acceleration and Escape of Ions from the Martian Atmosphere

Dave Brain (1), Y. Dong (1), H. Egan (1), T. Weber (1), K. Hanley (1), J. Halekas (2), J. McFadden (3), D. Mitchell (3), J.E.P. Connerney (4), Y. Ma (5), C. Dong (6), and B. Jakosky (1)
(1) LASP / University of Colorado, (2) University of Iowa, (3) SSL / University of California Berkeley, (4) NASA GSFC, (5) UCLA, (6) Princeton PPL

Multiple lines of evidence suggest that the Martian atmosphere has changed over billions of years from a state capable of supporting long-lived liquid surface water to the cold, thin atmosphere of the present epoch. A major driver of this atmospheric change may have been the loss of atmospheric particles to space. Atmospheric loss at Mars may have been particularly effective due to a combination of the small size of the planet and its lack of a global magnetic field to shield it from the solar wind. The Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has been orbiting Mars since September 2014, making measurements of the upper atmosphere and magnetosphere relevant to atmospheric escape. Here we present results from MAVEN about the loss of ions from the Martian atmosphere. We present estimates of current and past ion loss rates, and further discuss what MAVEN is revealing about the physics of ion acceleration near Mars - in a 'polar plume' of ions accelerated away from the ionosphere, and in the cusp regions of localized crustal magnetic fields.

The Martian ionosphere's response to Solar drivers

L. Andersson (1), C. M. Fowler (1) , E. Thiemann (1) , H. Akabari (1), M. Pilinski (1), J. Halekas (2), D. Mitchell (3), D. Larson (3), J. McFadden, M. K. Elrod (4), and G. A. DiBraccio (4).
(1) LASP, University of Colorado, (2) University of Iowa,
(3) SSL, University of California, (4) NASA GSFC.

Draping of the solar wind magnetic field about the Martian planetary obstacle results in the magnetic field strength within the ionosphere reaching strengths that are typically 5-10 times that of the upstream solar wind magnetic field. The Martian atmospheric density is several orders of magnitude smaller than at Earth and subsequently the Martian exobase is located below 200 km altitude. These characteristics, coupled with the relatively small physical size of the Martian system, mean that shocked solar wind plasma can penetrate to altitudes below 400 km during periods of enhanced solar wind pressure and disturbed solar wind conditions. During these times, the solar wind can directly couple with the Martian ionosphere and atmosphere and as a result, the Martian ionosphere can easily respond to changes in solar wind conditions and also solar EUV intensity. This presentation will show three different events and report on how the ionosphere responds in response to: a solar wind pressure pulse, a CME event, and a solar flare. The "strength" of the ionospheric response to each case will be discussed.

Variability of Jovian electron lightning whistlers detected by the Juno Waves Instrument

Ivana Kolmasova (1,2), Masafumi Imai (3), Ondrej Santolik (1,2), William S. Kurth (3), George B. Hospodarsky (3), Donald A. Gurnett (3), Scott J. Bolton (4) and John E. P. Connerney (5)
(1) Institute of Atmospheric Physics CAS, Prague, Czechia (2) Faculty of Mathematics and Physics, Charles University, Prague, Czechia (3) University of Iowa, Iowa City, IA, USA (4) Southwest Research Institute, San Antonio, TX, USA (5) NASA/Goddard Space Flight Center, Greenbelt, MD, USA

During seven close approaches to Jupiter between August 2016 and September 2017, mainly below radial distances of 2.7 Jovian radii, the Waves instrument onboard the Juno spacecraft recorded 1311 waveform snapshots containing one or more electron lighting whistlers. The length of each snapshot is 122.88 ms, the sampling frequency is 50 kHz. The total number of 1627 detected electron whistlers is much larger than the combined number of lightning events obtained from all previous missions to Jupiter. We detect peak occurrence rates of more than four whistlers per second, with an average rate of one whistler per second at midlatitudes, similar to thunderstorms at Earth. The detected whistlers are systematically observed to propagate from the planet which confirms their sources in the Jovian atmosphere below the spacecraft. We categorize the whistlers into two dispersion classes according to the difference of propagation delays at 2 and 5 kHz, whenever this was possible. Detected whistlers are often found to be frequency limited by upper cutoffs. We investigate the latitudinal, longitudinal and altitudinal variations in the occurrence rates of whistlers with different rates of their frequency drift and different upper cutoffs.

Juno observations of ion whistlers at Jupiter

Ondrej Santolik (1,2), Ivana Kolmasova (1,2), Masafumi Imai (3), Donald A. Gurnett (3), William S. Kurth (3), George B. Hospodarsky (3), John E. P. Connerney (4), and Scott J. Bolton (5)
(1) Institute of Atmospheric Physics CAS, Prague, Czechia, (2) Faculty of Mathematics and Physics, Charles University, Prague, Czechia, (3) University of Iowa, Iowa City, IA, USA,
(4) NASA/Goddard Space Flight Center, Greenbelt, MD, USA
(5) Southwest Research Institute, San Antonio, TX, USA

Lightning discharges in planetary atmospheres generate impulsive radio waves in a broad range of frequencies. These waves can be modified by their passage through the space plasma environment into the form of dispersed whistlers. In a plasma which contains traces of heavier ions, right-handed whistler waves which propagate upward but not exactly along the magnetic field lines encounter the crossover frequency where they change their polarization to left-handed, forming the ion whistlers which subsequently lose their power via the cyclotron resonance with protons. The unique low-altitude polar orbit of the Juno spacecraft allows us for the first time to observe ion whistlers at Jupiter in the two-component waveform recordings of the Waves instrument. Comparison of the frequency-time structure of the observed ion whistlers with our calculation of their frequency dependent group delay allows us to estimate parameters of the plasma environment of Jupiter.

Numerical simulation of the Io-torus-driven radial plasma transport

Chuxin Chen
CAS Key Laboratory of Geospace Environment, Department of Geophysics and Planetary Sciences, School of Earth and Space Sciences, University of Science and Technology of China, China

A series of six axis symmetric equilibrium models for Jupiter's inner magnetosphere was constructed. Upon which, the motion of an Io torus generated, mass over-loaded magnetic flux tube on a meridian plane of the inner Jovian magnetosphere was studied numerically via magnetohydrodynamics (MHD) approach. The flux tube is represented as a one-dimensional filament, while the Jovian magnetosphere is represented as a two-dimensional stationary medium. With only cold plasma included in the model, such heavy filament is unstable. However, when both cold and hot plasma are included in the models, the heavy filament is stabilized by the huge thermal pressure gradient for the Voyager period. For the Galileo period, the situation is less definitive because there is no observation based hot plasma pressure data available within 6.75 Jovian radii. Nevertheless, our simulations in two models suggested that even with both cold and hot plasma included in the models, the heavy filament is still unstable for this period. The filament moves outward toward the middle and/or outer magnetosphere due to the interchange instability. The mass elements in the unstable filament are propelled along its length by the centrifugal force toward the equatorial plane. This filament tends to be more stretched in the outward direction than its neighbors as time elapses. The outward moving speed of the filament within 7.1 Jovian radii is comparable with the Galileo spacecraft's observation in the Io torus on December 7, 1995.