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Investigation of wave particle interaction in the Earth's magnetosphere using conjugated observations

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14. ABSTRACT
The main goal of the project is to investigate the fundamental physical process that connect wave in the magnetosphere and precipitating ion/electrons in the low altitude ionosphere region, and to develop a physics-based precipitation model along a field line. During the entire project period 2016/9/1-2020/8/31, we have published 24 papers (listed in Publications section at the end of this report) in major scientific journals relevant to this project. Among these, 9 publications were made in Journal of Geophysical Research, 12 in Geophysical Research Letters, 1 as Book Chapter, and 2 in Physics of Plasmas. During the final-year period (2019/9/1-2020/8/31), 5 publications were made. The most significant accomplishments from this grant are summarized below.
Short-lived but intense electron precipitation, known as "microbursts," may contribute significantly to electron losses in the outer radiation belt. Their origin has been suggested to correlate with resonant scattering by whistler-mode chorus waves, but existing models cannot fully explain the properties of microbursts, in particular, the bouncing electron packets in the form of a microburst that have been recently observed. A numerical model is presented that reproduces a series of electron bounce packets in response to individual chorus elements. Results indicate that the actual precipitation only occurs in the leading electron packet whereas subsequent packets form because of the following bounce motions of remaining fluxes. An analysis based on wave propagation and resonance condition yields an approximate time-energy regime of electron microbursts. Such a model is valuable for interpreting and modeling low Earth-orbiting satellite observations of electron flux variation in response to the interaction with magnetospheric chorus waves. The model developed in this study fulfills the main goal of the project to develop the physics-based precipitation model along a field line. The results have been published

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The main goal of the project is to investigate the fundamental physical process that connect wave in the magnetosphere and precipitating ion/electrons in the low altitude ionosphere region, and to develop a physics-based precipitation model along a field line. During the entire project period 2016/9/1-2020/8/31, we have published 24 papers (listed in **Publications section** at the end of this report) in major scientific journals relevant to this project. Among these, 9 publications were made in *Journal of Geophysical Research*, 12 in *Geophysical Research Letters*, 1 as *Book Chapter*, and 2 in *Physics of Plasmas*. During the final-year period (2019/9/1-2020/8/31), 5 publications were made. The most significant accomplishments from this grant are summarized below.

Short-lived but intense electron precipitation, known as “microbursts,” may contribute significantly to electron losses in the outer radiation belt. Their origin has been suggested to correlate with resonant scattering by whistler-mode chorus waves, but existing models cannot fully explain the properties of microbursts, in particular, the bouncing electron packets in the form of a microburst that have been recently observed. A numerical model is presented that reproduces a series of electron bounce packets in response to individual chorus elements. Results indicate that the actual precipitation only occurs in the leading electron packet whereas subsequent packets form because of the following bounce motions of remaining fluxes. An analysis based on wave propagation and resonance condition yields an approximate time-energy regime of electron microbursts. Such a model is valuable for interpreting and modeling low Earth-orbiting satellite observations of electron flux variation in response to the interaction with magnetospheric chorus waves. The model developed in this study fulfills the main goal of the project to develop the physics-based precipitation model along a field line. The results have been published in **Ref #20**: Chen, L., Breneman, A. W., Xia, Z., & Zhang, X.-J. (2020). Modeling of bouncing electron microbursts induced by ducted chorus waves. *Geophysical Research Letters*, 47, e2020GL089400.

Observations of THEMIS and Van Allen Probes were used to statistically study the modulations of chorus emissions by variations of background magnetic field and plasma density in the ultra-low frequency range. The modulation events are identified automatically and divided into three types according to whether the chorus intensity correlates to the variations of the magnetic field only (Type B), plasma density only (Type N), or both (Type NB). For the THEMIS observations, the occurrences of the Types B and N are larger than Type NB, while for the Van Allen Probes observations, most events are of Type N. The chorus intensity is mostly correlated to the magnetic field strength negatively and plasma density positively. The chorus intensity tends to increase when the magnitude of the magnetic field perturbation increases, but little dependence on plasma density perturbation amplitude is found. The results have a great impact on understanding the effect of density and magnetic field perturbations on the interaction between chorus waves and energetic electrons in that those perturbations significantly affect the intensity of chorus waves and thus resultant electron precipitation. The results have been published as **Ref #21**: Xia, Z., Chen, L., & Li, W. (2020). Statistical study of

chorus modulations by background magnetic field and plasma density. *Geophysical Research Letters*, 47, e2020GL089344.

The propagation of whistler mode waves near the local lower hybrid resonance (LHR) frequency in a dipole field was investigated with a two-dimensional full-wave model. Our full-wave model shows that (1) a quasi-electrostatic whistler reflects where the wave frequency is below the local LHR frequency and propagates to a larger L-shell and lower latitude, (2) a strong standing-wave pattern is formed in the LHR reflection region, and (3) the whistler emission turns from right-hand circularly polarized to linearly polarized near the reflection region. Simulation with the presence of a small-scale density irregularity shows that a small portion of quasi-electrostatic whistler energy can be coupled to a parallel whistler, which can propagate to a much lower altitude while most of the wave energy experiences LHR reflection. Moreover, the mode coupling depends on the transverse and longitudinal sizes of the density irregularity. This makes a possible explanation of ground observations of nonducted whistler-mode emission, which could have been reflected in the high-latitude ionosphere and magnetosphere. The presence of parallel-propagating whistler waves at the high latitude will account for the scattering of relativistic electron precipitation, as resonance energy increases with latitudes. The results have been published as **Ref #22**: Xu, X., Chen, L., Zhou, C., Liu, X., Xia, Z., Simpson, J. J., & Zhang, Y. (2020). Two-dimensional full-wave simulation of whistler mode wave propagation near the local lower hybrid resonance frequency in a dipole field. *Journal of Geophysical Research: Space Physics*, 125, e2019JA027750.

Propagation characteristics of low-altitude hiss in the ionosphere was investigated by numerical simulation with a two-dimensional full-wave model. The simulation results demonstrate that linear mode conversion from whistler to H⁺ band electromagnetic ion cyclotron wave and polarization reversal occur simultaneously where wave frequency matches the H⁺-He⁺ crossover frequency. This mode conversion efficiency shows sensitive dependence on wave normal angle and plays a significant role in the propagation of whistler emission near the local proton gyro-frequency in the ionosphere by redistributing the wave energy below and above the H⁺-He⁺ cutoff frequency, which can explain the low-altitude observation of hiss emissions by the Freja and Detection of Electromagnetic Emissions Transmitted from Earthquake Regions satellites, respectively. The energy of whistler-mode low-altitude hiss emission can be transferred to reflected left-hand polarized electromagnetic ion cyclotron through mode conversion and the efficiency reaches a maximum for intermediate incident wave normal angle (of 45°). Our results establish the connection of whistler-mode waves in the magnetosphere and low-altitude hiss waves, and therefore present a potential for remotely sensing the magnetospheric whistler mode emission using the low-earth-orbiting wave measurement. The results have been published as **Ref #23**: Xu, X., Zhou, C., Chen, L., Xia, Z., Liu, X., Simpson, J. J., & Zhang, Y. (2020). Two dimensional full-wave modeling of propagation of low-altitude hiss in the ionosphere. *Geophysical Research Letters*, 47, e2019GL086601.

Observations of Detection of Electromagnetic Emissions Transmitted from Earthquake Regions (DEMETER) satellite are used to study the spectral broadening of NWC ground

transmitter signals and examine key parameters that control the width and intensity of the broadening power. Individual event analysis and statistics analysis show that the width and intensity of broadening power are positively proportional to the NWC wave amplitude. The statistical analysis also indicates a significantly negative correlation of broadening spectral intensity and width with the background plasma density. The observations are consistent with existing theories predicting that lower plasma density drives a lower threshold for spectral broadening. Since this spectral broadening process in the ionosphere takes energy away from NWC signals, it serves as attenuation mechanism for the NWC transmitter signals and thus would reduce the capability of the transmitter signals in the magnetosphere on the electron precipitation. The results have been published as **Ref #24**: Xia, Z., Chen, L., Zhima, Z., & Parrot, M. (2020). Spectral broadening of NWC transmitter signals in the ionosphere. *Geophysical Research Letters*, 47, e2020GL088103. <https://doi.org/10.1029/2020GL088103>.

In addition to these final-year accomplishments, the accomplishments in the reports of previous years (2016-2019) are listed below in connection to understanding fundamental wave-particle interaction processes and leading to the development of the particle precipitation model.

Ref #1. Using Van Allen Probe observations, we develop two empirical models to describe the hiss wave normal angle (WNA) and amplitude variations in the Earth's plasmasphere for different substorm activities. We find that the plasmaspheric hiss amplitudes on the dayside increase when substorm activity is enhanced (AE index increases), and the dayside hiss amplitudes are greater than the nightside. We also find that the propagation angles (WNAs) of hiss waves in most regions do not show strong dependence on substorm activity, except for the nightside low L-region. The propagation angles of plasmaspheric hiss increase with increasing magnetic latitude or decreasing radial distance (L-value). Such global characteristics of hiss WNAs and amplitudes can be well reproduced by our ray tracing models. Understanding the propagation characteristics of plasmaspheric hiss leads to a better quantification of electron scattering due to these waves.

Ref #2. We analyzed a dayside event from Van Allen Probes of modulated relativistic electron's butterfly pitch angle distributions (PADs). We find that those butterfly distributions were associated with localized magnetic dip driven by hot ring current ion (60–100 keV proton and 60–200 keV helium and oxygen) injections. We use test particle simulation and reproduce the electron's butterfly PADs at satellite's location. Our simulation results illustrate that a negative radial flux gradient contributes primarily to the formation of the modulated electron's butterfly PADs through inward transport due to the inductive electric field, while deceleration due to the inductive electric field and pitch angle change also makes in part contribution. The localized magnetic field perturbation, which is a frequent phenomenon in the magnetosphere during magnetic disturbances, should be of great importance for creating electron's butterfly PADs in the Earth's radiation belts.

Ref #3. Propagation properties of low-altitude hiss emission in the ionosphere observed

by DEMETER were analyzed. We find that there exist two types of low-altitude hiss: type I emission at high latitude is characterized by vertically downward propagation and broadband spectra, while type II emission at low latitude is featured with equatorward propagation and a narrower frequency band above the proton gyrofrequency. Ray tracing simulation demonstrates that both types of the low-altitude hiss at different latitude are connected and they originate from plasmaspheric hiss and in part chorus emission. Type I emission represents magnetospheric whistler emission that accesses the ionosphere. Equatorward propagation associated with type II emission is a consequence of wave trapping mechanisms in the ionosphere. Two different wave trapping mechanisms are identified to explain the equatorial propagation of Type II emission; one is associated with the proximity of wave frequency and local proton cyclotron frequency, while the other occurs near the ionospheric density peak. Revealing the mechanism of low-altitude hiss waves makes it possible to link them to magnetospheric whistler mode waves.

Ref #4. We simulate a self-consistent magnetic field that satisfies force balance with a model ring current that is radially localized, axisymmetric and has anisotropic plasma pressure. We use this model to identify the criteria of magnetic dip formation in the magnetosphere, which favors larger plasma beta and lower anisotropy. We also perform linear analysis on these self-consistent equilibria for second harmonic compressional poloidal modes of sufficiently high azimuthal wave number. We find that the compressional magnetic field component occurs primarily within 10 degrees of the equator on both inner and outer edge, with stronger compressional magnetic field component on the outer edge. We also identify the critical condition on plasma beta and pressure anisotropy of an Alfvén ballooning-instability.

Ref #5. The effect of the plasmapause on equatorially radially propagating fast magnetosonic (MS) waves in the Earth's dipole magnetic field is studied by using finite difference time domain method. We find that (1) without plasmapause the radially inward propagating MS wave can reach ionosphere and continuously propagate to lower altitude. (2) For simulation with a plasmapause with a scale length comparable to its wavelength, only a small fraction of the MS wave power is reflected by the plasmapause. (3) The multiple fine-scale density irregularities near the outer edge of plasmapause can effectively block the MS wave propagation, resulting in a terminating boundary for MS waves near the plasmapause.

Ref #6. Magnetosonic waves have been demonstrated as effective for bounce resonant scattering. Electron scattering rates due to bounce resonance interaction with magnetosonic waves are derived in a general form, where the effects of the finite Larmor radius, of violation in the first adiabatic invariant, and of latitudinal wave power distribution are considered. Such bounce resonance diffusion coefficients are important, but missing, from radiation belt modeling. Additionally, a parametric study was done to identify the factors that determine effective bounce resonant scattering. The derived diffusion coefficients can be used in larger-scale models to better predict the dynamics of the magnetosphere as a tool to help plan future space missions.

Ref #7. Electron cyclotron harmonic (ECH) waves play a dominant role in pulsating aurora formation and diffuse aurora formation in the outer magnetosphere at the nightside. We propose a new method to construct a controllable and quantifiable loss cone distribution and derive a linear growth rate formula of the electrostatic mode for a realistic and arbitrary distribution function. We find that the peak linear growth rate and the corresponding wave frequency increase with the loss cone size. The wave frequency of peak growth rate is about 1.5 and 2.5 times electron cyclotron frequency when loss cone is about 4–6 degrees wide. The wave normal angle corresponding to the growth rate peak decreases with the loss cone size. A parametric study is also done to identify the conditions favoring the ECH excitation. Our work greatly advances the understanding of ECH wave generation and their effects on electron precipitation.

Ref #8. Wave number vectors and minimum cyclotron resonant electron energies of electromagnetic ion cyclotron (EMIC) waves are analyzed via the phase differencing technique by using Magnetospheric Multiscale Mission data. We perform an event study and find that obtained wave vectors, roughly agreeing with the validity of cold plasma theory, might significantly vary from wave packet to wave packet. Numerical calculations indicate that E_{min} can range from 0.5 to tens of MeV, suggesting that EMIC waves can effectively interact with those relativistic electrons. This study enriches our understanding of the applicability of phase differencing. It further supports that EMIC waves can be responsible for the loss of electrons with an extremely broad energy range in the magnetosphere.

Ref #9. Signals of powerful ground transmitters at various places have been detected by satellites in near-Earth space. The study on propagation mode, ducted or nonducted, has attracted much attentions for several decades. Based on the statistical results from Van Allen Probes and low-earth-orbiting DEMETER satellite we present the ground transmitter signals distributed clearly in ionosphere and magnetosphere. The observed propagation route in the meridian plane in the magnetosphere for each of various transmitters from the combination of DEMETER and Van Allen Probes data in nighttime is revealed for the first time. By comparison with ray tracing, we demonstrate that the observed propagation route, with partial deviation from the field lines corresponding to ground stations, provides direct and clear statistical evidence that the nonducted propagation mode plays a main role, although with partial contribution from ducted propagation. The propagation characteristics of VLF transmitter signals in the magnetosphere are critical for quantitatively assessing their contribution to energetic electron loss in radiation belts.

Ref #10. A chapter was written to deal with recent advances in the understanding of bounce resonance between extremely low frequency waves and electrons in the Earth's radiation belts. This is a supplement to the well-documented reviews pertaining to resonances between very low frequency waves and gyration motion and between ultralow frequency waves and drift motions. The interaction between a monochromatic magnetosonic wave and electron bounce motion is illustrated and compared against Landau resonance and nonresonant interaction. Finally, quasi-linear theory describing bounce resonant interactions with broadband magnetosonic waves is reviewed.

Ref #11. Electromagnetic ion cyclotron (EMIC) waves in duskside plasmasphere and plasmaspheric plume scatter megaelectron volt electrons into the loss cone and are considered a major loss mechanism for the outer radiation belt. Wave-particle interaction between energetic electrons and EMIC waves has been studied extensively by the quasi-linear diffusion theory. However, EMIC waves are typically strong enough to trigger nonlinear wave-particle interaction effects and transport electrons in very different ways from quasi-linear diffusion. New mathematical method is therefore in demand to study the evolution of energetic electron distribution in response to nonlinear wave-particle interaction. In this work, we present a Markov chain description of the wave-particle interaction process, in which the electron distribution is represented by a state vector and is evolved by the Markov matrix. The Markov matrix is a matrix form of the electron response Green's function and could be determined from test particle simulations. Our modeling results suggest that electron loss rate is not significantly affected by phase bunching and phase trapping, but for strong EMIC waves, electron distribution is more saturated near loss cone than quasi-linear theory prediction, and negative electron phase space density slope develops inside loss cone.

Ref #12. Using the Van Allen Probes data, the variability of the total outer radiation belt electron energy content (TRBEEC) for energetic electrons (>300 keV) is investigated during 51 isolated storms spanning from October 2012 to May 2017. The statistical results show that the TRBEEC exhibits no change in 20% of the storms and gets enhanced during 80% of them. The subrelativistic electrons (300–500 keV) and relativistic electrons (0.5–2.0 MeV) equally contribute to the TRBEEC during the main phases, while in the recovery phases, the relativistic electrons contribute up to 80% of the TRBEEC. The results of the superposed epoch analysis of the solar wind parameters and geomagnetic indices indicate that the TRBEEC enhancement events preferably occur during the prolonged southward interplanetary magnetic field period when the solar wind-magnetosphere coupling is more efficient. Meanwhile, the high AE index with intense injections of several hundreds of kiloelectron volt seed electrons also favors the increase of the TRBEEC. Case study suggests that the enhancement of the TRBEEC is the consequence of the chorus acceleration. Understanding the energy budget of the outer zone electrons can provide more insight into the energy transfer from plasma waves to the energetic electron population, especially for revealing the underlying physics of the energization of outer radiation belt electrons via chorus wave acceleration.

Ref #13. The generation of unusually high-frequency plasmaspheric hiss (from 2 to 10 kHz) waves observed by Van Allen Probes was studied. The correlated observations of waves and particles indicate that the hiss is associated with the enhancement of electron flux during the substorm. Calculations of the wave linear growth rate show that the electron distribution after the substorm onset is efficient for the hiss generation. The energy of the contributing electrons is about 1–2 keV, which is consistent with the observation. These results support that the observed high-frequency plasmaspheric hiss is likely to be generated locally inside the plasmasphere due to the instability of injected kiloelectron volt electrons. Our results advance the understanding of plasmaspheric hiss and their roles in radiation belt dynamics.

Ref #14. Using Van Allen Probe wave observations, we investigated the statistical properties of exohiss waves, which are structureless whistler mode waves observed outside the plasmapause. The statistical analysis on exohiss wave properties shows that exohiss waves prefer to occur over $3 < L < 6$ from dawnside to noon and duskside during geomagnetic quiet times, and their wave power is larger at smaller values of L shell. Furthermore, the equatorward Poynting flux is comparable to the poleward Poynting flux at the equator and it becomes dominant at higher magnetic latitude $|\mathcal{A}| \sim 20^\circ$. Our observation results reveal the statistical features of exohiss waves for the first time and support the exohiss formation mechanism that exohiss originates from plasmaspheric hiss leakage. The results demonstrate exohiss as an important energy dissipation route for plasmaspheric hiss and significantly improve the understanding of plasmaspheric hiss evolution in the radiation belt region.

Ref #15. We developed a general relativistic linear growth rate formula of electromagnetic waves for any wave normal angle and a general distribution function in a uniform magnetized plasma with a dominant cold plasma component and a tenuous hot plasma component. Such a general linear growth rate formula can be applied to different plasma environments, such as the Jovian Magnetosphere and laboratory plasma. The relativistic resonant condition for different wave modes is discussed and summarized. Then, the formula is applied to a parametric study for local instability of Earth's plasmaspheric hiss.

Ref #16. We present a Magnetospheric Multiscale mission observation of quasiperiodic electromagnetic ion cyclotron (EMIC) variations corresponding to magnetic field depressions as well as proton pitch angle anisotropy enhancements. Numerical calculations demonstrate that the EMIC modulation period is comparable with the magnetic field line resonance period, suggesting that quasiperiodic solar wind enhancement compressing the magnetosphere and propagating as the fast mode can lead to the magnetic field line oscillation and hence the presence of quasiperiodic magnetic compressions and discrete proton anisotropy elements, which provides optimal conditions for modulating the EMIC instability. Current results provide a complete chain of self-consistent observational evidence to illustrate the process connecting solar wind variations to EMIC wave amplitude modulation in the magnetosphere.

Ref #17. We report on evidence for the generation of an ultra-low frequency plasma wave by the drift-mirror plasma instability in the dynamic plasma environment of Earth's inner magnetosphere. The plasma measurements are obtained from the Radiation Belt Storm Probes Ion Composition Experiment onboard NASA's Van Allen Probes Satellites. We show that the measured wave-particle interactions are driven by the drift-mirror instability. Theoretical analysis of the data demonstrates that the drift-mirror mode plasma instability condition is well satisfied. We also demonstrate, for the first time, that the measured wave growth rate agrees well with the predicted linear theory growth rate. Hence, the in-situ space plasma observations and theoretical analysis demonstrate that local generation of ultra-low frequency and high amplitude plasma waves can occur in the high beta plasma conditions of Earth's inner magnetosphere.

Ref #18. The primary power gap of chorus waves is statistically investigated using waveform data from THEMIS probes for the first time. Overall, $\sim 2/3$ of chorus events have a power gap between the lower and upper bands. Both the gap frequency and the frequency bandwidth of the gap have a broad distribution, which peaks at frequencies of $\sim 0.49f_{ce}$ and $\sim 0.07f_{ce}$, respectively. The gap frequency tends to increase with increasing $|\text{MLAT}|$ (magnetic latitude), while the frequency width gradually increases with L-shell. In most of banded events, the peak frequency of upper band is roughly twice that of lower band. Our study provides detailed observational constraints on potential mechanisms of the power gap formation and thus advances our understanding of chorus wave emission in the magnetosphere.

Ref #19. The observations of electromagnetic waves by low-earth-orbiting DEMETER satellite to investigate propagation characteristics of low-altitude ionospheric hiss. Our statistics results demonstrate that the ionospheric hiss power is stronger on the dayside than nightside, under higher geomagnetic activity conditions, in local summer than local winter. The wave power is confined near the region where the local proton gyrofrequency is equal to the wave frequency. A ray tracing simulation is performed to account for the dependence of wave power on frequency and latitude. The propagation characteristics of ionospheric hiss waves supports their origin being magnetospheric whistler emissions and lays foundation for the potential of using former emissions to monitor the latter emissions.

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