Relativistic electron precipiations associated with the pulsating aurora

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We investigate the wide energy electron precipiations from keV to MeV associated with the pulsating aurora. The EISCAT observations indicated that a few hundred keV electrons often precipitate into the middle atmosphere during the pulsating aurora. The satellite at the magnetosphere observes that intense rising tone emissions of chorus waves were observed in the magnetosphere. The chorus waves that propagate to the higher latitudes can modulate electrons for the wide energy range, and resultant precipiations take place. Our computer simulation confirmed this process; chorus waves propagating along the field line cause the wide energy electron precipitations. These precipiations have a great impact on the ion chemistory at the mesosphere. In fact, the computer simulation showed that significant enhancement of NOx and decrease of O3 occurs associated with the precipiation of pulsating aurora electrons.

Keywords: Pulsating aurora, radiation belts

Ultra-low-frequency wave-driven diffusion of radiation belt relativistic electrons

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Van Allen radiation belts are typically two zones of energetic particles encircling the Earth separated by the slot region. How the outer radiation belt electrons are accelerated to relativistic energies remains an unanswered question. Recent studies have presented compelling evidence for the local acceleration by Very Low Frequency (VLF) chorus waves. However, there has been a competing theory to the local acceleration, radial diffusion by Ultra Low Frequency (ULF) waves, whose importance has not yet been determined definitively. Here we report a unique radiation belt event with intense ULF waves but no detectable VLF chorus waves. Our results demonstrate that the ULF waves moved the inner edge of the outer radiation belt earthward 0.3 Earth radii and enhanced the relativistic electron fluxes by up to one order of magnitude near the slot region within about 10 hours, providing strong evidence for the radial diffusion of radiation belt relativistic electrons.

Keywords: Van Allen radiation belts, Ultra Low Frequency (ULF) waves, Radial diffusion, Electron acceleration

Excitation of Pc1-3 waves in the magnetosphere by external shear flows

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We present how Pc1-3 wave occurrences are affected by external sources in the magnetosheath. The Doppler shift motion of disturbances in the magnetosheath can continuously generate relatively high frequency component of ULF waves, which includes EMIC band. By adopting a theoretical technique of invariant imbedding method(IIM), it is shown how the solar wind and the IMF control the EMIC activities as well as Pc 1-3 wave occurrences. Our results are found to be very consistent with the observational feature of current statistical studies of EMIC wave events such that dominant occurrences are found at the outer shells, and that there is strong asymmetric distribution between dawn and dusk. In addition, our results are also consistent with Pc2-3 occurrences in the low-latitude ground stations and their relationship with the solar wind speed.

Keywords: magnetosphere, ULF wave

A predictor-corrector schema based upon Boris schema for the integration of the equation of motion of charged particles : Application to the Earth's inner magnetosphere

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A lot of numerical schemes are available for integrating the equations of motion of a charged particle in an electromagnetic field. The schema proposed by Boris (1970) is one of the most remarkable due to its simplicity and accuracy and hence is widely used in numerical plasma physics. Although being not a leap-frog schema due to the dependence of the electromagnetic force upon the velocity, it has a structure reminiscent of the leap-frog which imposes to stop and restart the integration in order to change the time step. Hence the original Boris’ schema does not allow a continuous adaptation of the time step. Changing the time step during self-consistent numerical simulations would be difficult, if not practically impossible, but it may be of interest for test particle simulations. We present a predictor-corrector schema making use of the acceleration substep of Boris’ algorithm which allows to vary continuously the time step. We have also designed a procedure for the automatic control of the time step. Applications to the motion of energetic particles in the terrestrial magnetosphere will be presented.

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Keywords: motion of charged particles in electromagnetic fields, numerical simulation, magnetospheres

Relation between the ionospheric convection observed by the SuperDARN Hokkaido Paif of (HOP) radars and low-latitude auroras

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Recent SuperDARN deployment toward lower latitudes made it possible to study ionospheric convection associated with low-latitude auroras (up to below 50 degrees geomagnetic latitude) with high temporal resolution (1 min). In this paper we report on the relationship between the appearance of low-latitude auroras for a few geomagnetic storm events (such as that on March 17, 2015 and on December 21, 2015) and ionospheric convection observed by the SuperDARN Hokkaido Pair of (HOP) radars. Associated with low-latitude auroral emission in the postmidnight sector, there was a sheared flow structure with westward flow equatorward of eastward flow, with the equatorward boundary of auroral emission embedded in the westward flow region. Such kind of flow distribution was also observed with other events such as that on January 20, 2016. The observations suggest that the presence of electric field distribution plays some roles in keeping low latitude auroral emission. Detailed discussion of the relationship between the low latitude auroras and the electric field distribution will be presented.

Keywords: SuperDARN Hokkaido Pair of (HOP) radars, low-latitude auroras, mid-latitude / subauroral latitude ionospheric convection

Cluster observations of equatorial magnetosonic waves with small inter-satellite separation

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The Cluster mission conducted the Inner Magnetosphere Campaign to probe the emissions that play key roles in the dynamics of energetic electrons in the outer radiation belt. We present the results of this campaign related to the equatorial magnetosonic waves. The wave and plasma data obtained in the wave generation region enabled the validatation of the model for the wave generation. Simultaneous measurements of these waves by the Cluster 3 and 4 spacecraft have been used to identify, directly from data, their dispersion relation. The equatorial magnetosonic waves possess a discrete spectrum, consisting of emissions at harmonics of proton gyro-frequency. It is shown that the resonance overlap criterion is fulfilled, and therefore the discrete wave spectrum can be approximated by the continuous spectrum within the quasilinear approach. The results of the Cluster Inner Magnetosphere Campaign related to other wave modes are also reviewed

Keywords: equatorial magnetosonic waves, radiation belts, wave-particle interaction

Radiation Belt Electrons Observed by Van Allen Probes and MMS

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The loss and rebuilding of the outer radiation belt is observed storm after storm by the Van Allen Probes, both as a result of CME events and high-speed stream events. The post storm enhancement of the outer belt relativistic electrons requires the presence of source (<75 keV) and seed (few hundred keV) electron populations during the main and early recovery phase along with intense VLF chorus waves. In addition, the Van Allen Probes have described the electron content of the slot region and inner radiation zone, which has been seldom studied because of lack of good access and the serious background conditions there. The backgrounds created by the high-energy protons that exist in the inner radiation zone and extending into the lower parts of the slot region made it difficult to obtain good measurements of the electron fluxes there. Similarly, the backgrounds from penetrating Bremsstrahlung x-rays produced by energetic electrons striking the spacecraft caused difficulty for measurements at outer edge of the slot region and inner edge of the outer zone. These difficulties have been remedied for the Van Allen Probes’ MagEIS data set. Now, with the successful launch of MMS there are additional electron seed population measurements taken over a wide altitude range to complement those from the Van Allen Probes. The Van Allen Probe radiation belt observations and preliminary results from the energetic electron sensors on MMS will be reviewed.

Keywords: Inner Magnetosphere, Radiation Belts, Van Allen Probes, Magnetospheric Multiscale

Two types of global poloidal waves in the inner magnetosphere: Satellite observations and implications on wave-particle interaction

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Poloidal waves in the magnetosphere are a unique type of ultra-low-frequency (ULF) waves that can exchange energy with ring current particles. These waves usually come with large azimuthal wavenumbers (*m*), making them difficult to detect from the ground. Here we summarize the recent satellite observations of two types of global poloidal waves that can potentially modulate energetic particles in the inner magnetosphere. The first type is known as the “global poloidal mode” that has a wave frequency independent of *L*. It has recently been found that, by rapidly sweeping through different longitudinal sectors in the low Earth orbit, the ST-5 satellites frequently observed this type of global poloidal waves as the Doppler-shifted high-*m* waves. Furthermore, it is found that this global poloidal mode can last many hours during geomagnetically quiet times. The second type of global poloidal waves is associated with the storm recovery phase. Evidence is demonstrated by an unprecedented combination of satellite observations, including those by five missions with 15 different probes, during the recovery phase of a major magnetic storm in June 2015. The poloidal waves were found at *L*-values between 5 and 10 as well as at all local times covered by these satellites. Observations of *L*-dependent frequencies support the concept of a discrete number of drift-bounce resonance regions across *L*-shells associated with this type of global poloidal waves. We conclude with possible wave excitation mechanisms for these two types of global poloidal waves, as well as their impact on particle energies in the inner magnetosphere.

Keywords: Poloidal ULF waves, Wave-particle interaction, Inner magnetosphere

Van Allen Probes observations of magnetic field dipolarization and its associated O^+ flux variations in the inner magnetosphere at L<6.6

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We investigate magnetic field dipolarization in the inner magnetosphere and its associated ion flux variations, using the magnetic field and energetic ion flux data acquired by the Van Allen Probes. From a study of 74 events that appeared at L=4.5–6.6 between 1 October 2012 and 31 October 2013, we reveal the following characteristics of the dipolarization in the inner magnetosphere: (1) its timescale is approximately 5 min, (2) it is accompanied by strong magnetic fluctuations that have a dominant frequency close to the O^+ gyrofrequency, (3) ion fluxes at 20–50 keV are simultaneously enhanced with larger magnitudes for O^+ than for H^+, (4) after a few minutes of the dipolarization, the flux enhancement at 0.1–5 keV appears with a clear energy-dispersion signature only for O^+, and (5) the energy-dispersed O^+ flux enhancement appears in directions parallel or anti-parallel to the magnetic field. From these characteristics, we argue possible mechanisms that can provide selective acceleration to O^+ ions at >20 keV. We conclude that O^+ ions at L=5.4–6.6 undergo nonadiabatic local acceleration caused by oscillating electric field associated with the magnetic fluctuations and/or adiabatic convective transport from the plasma sheet to the inner magnetosphere by the impulsive electric field. At L=4.5–5.4, however, only the former acceleration is plausible. We also conclude that the field-aligned energy-dispersed O^+ ions at 0.1–5 keV originate in the ionosphere and are extracted nearly simultaneously to the onset of the dipolarization.

Three-step development of the 17 March 2015 storm: Van Allen Probes/RBSPICE observations

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We investigate enhancements and losses of energetic (~10-~500 keV) protons and oxygen ions during an intense storm with Dst_min of -223 nT on 17 March 2015. We use >10 keV proton and oxygen ion data from the RBSPICE instrument onboard the two Van Allen Probes spacecraft.
During the storm event, Van Allen Probes traveled in the pre-midnight sector on the outbound path and around midnight on the inbound path. The orbits of the two spacecraft were in opposite phase. The Dst index displayed a two-step decrease with the first minimum at 9 UT and the second at 22 UT. Enhancements of ring current ions began at RBSPICE-B at ~7 UT, and RBSPICE-A entered the ring current region at ~8 UT. The RBSPICE data show penetration of the lower part of energetic proton populations (mu = 0.01-0.1 keV/nT, 20-80 keV at L~3.5) down to L~3.5 and the higher part (mu = 0.1-0.4 keV/nT, 80-100 keV at L ~ 4) down to L~4 during the first storm development. The protons penetrated more deeply during the second development, with the lower part to L ~ 2.5 and the higher part to L~3. During the storm maximum, the higher part was more enhanced in energy density without further penetration. Protons with mu up to ~0.8 keV/nT, ~300 keV at L ~ 3.5 made a significant contribution to the total energy density. Flux of energetic oxygen ions (>50 keV) was suddenly enhanced at ~9 UT. The oxygen-to-proton energy density ratio for >50 keV, which was below 0.1 prior to the storm, reached ~1 during the first development. Although the ratio remained high between 0.1 to 1.0 during the second and third development phases, it did not increase over unity.
We conclude that the 17 March 2015 storm developed in three phases: penetration of cold plasma sheet population, further penetration of the population and oxygen energization (acceleration and/or transport), and deep penetration of hot plasma sheet population. We will examine the evolution of ion energy spectra to identify how oxygen ions were energized and to determine source plasma sheet population that can make the most contribution to each phase of the ring current buildup.

Keywords: ring current and magnetic storms, transport and acceleration of energetic oxygen ions, injections in the inner magnetosphere

Acceleration of MeV radiation belt electrons through interaction with whistler-mode chorus emissions

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We perform test particle simulations [1] of energetic electrons interacting with whistler mode chorus emissions. We compute trajectories of a large number of electrons forming a delta function with the same energy and equatorial pitch angle. The electrons are launched at different locations along the magnetic field line and different timings with respect to a pair of chorus emissions generated at the magnetic equator. We follow the evolution of the delta function and obtain a distribution function in energy and equatorial pitch angle, which is a numerical Green's function for one cycle of chorus wave-particle interaction. We obtain the Green's functions for the energy range 10 keV-6 MeV and all pitch angles greater than the loss cone angle. By taking the convolution integral of the Green's functions with the distribution function of the injected electrons repeatedly, we follow a long-time evolution of the distribution function. We find that the energetic electrons are accelerated effectively by relativistic turning acceleration [2] and ultra-relativistic acceleration [3] through nonlinear trapping by chorus emissions. Further, these processes result in the rapid formation of a dumbbell distribution of highly relativistic electrons within a few minutes after the onset of the continuous injection of 10-30 keV electrons. We also compare the efficiency of electron acceleration by the cyclotron resonance and that of Landau resonance in oblique propagation [4]. We also study the effects of sub-packet structures found in chorus elements on electron acceleration.

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Keywords: radiation belts, wave-particle interaction, computer simulations

Nonlinear effect in the pitch angle scattering of energetic electrons by coherent whistler-mode waves

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Coherent whistler-mode waves, such as chorus emissions, are frequently observed by various satellites in the Earth's inner magnetosphere. Coherent whistler-mode waves are generated by energetic electrons in the kinetic energy range from a few to tens of keV through nonlinear wave-particle interactions, and energetic electrons are scattered their pitch angle by the generated whistler-mode waves. The pitch angle scattering is closely related to energetic electron precipitation into the ionosphere, contributing to diffuse and/or pulsating aurora. Hikishima et al. (2009, 2010) showed a nonlinear effect in the pitch angle scattering and reproduced the microburst precipitation using a self-consistent full particle simulation, and Saito et al. (2012) and Miyoshi et al. (2015) reproduced the energy spectrum of energetic electrons simultaneously observed with pulsating aurora by a test particle simulation. These results suggest that the significance of investigating the detailed mechanism of pitch angle scattering. We carry out a spatially one dimensional test particle simulation with a coherent whistler-mode wave propagating along the dipole magnetic field, and reproduce the interaction between electrons and coherent whistler-mode waves in the region close to the magnetic equator. In this study, we assume two cases; the case A is pitch angle scattering of electrons with pitch angle around 80 degrees cased by coherent waves of frequency of 0.5 f_{ce0}, where f_{ce0} is the electron cyclotron frequency at the magnetic equator, and the case B is pitch angle scattering of electrons near the loss cone angle (~ 5 degrees) cased by coherent waves of frequency of 0.3 f_{ce0}. In the simulation result of the case A, we reproduce trajectories of trapped/un-trapped electrons as discussed in previous studies (e.g., Omura et al., 2008, 2009) and pitch angle of un-trapped particles is scattered toward the loss cone. In the case B, results indicate that the pitch angle variation due to the nonlinear effect strongly depends on the wave amplitude and the length of the wave packet. In particular, for the case of the large amplitude wave and relatively long wave packet, most of resonant electrons are trapped by the coherent wave and are efficiently scattered away from the loss cone, resulting in less precipitating electrons. In this presentation, we discuss the parameter dependence of the trapping (or un-trapping) in the Poincare diagram and that nonlinear effect for pitch angle scattering of energetic electrons.

Keywords: pitch angle scattering, nonlinear wave-particle interaction, whistler-mode waves

Simulation of interaction between energetic plasmas and EMIC triggered emissions

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Electromagnetic ion cyclotron (EMIC) rising-tone (triggered) emission is known as a fine structure of EMIC waves. Theoretical studies suggest that EMIC triggered emissions can induce significant loss of the relativistic electrons through the nonlinear trapping. We perform test particle simulations of the electrons interacting with the EMIC triggered emissions reproduced by real scale hybrid simulation. Relativistic electrons with a few MeV kinetic energy are scattered in wide pitch angle range. The lower energetic electrons are also scattered since the frequency of the triggered emissions reaches near the proton cyclotron frequency and the helium band waves are also induced close to the helium gyro frequency. Broadband EMIC rising waves generated in the small ambient magnetic field gradient model cause rapid precipitation of the relativistic electrons. Simultaneous precipitations of the energetic protons and relativistic electrons are also reproduced in the hybrid and test particle simulations, respectively.

Keywords: EMIC waves, nonlinear wave particle interaction, computer simulation

Relativistic electron precipitation induced by large amplitude EMIC rising-tone emissions

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We study dynamics of radiation belt electrons interacting with large amplitude EMIC rising-tone emissions by performing test particle simulations. *Engebretson et al.* [JGR, 2015] reported depletion of radiation belt electrons in the distribution took place when EMIC rising-tone emissions peaking above 11 nT were excited outside the plasmapause. In the work of *Omura and Zhao* [JGR, 2012, 2013] and *Kubota et al.* [JGR, 2015], anomalous cyclotron gyroresonance between relativistic electrons and EMIC rising-tone emissions are only tested with plasmaspheric conditions. Therefore, we study both cases; inside and outside the plasmasphere. We set up the EMIC model waves in a localized region in longitude and distribute test electrons all around the Earth corresponding to the radiation belt at L=5.5. The electrons moving eastward encounter the localized EMIC waves and some of the resonant electrons are precipitated into the atmosphere. The wave potential generated by coherent EMIC emissions traps a fraction of the resonant electrons, resulting in efficient decrease of their pitch angles. After the nonlinear wave trapping, some electrons at low pitch angles, however, cannot enter into the loss cone. Based on theoretical and numerical analyses, we find another phenomenon named SLPA (Scatter at Low Pitch Angle). Some of the electrons at low pitch angles are further transported into the loss cone rapidly through SLPA. We obtain time evolution of the electron distribution as functions of equatorial pitch angle and kinetic energy. For comparison with observations of relativistic electron precipitation, we monitor fluxes of electrons being lost into the atmosphere in a narrow longitudinal range. Inside the plasmapause, electrons with energy 0.1-8 MeV are precipitated efficiently. Outside the plasmapause, on the other hand, only highly relativistic electrons with energy >2 MeV are precipitated. Furthermore, we find echos of electron depletion in the distribution because of eastward drift around the Earth.

Keywords: Radiation belt, EMIC , relativistic electrons

Relativistic electron microbursts and local acceleration of MeV electrons by chorus: SAMPEX and Van Allen Probes observations

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It has been suggested that whistler mode chorus is responsible for both acceleration of MeV electrons and relativistic electron microbursts through resonant wave-particle interactions. Relativistic electron microbursts have been considered as an important loss mechanism of radiation belt electrons. Here we report on the observations of relativistic electron microbursts and flux variations of trapped MeV electrons during the 8-9 October 2012 storm, using the SAMPEX and Van Allen Probes satellites. Observations by the satellites show that relativistic electron microbursts correlate well with the rapid enhancement of trapped MeV electron fluxes by chorus wave-particle interactions, indicating that acceleration by chorus is much more efficient than losses by microbursts during the storm. It is also revealed that the strong chorus wave activity without relativistic electron microbursts does not lead to significant flux variations of relativistic electrons. We also find that the microburst occurrence rate during the acceleration event has a peak around which the phase space density peak is identified by the Van Allen Probes satellites. We conclude that effective acceleration of relativistic electrons is caused by chorus that can cause relativistic electron microbursts, and that microbursts can be a proxy of internal acceleration of MeV electrons by whistler-mode chorus.

Keywords: radiation belts, chorus waves

Limitation of energetic ring current ion spectra

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We address the problem of determining the limiting energetic ring current ion spectrum resulting from electromagnetic ion cyclotron (EMIC)-wave-ion-interactions. We solve the problem in a relativistic regime, incorporating a cold background multi-ion plasma component and without assuming a predetermined form for the energy distribution. The limiting spectrum is determined by the condition that the EMIC waves acquire a specified gain over a given convective length scale for all frequencies over which wave growth occurs. We find that the limiting ion spectrum satisfies an integral equation that must be solved numerically. However,at large particle energy E, the limiting spectrum takes the simple form J ~ 1/E . Moreover,this 1/E spectral shape does not depend on the energetic ion in question nor on the background multi-ion plasma composition. We provide numerical solutions for the limiting spectra for Earth-like parameters. In addition, at Earth and four other planets we compare measured ion spectra with corresponding numerical limiting spectra.

Keywords: ring current ion spectra, EMIC waves, limiting ion spectrum

