Geospace Exploration Project: Arase (ERG)

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The ERG (Exploration of energization and Radiation in Geospace) is a geospace exploration project. The project focuses on the geospace dynamics in the context of the cross-energy coupling via wave-particle interactions. The project consists of the satellite observation team, the ground-based network observation team, and integrated-data analysis/simulation team. The Arase (ERG) satellite was sucefully launced in December, 2016. Comprehensive instruments for plasma/particles, and field/waves are installed in the ERG satellite to understand the cross-energy coupling system. In the ERG project, several ground-network teams join; magnetometer networks, radar networks, optical imager networks, etc. Moreover, the modeling/simulations play an important role for the quantitative understanding. In this presentation, we will talk about an overview of the Arase (ERG) project.

Keywords: Arase, Geospace, radiation belts

Plasma Wave Experiment (PWE) on board the ARASE (ERG) Satellite (Initial Report)

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The ERG (Exploration of energization and Radiation in Geospace) project is a mission to study acceleration and loss mechanisms of relativistic electrons around the Earth. To achieve comprehensive observations of plasma/particles, fields, and waves, the Plasma Wave Experiment (PWE) is installed on board the ERG satellite to measure electric field in the frequency range from DC to 10 MHz, and magnetic field in the frequency range from a few Hz to 100 kHz. Varieties of operational modes are implemented in the PWE, and the telemetry data consists of several kinds of data such as power spectrum, waveform, spectral matrix and DC E-field. Innovative instruments named S-WPIA (Software-Type Wave Particle Interaction Analyzer) was installed on the satellite to measure energy exchange processes between plasma waves and particles directly, and the PWE will provide raw waveform data to the S-WPIA collaborating with the other scientific instruments.
The PWE will generate two kinds of mission data; nominal data and burst data. The former consists of wave spectra in VLF/HF range and waveforms in ELF range, and will be generated continuously as survey data. The nominal data will be downloaded to the ground. On the other hand, the latter is essentially raw waveform data in VLF range and the data amount is quite huge. They will be once stored in the mission data recorder (MDR) and partial data will be downloaded after data selection. In order to obtain maximum science output, it is very important to check and analyze the nominal data quickly and select valuable data from burst data stored in the MDR.
The ARASE has passed its critical operation phase and we have confirmed successful extension of the wire-probe antennas as well as the masts. The onboard instruments including the PWE are now in the initial check out phase. In the present paper, we introduce the specification of the PWE and its initial data. We also introduce our data processing plan on the ground.

Keywords: Plasma Wave Experiment (PWE), Arase (ERG), Inner Magnetosphere, Chorus, EMIC, Ground data processing

Initial Report of the High Frequency Analyzer (HFA) onboard the ARASE (ERG) Satellite

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The ERG (Exploration of energization and Radiation in Geospace, ARASE) was launched on December 20, 2016. The purpose of the ERG is to explore the dynamics od the Earth' s radiation belt using electric and magnetic field instruments covering a wide frequency range and electron and ion detectors over a wide energy range. New instruments named S-WPIA (Software-Type Wave Particle Interaction Analyzer) was installed on the satellite to measure energy exchange processes between plasma waves and particles directly.
High Frequency Analyzer (HFA) is a subcomponent of the Plasma Wave Experiment (PWE) for observation of radio and plasma waves in a frequency range from 0.01 to 10 MHz. The bandwidth is 1.2 kHz in 0.01-1 MHz, and 12 kHz in 1-10 MHz. The time
In ERG mission, HFA is expected to perform the following observations:
(1) Observation of upper hybrid resonance (UHR) waves in order to determine the electron number density around the spacecraft and provide it to SWPIA.

Keywords: The ARASE (ERG) satellite, PWE, HFA

Initial results of the magnetic field experiment by the magnetometer (MGF) for the ARASE (ERG) mission

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The acceleration process of the charged particles in the inner magnetosphere is considered to be closely related to the deformation and perturbation of the magnetic field. Accurate measurement of the magnetic field is required to understand the acceleration mechanism of the charged particles, which is one of the major scientific objectives of the ARASE (ERG) mission. We designed a fluxgate magnetometer which is optimized to investigate following topics;
(1) accurate measurement of the background magnetic field - the deformation of the magnetic field and its relationship with the particle acceleration.
(2) MHD waves - measurement of the ULF electromagnetic waves of frequencies about 1mHz (Pc4-5), and investigation of the radiation-belt electrons radially diffused by the resonance with the ULF waves.
(3) EMIC waves - measurement of the electromagnetic ion-cyclotron waves of frequencies about 1Hz, and investigation of the ring-current ions and radiation-belt electrons dissipated by the interaction with the EMIC waves.
A fluxgate magnetometer (MGF) was built for the ARASE satellite to measure DC and low-frequency magnetic field. The design is based on MGF-I, one of the magnetometers for BepiColombo MMO, Mercury orbiter, which would also suffer high radiation on the Mercury orbit.
The requirements to the magnetic field measurements by ARASE was defined as (1) accuracy of the absolute field intensity is within 5 nT (2) angular accuracy of the field direction is within 1 degree (3) measurement frequency range is from DC to 60Hz or wider. MGF measures the vector magnetic field with the original sampling frequency of 256 Hz. The dynamic range is switched between +/-8000nT and +/-60000nT according to the background field intensity.
The MGF initial checkout was carried on January 10th 2017, three weeks after the launch of ARASE. The MGF normal performance and downlinked data were confirmed. The MAST for the sensor was deployed on 17th January.
The initial results of the magnetic field observation and data examination will be shown in the presentation.

Keywords: Geospace, Radiation belt, magnetic field

Preliminary results of the first ERG-ground campaign observation of the inner magnetosphere using the PWING ground network

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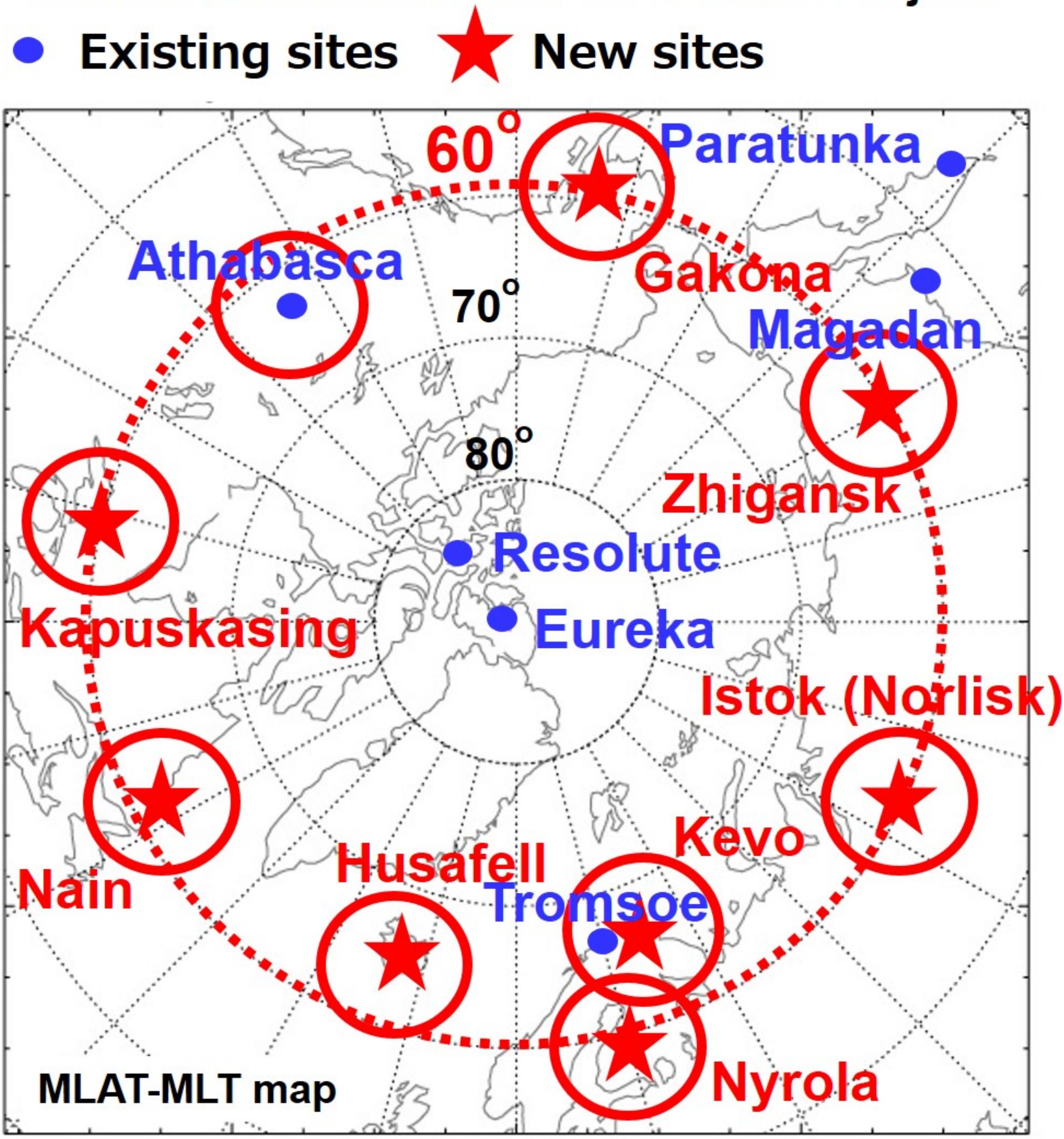
Dynamical variation of particles and waves in the inner magnetosphere is one of the most important research topics in recent space physics. The inner magnetosphere contains plasmas in wide energy ranges from below electron volts to Mega-electron volts. These plasmas (electrons and ions) interact with ULF/ELF/VLF waves at frequencies of 0.1 Hz to 10 kHz to cause their energization in the equatorial plane of the magnetosphere and loss into the ionosphere. In order to provide global distribution and quantitative evaluation of the dynamical variation of plasmas and waves in the inner magnetosphere, we have started PWING Project (study of dynamical variation of Particles and Waves in the INner magnetosphere using Ground-based network observations, http://www.isee.nagoya-u.ac.jp/dimr/PWING/PWING_web_e.htm), which will last for 5 years from April 2016, as a Grant-in-Aid for Specially Promoted Research of the Japan Society for the Promotion of Science (JSPS). In this PWING project, we operate all-sky aurora/airglow imagers, 64-Hz sampling induction magnetometers, 40-kHz sampling ELF/VLF receivers, and 64-Hz sampling riometers at 8 stations at ~60 MLAT around the north pole, as well as two EMCCD cameras at two stations. The stations are distributed in Canada, Iceland, Finland, Russia, and Alaska. We combine these longitudinal network observations with the ERG (Arase) satellite, which was launched on December 20, 2016, and global modeling. The first campaign observation of PWING project with the newly-launched ERG satellite is planned in the second half of March 2017. In this presentation, we show preliminary results obtained from this first campaign observations based on the PWING ground network observations of these instruments.

Keywords: inner magnetosphere, ERG satellite , PWING project , longitudinal network

Ground-based stations of the PWING Project.



Transportation and acceleration of outer belt electrons in the slot region responsible for the formation of new radiation belt during big magnetic storm

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It was reported that relativistic electrons in the outer radiation belt have been transported into the slot region during big magnetic storms (Obara and Matsumoto, 2016 and references therein). Baker et al.(2013) further reported a new radiation belt has been made in some cases.

We have examined electron data in the radiation belt during magnetic storms paying a particular attention to the formation of new radiation belt. Issues, we like to clarify, will be followings: i.e. 1) electrons injected into the slot region will have additional (local) acceleration there ? 2) what is the cause of electron acceleration ? 3) how long electrons will feel acceleration ? and 4) what mechanism will be essential for the formation of new radiation belt ?

We have analyzed two events; one is March 24-th, 1991 event and the other is July 14-th, 2000 event. New radiation belt has been made at round L˜3 in both cases and it persisted for almost two weeks. In both cases, we have confirmed local acceleration. Intense very low frequency (VLF) plasma waves have been observed. We are considering additional acceleration has been made by these waves.

New point of our result will be the identification of local acceleration of electrons in very near Earth region; i.e. L˜3, and it also confirms the results by Baker et al.(2013).

Keywords: New radiation belt, Slot region, Electron acceleration

Results of wave observations during Cluster Inner Magnetospheric Campaign

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The study of the growth and evolution of waves and structure that typically occur within the inner magnetosphere requires multipoint measurements at small separation distances. The Cluster Inner Magnetosphere Campaign was aimed to provide closely spaced (down to separations of the order of 10^1 km) measurements of waves at high temporal resolution. This enables the investigation of composition of the turbulence, its dispersion, linear and nonlinear processes the contribute to the wave field, and interaction with the local plasma populations. Results of Cluster Inner Magnetospheric Campaign related to Equatorial Noise, EMIC waves and other emmisions are reviewed.

Keywords: Magnetosphere, Energetic electrons , wave particle interactions

Coincident Compression Generated EMIC Chorus and Hiss waves

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Electron radiation belt dynamics are controlled by the competition of multiple acceleration and loss mechanisms. Electromagnetic ion cyclotron (EMIC), chorus, and hiss waves have all been implicated as potential loss mechanisms of radiation belt electrons along with Chorus waves proposed as a mechanism for accelerating the lower energy source population to MeV energies. Understanding the relative importance of these waves as well as where and under what conditions they are generated is vital to predicting radiation belt dynamics.

Although the size of the solar wind compression on 9 January 2014 event discussed here was modest, it has given us an opportunity to observe clearly how a magnetospheric compression can lead to the generation of EMIC, chorus, and hiss waves. The ICME generated shock encountered the Earth’s magnetosphere on 9 January 2014 at ~20:11 UT, and the Van Allen Probes observe the coincident excitation of EMIC and Chorus waves outside the plasmasphere, and hiss waves inside the plasmasphere. As the shock encountered the magnetosphere, an electric field impulse was observed to generate an increase in temperature anisotropy for both ions and electrons. This increased temperature anisotropy led to increased wave growth on both the ion and electron cyclotron branches. The simultaneous generation of multiple types of waves may lead to significant impacts on the acceleration and loss of radiation belt electrons, especially during geomagnetic compressions observed during substorms, and the storm sudden commencement and main phases of geomagnetic storms, as well as during quiet time sudden impulse events. For example, the excitation of both EMIC and chorus waves at the same place, and at the same time, may complicate studies seeking a causal connection between specific individual plasma wave bursts and observations of particle precipitation into the atmosphere. During this relatively small event BARREL had three payloads in conjunction with the Van Allen Probes, two of the payloads inferred electron precipitation within the energy range typically associated with chorus wave pitch angle scattering. One can hypothesis that with larger and/or longer lasting ICME-shocks, or with a larger initial population of radiation belt electrons, more electron precipitation, and a larger range of energies, may be observe.

Keywords: Plasma Waves, Geomagnetic compression, Electromagnetic Ion Cyclotron waves, Electromagnetic electron cyclotron waves

Modeling of cavity modes and field line resonances in the inner magnetosphere

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Ultra-low-frequency (ULF) waves are a major means to transport energy through the magnetosphere and play an important role in energization and transport of radiation belt particles. In the inhomogeneous inner magnetosphere, ULF waves frequently are affected by the density structure of the magnetosphere as well as by the ionospheric boundary conditions. We have developed a three-dimensional numerical code in dipole geometry to describe the propagation of ULF waves in the inner magnetosphere. In particular, we model the response of the inner magnetosphere to impulsive compressions that occur on the dayside due to shocks impinging on the magnetosphere and on the nightside due to dipolarization fronts during substorms. These compressions can lead to the development of plasmaspheric cavity modes in the inner magnetosphere that have periods of 1-2 minutes. Furthermore, compressional waves can mode convert to shear Alfvén mode field line resonances that stand on field lines when the compressions contain wave power at the frequency corresponding to harmonics of the fundamental wave period. A special case of field line resonances occurs near the terminator during solstice conditions when one end of the field line is sunlit while the other end is in darkness. Under these circumstances, quarter-wave modes can result in which one end of the field line is a node of the electric field while the other end is an antinode. The model results compare favorably with observations from the Van Allen Probe satellites as well as fields measured by ground magnetometers.

Keywords: ULF Wave Modeling, Radiation Belts, Magnetosphere-Ionosphere Coupling

Rapid Variations of Energetic Electron Pitch Angle Distributions and Associated Wave Emissions

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Injections of energetic electrons into the inner magnetosphere are a common feature of spacecraft observations. The electron flux rises very rapidly and then recovers smoothly to the pre-event level over a period of several hours. Recent high resolution angular measurements by the Magnetic Electron and Ion Spectrometer (MagEIS) instrument on the Van Allen Probes have observed rapid variations in the recovery of the electron pitch angle distributions at energies in range 20-100 keV. These features can take several forms, one of which is peaks in narrow ranges of pitch angle that occur quasiperiodically every few minutes. In many cases, these electron flux bursts appear to correlate with simultaneously detected plasma wave emissions. Fennell et al. [J. Geophys. Res., 2014] reported one such event in which several flux bursts were highly correlated with upper band whistler-mode chorus waves. One difficulty with identifying and cataloging these events is the obscuration of the rapid variations by the slow trends of the background plasma. Algorithms are being developed to detrend the electron flux by subtracting out this slowly varying background and revealing the rapid burst features. Use of this procedure shows that the rapid variations in pitch angle distributions are a common feature of substorm-generated electron injections in the inner magnetosphere. Over 400 such events have been identified with more 3000 individual pitch angle featured detected. The characteristics of the bursts and associated waves are being cataloged, including the energy and pitch angle of the electron bursts, the anisotropy of the background plasma, the wave frequency and mode, the observation location, and the geomagnetic conditions during the events.

Keywords: Plasma waves, Energetic electrons, Substorm particle injections

One year comparison of lighting activity and variations in electron fluxes of the inner radiation belt

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In the radiation belts, energetic electrons with energies above 100 keV undergo cyclotron resonant interactions with whistler-mode plasma waves. These wave-particle interactions lead to either acceleration or loss of particles by energy diffusion or pitch angle scattering. Lightning discharges are known to radiate electromagnetic energy over a wide range of latitudes around their source. Part of this energy propagates in the whistler-mode through the ionospheric plasma and can then interact with electrons in the radiation belts causing whistler-induced electron precipitation. There have been several studies that focus on the effects of these whistler-induced precipitation and their immediate relationship to lightning strikes [Rodger et al. (2004), Clilverd et al. (2004)]. However, there is little research that concentrates on the long-term effects of these electron losses on the population of the inner radiation belts. In this study, we use data from the World Wide Lightning Location Network (WWLLN), continuously monitoring global lightning since 2004, to examine one year of lightning data (January to December 2013) and locate the L-shells with strong lighting activity. Then we use the Energetic Particle, Composition, and Thermal Plasma Suite (ECT) from both Van Allen Probes (RBSP–A and –B) to measure electron fluxes in the inner radiation belt at the L-shells of strong lightning activity. We examine the influence that lightning activity has on long-term electron precipitation using RBSP trapped omnidirectional fluxes, as well as pitch angle distributions, dayside/nightside differences and geomagnetic activity. We use several case studies in order to quantify the loss effects to the radiation belts due to lightning activity.

Keywords: Lightning, Inner radiation belt, whistler induced precipitation, electron loss

Recent Science Highlights of the Van Allen Probes Mission

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The morning of 30 August 2012 saw an Atlas 5 rocket launch NASA’s second Living With a Star spacecraft mission, the twin Radiation Belt Storm Probes, into an elliptic orbit cutting through Earth’s radiation belts. Renamed the Van Allen Probes soon after launch, the Probes are designed to determine how the highly variable populations of high-energy charged particles within the radiation belts, dangerous to astronauts and satellites, are created, respond to solar variations, and evolve in space environments. The Van Allen Probes mission extends beyond the practical considerations of the hazard’s of Earth’s space environment. Twentieth century observations of space and astrophysical systems throughout the solar system and out into the observable universe have shown that the processes that generate intense particle radiation within magnetized environments such as Earth’s are universal. During its mission the Van Allen Probes verified and quantified previously suggested energization processes, discovered new energization mechanisms, revealed the critical importance of dynamic plasma injections into the innermost magnetosphere, and used uniquely capable instruments to reveal inner radiation belt features that were all but invisible to previous sensors. This paper gives a brief overview of the mission, presents some recent science highlights, and discusses plans for the extended mission.

Keywords: Inner magnetosphere, Radiation belts, Space weather

Multipoint Observations of Cavity Mode Oscillations Excited by an Interplanetary Shock

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Cavity mode oscillations (CMOs) are basic magnetohydrodynamic eigenmodes of the magnetosphere predicted by theory. Excitation of CMOs is expected when an interplanetary shock impulsively compresses the magnetosphere, but observational studies of shock-induced CMOs have been sparse. We present a case study of a dayside ULF wave event that exhibited CMO properties. The event occurred when an interplanetary shock impacted the magnetosphere at 0829 UT on 15 August 2015. The shock was observed in the solar wind by THEMIS-B and -C, and magnetospheric ULF waves were observed by multiple spacecraft including Van Allen Probes-A and -B, THEMIS-D, -E, and -A, GOES-13 and -15, and ETS-VIII. The Van Allen Probes were located in the dayside plasmasphere at L=1.5 and L =2.4, and both spacecraft detected compressional poloidal mode oscillations at ˜13 mHz (fundamental) and ˜26 mHz (second harmonic). At both frequencies, the compressional component of the magnetic field led the azimuthal component of the electric field by ˜90 degrees. The frequencies and the phase delay are in good agreement with CMOs generated in a dipole magnetohydrodynamic simulation that incorporates a realistic plasma mass density distribution and an ionospheric boundary condition. The poloidal oscillations were also detected on the ground by the European quasi-Meridional Magnetometer Array, providing additional evidence for the global nature of the waves.

Keywords: Caviy mode oscillations, Interplanetary shock, Observation and simulation

Occurrence of EMIC waves and plasmaspheric plasmas derived from THEMIS observations in the outer magnetosphere

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We have statistically studied the relationship between electromagnetic ion cyclotron (EMIC) waves and cold plasmaspheric plasma (N_{sp}) in the L range of 6-12 using the Time History of Events and Macroscale Interactions during Substorms (THEMIS) data for 2008-2011. The important observational results are as follows: (1) Under quiet geomagnetic conditions (Kp = 0-1), the maximum occurrence rate of the hydrogen (H) band EMIC waves appears in the early morning sector (0600-0900 MLT) at the outermost region (L = 10-12). (2) Under moderate and disturbed conditions (Kp > 2), the H-band occurrence rate is higher in the morning-to-early afternoon sector for L > 10. (3) The high occurrence region of helium (He) band waves for Kp = 0-1 varies from L = 7 to 12 in radial distances along the local time (i.e., at L ~ 7 near noon and at L = 8-12 near late afternoon). (4) The He-band waves for Kp > 2 are mainly localized between 1200 and 1800 MLT with a peak around 1500-1600 MLT at L = 8-10. (5) N_{sp} is much higher for the He-band intervals than for the H-band intervals by a factor of 10 or more. The He-band high occurrence appears at a steep N_{sp} gradient region. (6) The morning-afternoon asymmetry of the normalized frequency seen both in H and He bands 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 a morning-afternoon asymmetry of the EMIC wave properties can be explained by the spatial distribution of cold plasmaspheric plasma.

Keywords: EMIC waves, Plasmaspheric plasma

Nature's Grand Experiment: Linkage Between Magnetospheric Convection, Substorms, and the Radiation Belts

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The solar minimum of 2007-2010 was unusually deep and long-lived. In the later stages of this period the electron fluxes in the radiation belts dropped to extremely low levels. The flux of relativistic electrons (>1 MeV) was significantly diminished, and at times were below instrument thresholds both for spacecraft located in geostationary orbits and also those in low-Earth orbit. This period has been described as a natural "grand experiment" allowing us to test our understanding of basic radiation belt physics and in particular the acceleration mechanisms which lead to enhancements in outer belt relativistic electron fluxes.
Here we test the hypothesis [1] that processes driven by magnetospheric convection initiate repetitive substorm onsets, which in turn triggers enhancement in whistler mode chorus that accelerates radiation belt electrons to relativistic energies. Conversely, individual substorms would not be associated with radiation belt acceleration. Contrasting observations from multiple satellites of energetic and relativistic electrons with substorm event lists, as well as chorus measurements, shows that the data are consistent with the hypothesis.
We show that repetitive substorms are associated with enhancements in the flux of energetic and relativistic electrons and enhanced whistler mode wave intensities. Our finding is consistent with the recent RBSP case studies [2], which suggested that substorms were the trigger for chorus which lead to acceleration of radiation belt electrons to relativistic energies. However, in our study we see a two stage chorus wave power enhancement, the first starts slightly before the repetitive substorm epoch onset, suggesting that magnetospheric convection leading the chorus activity may be the trigger. This conclusion requires some care, as the second and strongest enhancement in chorus is very slightly after the onset, complicating the picture.
During the 2009/2010 period the only relativistic electron flux enhancements that occurred were preceded by repeated substorm onsets, consistent with enhanced magnetospheric convection and repetitive substorms as a trigger for outer radiation belt electron acceleration. This work has been recently published in JGR [3].

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Keywords: outer radiation belt, electron acceleration, coupling processes, whistler mode chorus

Relativistic electron flux dropout due to field line curvature during the storm on 1 June 2013

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A relativistic flux dropout is a sudden and significant decrease in the relativistic electron (> 1 MeV) population of the outer radiation belt occurring over timescales of a few hours. A significant dropout of relativistic electrons was observed by Van Allen Probes during the storm main phase on June 1, 2013. During the same period, MeV electron precipitation with isotropic pitch-angle distribution was also observed from POES but no EMIC waves were detected from either space- or ground-based magnetometers. Based on Tsyganenko empirical magnetic field model, magnetic field lines are highly non-dipolar and stretched at the night side in the inner magnetosphere. This condition can break the first adiabatic invariant (conservation of magnetic moment) and generate pitch-angle scattering of relativistic electron to the loss cone. To understand the relative roles of different physical mechanisms on this dropout event, we simulate flux and phase space density of relativistic electrons with event specific plasma wave intensities using the Comprehensive Inner Magnetosphere and Ionosphere (CIMI) model. We also employ pitch-angle scattering due to field line curvature in the CIMI model. We re-configure magnetic field every minute and update electric field every 20 seconds to capture convective and diffusive radial transport. CIMI-simulation with pitch-angle scattering due to field line curvature shows more depletion of relativistic electron fluxes and better agreement to observation. We conclude that pitch-angle scattering due to field line curvature is one of the dominant processes for the relativistic electron flux dropout.

Keywords: relativistic electron dropout, loss, field line curvature

Van Allen Probes observation of plasmaspheric electron acceleration by ULF waves at the plasmaspheric boundary layer

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In this study, we report the plamsmaspheric electron acceleration caused by drift-bounce resonance with ULF waves at the plasmaspheric boundary layer. Long-lasting ULF waves in the period of about 1 min, identified as second harmonic mode, were observed by Van Allen Probe B during two successive orbits. During ULF wave appearance, both plasmaspheric electrons (<200 eV) and energetic protons (10-20 keV) showed bi-directional pitch angle signature, which is caused by drift-bounce resonance with N=1. And the averaged plasmaspheric electron flux enhanced up to 5 times of that when there were no ULF wves. Based on multi-spacecraft observation using two Van Allen Probes, two GOES satellites (GOES 13 and GOES15) and MMS 1, these ULF waves mainly distributed in the duskside, and MMS 1 observed no external sources when travelling inbound and outbound in the magnetosphere, which suggests that these ULF waves were excited through drift-bounce resonant instability caused by substorm-injected energetic protons.

Keywords: Plasmaspheric electron acceleration, ULF waves, Drift-bounce resonance, Wave exciting mechanism, Multi-spacecraft observation

Spectral structures of energetic electrons in the inner magnetosphere

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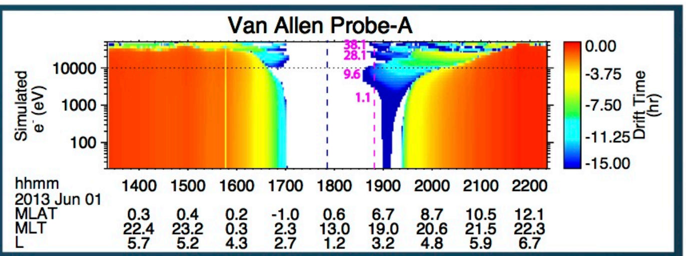
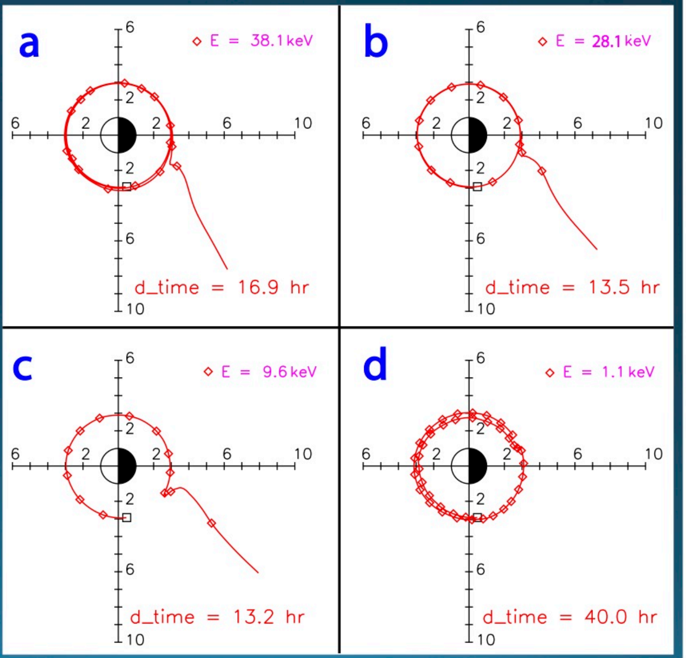
Electron spectral structures in the energy-time flux spectrograms are the observational signatures of electron acceleration, transport, and loss in the global magnetosphere. Combining *in situ* measurements with backward particle drift path simulations, we studied electron spectral structures in the inner magnetosphere before and during the 1 June 2013 storm (min. *Dst* = -119 nT). For the purpose of comparison, proton results were also included. Electron spectral structures were less dynamic during storm time than quiet time, because deeper transport and more enhanced fluxes smeared the spectral structures. Electron injection depth and some spectral features were fairly well reproduced with the Weimer96 electric field and the dipole magnetic field. Although always drifting eastward, electrons could still display multiple spectral structures. Their formation was attributed to “drift resonance”, i.e., electrons with different energies drifting around the Earth by a different number of loops. Pitch angle scattering loss played an important role in the formation of electron spectral features.

Keywords: Magnetospheric configuration and dynamics, Plasma convection , Plasma sheet , Ring current, Solar wind/magnetosphere interactions

Formation of Multiple Electron "Noses"

- Backward Drift Path Tracings at 1850:48 UT:
  - Start at L = 3.0 & MLT = 18.6
  - End at L =10.0 or Drift Time (d_time) > 40 hrs
- Drift Paths:
  - 38.1 keV: (2, 3) loops
  - 28.1 keV: (1, 2) loops
  - 9.6 keV: < 1 loop
  - 1.1 keV: trapped, i.e., no access to the tailward source region





Recent progresses in understanding the contribution of EMIC waves to radiation belt electron scattering

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Resonant wave-particle interactions are long thought as a fundamental cause driving the dynamic variability of Earth's electron radiation belts. In terms of violating one or more adiabatic invariants, magnetospheric waves have been regarded as a necessary agent to transfer energies between different populations of particles. This presentation focuses on some recent progresses in understanding the electron scattering effects of EMIC waves. While cyclotron resonant electron scattering by EMIC waves has been well studied and found to be a potentially crucial electron scattering mechanism, the recent investigation demonstrates that bounce resonant electron scattering may also be very important in a manner to resonate with near-equatorially mirroring electrons over a wide range of L-shells and energies. It is strongly suggested that bounce resonance scattering by EMIC waves should be incorporated into future modeling efforts of radiation belt electron dynamics.

Keywords: Earth's radiation belts, resonant wave-particle interactions, EMIC waves

Observational and numerical studies about frequency chirping of chorus waves

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The underlying physical mechanism of the nonlinear frequency chirping of whistler mode chorus waves has been investigated for more than fifty years; nevertheless, a consensus has yet to be reached. In this talk, we will present some of our recent observational studies about the dependence of the chorus wave frequency chirping rate on both background plasma parameters and wave amplitude. Comparison with different previously published theoretical models will be given. We will also present numerical simulation demonstrating the amplitude modulation of chorus waves that has also been found in observation. With phase space diagnostics, we suggest that the amplitude modulation is caused by phase space trapping of resonant particles.

Keywords: chorus waves, frequency sweep rate

Landau Resonance Acceleration of MeV Electrons by Obliquely Propagating Whistler-mode Chorus Emissions

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A recent analysis of wave and particle data obtained by the Van Allen Probes [Foster et al., 2017] demonstrates highly efficient acceleration of relativistic electrons by whistler-mode chorus emissions. The analysis identified that the acceleration is mostly due to the cyclotron resonance of relativistic electrons with chorus emissions propagating quasi-parallel to the ambient magnetic field. As the energy of an electron becomes relativistic (1 - 2 MeV), the parallel resonance velocity approaches zero near the equator, where nonlinear trapping of resonant electrons becomes possible, resulting in relativistic turning acceleration [Omura et al., 2007]. The detailed subpacket analysis shows that there arises a parallel wave electric field that can trap energetic electrons through Landau resonance. A recent test particle simulation [Hsieh and Omura, 2017], however, shows that the perpendicular wave electric field can also play a significant role in trapping and accelerating relativistic electrons through Landau resonance. We present a theoretical analysis of the Landau resonance acceleration, and verify it by the subpacket analysis of chorus emissions observed by Van Allen Probes. We compare the efficiencies of accelerations by the cyclotron resonance and the Landau resonance.

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Keywords: wave-particle interaction, radiation belts, particle acceleration

Formation process of outer radiation belt electron flux through interaction with lower-band chorus emissions with subpacket structures

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We perform test particle simulations of relativistic acceleration processes of energetic electrons interacting with chorus emissions with sub-packet structures. Recent analyses of whistler-mode chorus emissions observed by spacecraft show that a wave packet of a rising-tone chorus element consists of many sub-packets with gradually increasing frequencies [*Santolik et al.,* JGR, 2014; *Foster et al.,* JGR 2017]. The strong modulation of the wave amplitude affects dynamics of resonant electrons, making them detrapped from the wave potential or entrapped into it. We set up two wave models, i.e., a chorus element with and without subpacket structures. We compare the acceleration efficiencies in the two different wave models by tracing the formation processes through many interactions with the wave packets of chorus emissions based on the Green's function method proposed by *Omura et al.* [JGR 2015]. In both cases, resonant electrons undergoing the cyclotron resonance with the waves are efficiently accelerated by nonlinear wave trapping. In the case of the wave model with the subpacket structure, a larger number of electrons are entrapped into the wave potentials, while the acceleration efficiency in energy is decreased due to shorter interaction. In the case of the wave model without the subpackets, the acceleration efficiency in energy is much higher while the number of electrons undergoing the acceleration is decreased. Eventually the total acceleration efficiencies in forming the relativistic electron flux are not much different in the two different wave models. In both cases, we find formation of butterfly distributions of MeV electrons.

Keywords: radiation belt, chorus, acceleration, relativistic electron

Van Allen Probes Observations of Particle Injections and ULF Waves During Lapping Events

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The twin Van Allen Probes mission provides unique data sets for the studies of radiation belt and ring current dynamics thanks to their orbit configuration and coverage, and state of the art instrumentation with high energy and time resolutions. This study presents mid- to high-energy particle injection and wave events associated with storm and substorm activities when the twin spacecraft were very close to each other (called "lapping event"). The lapping events enable us to investigate the wave-particle interaction on an unprecedented spatial and temporal scale. The events presented here show that mid-energy (a few to hundreds of keV) injected particles provide energy to generate electromagnetic ion cyclotron (EMIC) and ultra low frequency (ULF) waves, resulting in scattering of high-energy (a few MeV) electrons in the radiation belt. Clear one-to-one correspondence between waves and particles with high energy and time resolution is demonstrated. Because of the spacecraft's lapping during multiple consecutive fly-bys, detailed spatial and temporal structures of the wave-particle interaction are revealed.

Keywords: Ring current, ULF waves, injection

Energetic ring current proton spectra measured by the Van Allen Probes

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We examine two geomagnetic storm periods,namely March 17-20,2013 and March 17-20,2015,and analyze proton spectra measured by the Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) on board the Van Allen Probes. In particular,we consider the most intense proton spectra over the energy range 50 - 600 keV ,for outer-zone L-shells, during these storm periods. Recent theory has been developed to model the limitation of energetic ring current ion spectra resulting from the action of pitch-angle scattering by electromagnetic ion cyclotron (EMIC) waves. The theory suggests that a limiting (extreme) spectrum is achieved when the EMIC waves acquire a certain gain over a given convective length scale for all frequencies over which wave growth occurs. We obtain the theoretical limiting spectrum numerically, and also show that the limiting spectrum varies as 1/E for large kinetic energy E. Comparison of the observed extreme proton spectra with the corresponding numerical limiting spectra provides evidence that the extreme spectra are controlled by EMIC wave scattering.

Keywords: ring current protons, extreme proton spectra, Van Allen Probes

