Statistical Study of Strong Diffusion of Low-Energy Electrons by Chorus and ECH Waves Based on In Situ Observations

Mizuki Fukizawa[1], Takeshi Sakanoi[1], Yoshizumi Miyoshi[2], Yoichi Kazama[3], Yuto Katoh[1], Yoshiya Kasahara[4], Shoya Matsuda[4], Atsushi Kumamoto[1], Fuminori Tsuchiya[1], Ayako Matsuoka[5], Satoshi Kurita[5], Satoko Nakamura[2], Masafumi Shoji[6], Mariko Teramoto[7], Shun Imajo[5], Iku Shinohara[8], Shiang-Yu Wang[3], Sunny W. Y. Tam[9], Tzu-Fang Chang[2], Bo-Jhou Wang[3], and Chae-Woo Jun[2]

[1]Tohoku University
[2]Institute for Space-Earth Environmental Research, Nagoya University
[3]Academia Sinica Institute of Astronomy and Astrophysics
[4]Kanazawa University
[5]Kyoto University
[6]Nagoya University
[7]Kyushu Institute of Technology
[8]Japan Aerospace Exploration Agency
[9]National Cheng Kung University

November 23, 2022

Abstract

Inner magnetospheric electrons are precipitated into the ionosphere via pitch-angle (PA) scattering by lower band chorus (LBC), upper band chorus (UBC), and electrostatic electron cyclotron harmonic (ECH) waves at different magnetic latitudes. The PA scattering efficiency of low-energy electrons (0.1–10 keV) is yet to be investigated via *in situ* observations because of difficulties in flux measurements inside loss cones at the magnetosphere. In this study, we demonstrate that LBC, UBC, and ECH waves contribute to PA scattering of electrons at different energies using the Arase (ERG) satellite observation data and successively detected the loss cone filling, i.e., strong diffusion. For LBC waves, strong diffusion occurred at energies above ~1 keV, whereas it occurred below ~1 keV for UBC and ECH waves. The occurrence rate of the strong diffusion by high-amplitude LBC (>50 pT), UBC (>20 pT), and ECH (>10 mV/m) waves, respectively, reached ~70%, 20%, and 40% higher than that without simultaneous wave activity. The energy range where the occurrence rate was high agreed with the range where the PA diffusion rate of each wave exceeded the strong diffusion level based on the quasilinear theory.

Hosted file

`fukizawa_si_v2.docx` available at https://authorea.com/users/524142/articles/600913-statistical-study-of-strong-diffusion-of-low-energy-electrons-by-chorus-and-ech-waves-based-on-in-situ-observations

Hosted file

`essoar.10510087.1.docx` available at https://authorea.com/users/524142/articles/600913-statistical-study-of-strong-diffusion-of-low-energy-electrons-by-chorus-and-ech-waves-based-on-in-situ-observations

M. Fukizawa[1*], T. Sakanoi[1], Y. Miyoshi[2], Y. Kazama[3], Y. Katoh[1], Y. Kasahara[4], S. Matsuda[4], A. Kumamoto[1], F. Tsuchiya[1], A. Matsuoka[6], S. Kurita[7], S. Nakamura[2], M. Shoji[2], M. Teramoto[8], S. Imajo[6], I. Shinohara[5], S-Y. Wang[3], S. W-Y. Tam[9], T.-F. Chang[9], B.-J. Wang[3], C.-W. Jun[2]

[1] Graduate School of Science, Tohoku University, Sendai, Japan

[2] Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan

[3] Academia Sinica, Institute of Astronomy and Astrophysics, Taipei, Taiwan

[4] Graduate School of Natural Science and Technology, Kanazawa University, Kanazawa, Japan

[5] Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Japan

[6] Graduate School of Science, Kyoto University, Kyoto, Japan

[7] Research Institute for Sustainable Humanosphere, Kyoto University, Uji, Japan

[8] Department of Space Systems Engineering, Faculty of Engineering, Kyushu Institute of Technology, Kitakyushu, Japan

[9] Institute of Space and Plasma Sciences, National Cheng Kung University, Tainan, Taiwan

Corresponding author: Mizuki Fukizawa (`fukizawa.m@pparc.gp.tohoku.ac.jp`)

Key Points:

- The pitch-angle scattering efficiencies of low-energy electrons by chorus and electrostatic electron cyclotron harmonic (ECH) waves are statistically investigated via *in situ* observations.
- Lower band chorus waves scatter electrons into a loss cone at energies above ~1 keV.
- Upper band chorus and ECH waves scatter electrons into a loss cone at energies below ~1 keV.

Abstract

Inner-magnetospheric electrons are precipitated into the ionosphere via pitch-angle (PA) scattering by lower band chorus (LBC), upper band chorus (UBC), and electrostatic electron cyclotron harmonic (ECH) waves at different magnetic latitudes. The PA scattering efficiency of low-energy electrons (0.1–10 keV) is yet to be investigated via *in situ* observations because of difficulties in flux measurements inside loss cones at the magnetosphere. In this study, we demonstrate that LBC, UBC, and ECH waves contribute to PA scattering of electrons at different energies using the Arase (ERG) satellite observation data and successively detected the loss cone filling, i.e., strong diffusion. For LBC waves, strong diffusion occurred at energies above ~1 keV, whereas it occurred below ~1 keV for UBC and ECH waves. The occurrence rate of the strong diffusion by high-amplitude LBC (>50 pT), UBC (>20 pT), and ECH (>10 mV/m) waves, respectively, reached ~70%, 20%, and 40% higher than that without simultaneous wave activity. The energy range where the occurrence rate was high agreed with the range where the PA diffusion rate of each wave exceeded the strong diffusion level based on the quasilinear theory.

1 Introduction

In Earth's magnetospheric equatorial region, various plasma waves are excited through wave–particle interactions. Whistler-mode chorus waves and electrostatic electron cyclotron harmonic (ECH) waves precipitate magnetospheric electrons into the ionosphere using cyclotron resonance. Lower band chorus (LBC) waves can resonate with electrons of energy ranging from a few keV to a few MeV and contribute to cause diffuse and pulsating auroras (e.g., S. Kasahara, Miyoshi, et al., 2018; Kazama et al., 2018; Miyoshi et al., 2010, 2020; Miyoshi, Oyama, et al., 2015; Miyoshi, Saito, et al., 2015; Nishimura et al., 2010). It was suggested that relativistic electron precipitation by LBC waves could yield significant production of odd hydrogen and nitrogen, followed by catalytic reactions that destroy ozone (Miyoshi et al., 2021; Tesema et al., 2020; Turunen et al., 2016). Moreover, upper band chorus (UBC) and ECH waves can resonate with electrons of energy ranging from a few hundred eV to a few keV and contribute to cause diffuse and pulsating auroras and electron density enhancements in the ionospheric lower *F* region (Fukizawa et al., 2018, 2020, 2021; Horne et al., 2003; Liang et al., 2010; Miyoshi, Saito, et al., 2015). It was also theoretically suggested that ECH waves could fill a loss cone, called strong diffusion (e.g., Lyons, 1974), in the energy range of a few hundred eV (Horne et al., 2003; Horne & Thorne, 2000; Lyons, 1974; Tripathi et al., 2011) and contribute to ~10%–20% of the total electron energy precipitation flux due to ECH, LBC, and UBC waves (Khazanov et al., 2015; Tao et al., 2011; Thorne et al., 2010; Tripathi et al., 2013). However, the pitch-angle (PA) scattering efficiencies of low-energy electrons (0.1–10 keV) by each wave have not been investigated via *in situ* observations due to the measurement difficulty of electron fluxes inside loss cones at the magnetosphere.

Although a loss cone is usually too small to be resolved in conventional electron measurements in the magnetosphere, the advent of the Arase (ERG) satellite (Miyoshi, Shinohara, Takashima, et al., 2018) has enabled direct evaluation of loss cone electron fluxes, with an advantage of the relatively high angular resolution of low-energy and energetic electron instruments. S. Kasahara et al. (2019) reported that the strong diffusion of high-energy electrons (10–100 keV) by LBC waves commonly occurs using *in situ* observation data obtained using medium-energy particle experiments-electron analyzer (S. Kasahara, Yokota, et al., 2018) onboard the Arase satellite. In this study, we demonstrate that the strong diffusion of low-energy electrons associated with LBC, UBC, and ECH waves is commonly observed in the magnetospheric equatorial region using electron data obtained from low-energy particle experiments-electron analyzer (LEPe) (Kazama et al., 2017), wave data obtained from the plasma wave experiment (PWE)/onboard frequency analyzer (OFA) instrument (Kasaba et al., 2017; Y. Kasahara, Kasaba, et al., 2018; Matsuda et al., 2018; Ozaki et al., 2018), electron density data from PWE/high-frequency analyzer (HFA) (Kumamoto et al., 2018), and magnetic field data from magnetic field experiments (MGF) onboard the Arase satellite (Matsuoka, Teramoto, Nomura, et al., 2018).

2 Observations and Analyses

2.1 A Case Study

Figure 1 depicts a typical example of wave and electron observation data obtained with the Arase satellite. The Roederer's L-parameter L^*, magnetic local time (MLT), and magnetic latitude (MLAT) of the Arase satellite are shown as labels in Figure 1. The value of L^* was derived for a 90° PA using the TS04 model (Tsyganenko & Sitnov, 2005). The Arase satellite crossed the magnetic equator from the southern hemisphere to the northern hemisphere at 23:43 UT for this event. During this event, the *Kp* index was 6+, 4, and 5+ for 18:00–21:00 UT on March 27, 2017, 21:00–24:00 UT on March 27, 2017, and 0:00–3:00 UT on March 28, 2017, respectively. The *Dst* index indicated that this event occurred during the recovery phase of storm (not shown).

Figures 1a and 1b show the power spectral density of wave electric and magnetic fields, respectively. To identify LBC, UBC, and ECH waves, black lines indicate $0.1f_{\mathrm{ce}}$, $0.5f_{\mathrm{ce}}$, and an integer multiple of f_{ce} from bottom to top in panels, where f_{ce} is the electron cyclotron frequency at the magnetic equator. f_{ce} was calculated from the equatorial magnetic field intensity traced by the TS04 model. When the traced magnetic field was larger than the local magnetic field observed by MGF at the magnetic equator, the local one was used to calculate f_{ce}. Figures 1c, 1d, and 1e depict the amplitudes of the ECH, UBC, and LBC waves in the frequency bands of 1.00–2.00f_{ce}, 0.50–0.90f_{ce}, and 0.10–0.45f_{ce}, respectively. During this event, ECH and UBC waves were observed near the magnetic equator (MLAT from −1° to 3° and MLAT from −3° to 8°). Moreover, LBC waves were observed from the magnetic equator to the off-equator (MLAT from −20° to 15°). The LBC wave amplitude was larger at the off-equator than near the magnetic equator, whereas the ECH and UBC wave amplitudes were larger near the magnetic equator.

Figures 1f and 1g depict differential fluxes inside the loss cone (PA ranges of 0°–5° and 175°–180°) electrons, whereas Figures 1h and 1i show differential fluxes averaged in PA of 5°–90° and 90°–175°. Figures 1j and 1k show the loss cone filling ratios for parallel and antiparallel electrons, defined as $j(0°–5°)\ /\ \langle j(5°–90°)\rangle$ and $j(175°–180°)\ /\ \langle j(90°–175°)\rangle$, respectively, where j is the energy flux of electrons. The cyclotron resonance energies of chorus waves (Kennel & Petschek, 1966) with frequencies of $0.3f_{\mathrm{ce}}$, $0.5f_{\mathrm{ce}}$, and 0.7 f_{ce} are shown by the black solid lines from top to bottom in Figures 1f–1k. The cyclotron resonance energies of ECH waves with frequencies of $1.2f_{\mathrm{ce}}$ and $1.8f_{\mathrm{ce}}$ are shown by the black dashed lines from bottom to top in Figures 1f–1k. The cyclotron resonance velocities of ECH waves were derived using wave frequency and wavenumber estimated from the dispersion relation. The dispersion relation was solved with Kyoto University Plasma Dispersion Analysis Package (KUPDAP; Sugiyama et al., 2015). It was assumed that electrons comprised cold and hot components (1 eV and 1 keV, respectively). The cold and hot components were, respectively, Maxwellian and subtracted Maxwellian distributions (e.g., Ashour-Abdalla & Kennel, 1978; Horne, 1989) with loss cone depth and width of $\Delta = 5$ and $\beta = 0.02$ and 89.5° wave normal angle (Horne & Thorne, 2000). We calculated the cyclotron resonance energies of ECH waves for five typical electron densities (1, 5, 10, 50, and 100 cm^{-3}); one of them, which was the nearest to the electron density derived from the upper hybrid resonance frequency observed by HFA (not shown), is shown in Figures 1f–1k. It was assumed that the cold electron density was two orders of amplitude larger than the hot electron density (cf., Kazama et al., 2018) and that the background magnetic field was 100 nT. The loss cone filling ratio enhancement at energies from the cyclotron resonance energies of $0.3f_{\mathrm{ce}}$, $0.5f_{\mathrm{ce}}$, and $1.2f_{\mathrm{ce}}$ to those of $0.5f_{\mathrm{ce}}$, $0.7f_{\mathrm{ce}}$, and $1.8f_{\mathrm{ce}}$, respectively, are correspondingly attributable to LBC, UBC, and ECH waves.

Both parallel and antiparallel loss cone fluxes (Figures 1f and 1g) and filling ratios (Figures 1j and 1k) in the cyclotron resonance energies of UBC and ECH waves were enhanced with high-amplitude ECH and UBC waves near the magnetic equator (MLAT from −4° to 2°) from 23:10 to 00:00 UT. In addition, those in the cyclotron resonance energies of LBC waves are enhanced with high-amplitude LBC waves from the magnetic equator to the off-equator (MLAT = −10° to −2.5°) from 22:00 to 23:20 UT. These enhancements were expected to be due to PA scattering with each wave.

Notably, the loss cone filling ratios in the cyclotron resonance energies of UBC and ECH waves from 22:00 to 22:20 UT were enhanced without enhancements of UBC and ECH wave amplitudes. It was expected that these enhancements were due to PA scattering with UBC or ECH waves propagated from the different magnetic field lines (Horne et al., 2003) because the differential flux at PA = 90° was not enhanced (Figures 1h and 1i).

In addition, the loss cone filling ratios exceeded 1 from 20:00 to 21:50 UT (Figures 1j and 1k). The differential flux of 180-eV electrons is shown in Figure 1l. Electron beams were observed during these excessive enhancements. These beams would not be due to the PA scattering by plasma waves. Therefore, electron data where the loss cone filling ratio exceeds 1 should be excluded in the following statistical analyses because our focus is on the PA scattering by various plasma waves.

2.2 Statistical Analyses

To obtain a statistical view for the strong electron scattering by LBC, UBC, and ECH waves, we analyzed a dataset of waves and electrons obtained with the Arase satellite from March 24, 2017 to August 31, 2020. The Arase satellite has started the nominal observations since March 24, 2017 after commissioning phase operations. The number of data sampling in the L^*–MLAT plane are shown in Figure 2g. One sample corresponds to one satellite spin (~8 s) for this plot. To select typical- to high-amplitude wave events from the dataset, we set the threshold amplitude for LBC, UBC, and ECH waves in the 0.10–0.45f_{ce}, 0.50–0.90f_{ce}, and 1.00–2.00f_{ce} frequency bands to 3 pT, 3 pT, and 0.1 mV/m, respectively. LBC, UBC, and ECH wave distributions that exceeded each threshold amplitude are shown in Figures 2a–2c. A moving average is calculated for each wave amplitude with a 1-min time window. Active LBC waves were frequently observed from the magnetic equator to the off-equator, whereas active UBC and ECH waves were frequently observed near the magnetic equator. It is not easy to investigate the one-to-one correspondence between the loss cone filling ratio and individual wave amplitude because these waves are often observed simultaneously as seen in Figures 1a–1e.

We selected the dataset when the wave amplitude of interest was higher than the threshold amplitude and the other two wave amplitudes were smaller. Figures 2d–2f show occurrence rates of LBC waves excluding UBC and ECH waves, UBC waves excluding LBC and ECH waves, and ECH waves excluding LBC and UBC waves in the L^*–MLAT plane. The definition of the occurrence rate is shown in Figure 2.

The cyclotron resonance energy of LBC waves increased as LBC waves propagated to higher MLAT from the magnetic equator, and the energy reached a few MeV (Miyoshi et al., 2020; Miyoshi, Oyama, et al., 2015) while the upper limit energy of LEPe observations was ~20 keV. In addition, the loss cone filling ratios observed at the off-equator included the effect of PA scattering near the magnetic equator. Therefore, we used the dataset obtained near the magnetic equator (MLAT $< 5°$).

To remove the dataset possibly related to the plasma sheet phenomena, we discarded the dataset if the angle between the background magnetic field and the model dipole field was $>30°$ (cf., S. Kasahara et al., 2019). In addition, we only used the dataset obtained outside the plasmapause ($L^* > 4$ and the electron density < 30 cm^{-3}) to exclude the contribution from the plasmaspheric hiss. Visual inspection confirmed that this threshold successfully removed whistler hiss, without significant omission of chorus activities. Finally, we did not use the wave data 1 min before and after calibration pulses of the PWE instrument (Matsuda et al., 2018) and the electron data during commissioning operations.

Examples of extracted data of wave amplitudes and loss cone filling ratios are shown in Figure 3 as scatter plots of LBC, UBC, and ECH wave amplitudes versus the loss cone filling ratios of 0.11-, 2.6-, and 19-keV electrons in logarithmic scales. Scatter plots for electrons of all energy are shown in Figures S1–S3. To exclude the contribution from electron beams, we excluded the dataset when the loss cone filling ratios exceeded 1 and the wave amplitudes were less than 3 pT, 3 pT, and 0.1 mV/m for LBC, UBC, and ECH waves, respectively. Red filled and open circles show median values of loss cone filling ratios obtained with amplitude intervals of the logarithms of 0.1 pT, 0.05 pT, and 0.2 mV/m for LBC, UBC, and ECH waves, respectively. Red open circles show the median value where the amount of data used to calculate the median value is 1% of the total amount of data. To quantify the contribution of the PA scattering by each wave, we estimated the slope of the regression line determined by the least square method using the red filled circles. The slope, s, and its uncertainty, σ, are shown at the top of each panel in Figure 3. In addition, to confirm the accuracy of the contribution estimation, we calculated Kendall's rank correlation coefficients, τ, and the two-sided significance of its deviation from zero, p, using the red filled circles. They are also shown at the top of each panel in Figure 3.

The estimated slopes and correlation coefficients for all energies are shown in Figure 4. The LBC wave has a positive slope with a statistically significant correlation coefficient at energies above ~2 keV, whereas the ECH wave has a smaller positive slope with a statistically significant correlation coefficient at energies below ~2 keV. These energy ranges agreed with the typical cyclotron resonance energy range of each wave mode. The UBC wave has a positive slope with a statistically significant correlation coefficient at energies of 0.4 and 5 keV. In the energy range higher than a few keV, the influence of LBC waves has not been eliminated because it is higher than the typical cyclotron resonance energy of UBC waves.

To investigate how often the strong diffusion occurs by LBC, UBC, and ECH waves, we also calculated occurrence rates using the same extracted dataset. Figure 5a shows the occurrence rates of strong diffusion with typical-amplitude LBC, UBC, and ECH waves and without wave activity. The occurrence rates of strong diffusion with LBC, UBC, and ECH waves were calculated using $n(r > 0.5$, 10 pT $\leq B_{\mathrm{LBC}} < 50$ pT, $B_{\mathrm{UBC}} < 3$ pT, and $E_{\mathrm{ECH}} < 0.1$ mV/m) / n, $n(r > 0.5$, $B_{\mathrm{LBC}} < 3$ pT, 10 pT $\leq B_{\mathrm{UBC}} < 20$ pT, and $E_{\mathrm{ECH}} < 0.1$ mV/m) / n, and $n(r > 0.5$, $B_{\mathrm{LBC}} < 3$ pT, $B_{\mathrm{UBC}} < 3$ pT, and 1 mV/m $\leq E_{\mathrm{ECH}} < 10$ mV/m) / n, respectively, where r is the loss cone filling ratio. The occurrence rate of strong diffusion without wave activity is defined to be $n(r > 0.5$, $B_{\mathrm{LBC}} < 3$ pT, $B_{\mathrm{UBC}} < 3$ pT, and $E_{\mathrm{ECH}} < 0.1$ mV/m) $/n$ and is labeled as "No wave" in Figures 5a and 5b. The loss cone is not empty, even if the simultaneous wave activity is not observed, especially at lower energies (< ~1 keV), attributable to the effect of PA scattering at different MLATs on the same magnetic field line or effect of backscattered electrons. Therefore, the contribution for the strong diffusion by wave activity can be seen by comparing the occurrence rate with each wave activity and that without wave activity. At energies above 1 keV, the occurrence rate by LBC waves was the highest of the three waves and ~10%–30% higher than those without wave activity. Meanwhile, at energies below 1 keV, the occurrence rate by UBC waves was highest and ~10%–20% higher than those without wave activity.

Figure 5b shows the occurrence rate of strong diffusion by higher-amplitude waves. The occurrence rate was calculated using the threshold value of wave amplitude shown at the top of Figure 5b. At energies above 1 keV, the occurrence rate by higher-amplitude LBC waves (Figure 5b) was higher than that by lower-amplitude LBC waves (Figure 5a) and ~40%–70% higher than that without simultaneous wave activity. At energies below 1 keV, the occurrence rate by ECH waves was the highest of the three waves and ~20%–40% higher than that without simultaneous wave activity. These results indicate that the contribution to the strong diffusion by ECH waves is dominant among the three waves when the wave amplitude is high ($\gtrsim \geq 10$ mV/m).

To examine the energy range where each wave can fully fill the loss cone, we calculated the bounce-averaged PA diffusion coefficient $\langle D \ \rangle$ at PA = 2.5° and $L = 6$ as a function of energy and compared it with the strong diffusion level (Horne & Thorne, 2000). The bounce-averaged first-order cyclotron resonance diffusion coefficient was calculated based on the method in Shprits et al. (2006) for parallel propagating LBC and UBC waves. The bounce-averaged first- to tenth-order cyclotron resonance and Landau resonance diffusion coefficients were calculated based on Horne and Thorne (2000) for ECH waves. The contribution from the first- and second-order cyclotron resonance was dominant for ECH waves (not shown). The power spectral density was assumed to be Gaussian centered at $f_{\mathrm{m}} = 0.35 f_{\mathrm{ce}}$ and $f_{\mathrm{m}} = 0.65 f_{\mathrm{ce}}$ for LBC and UBC waves, respectively, with a standard deviation (bandwidth) $f = 0.15 f_{\mathrm{ce}} \ / \ \sqrt{2}$ and bounded by upper ($f_{\mathrm{m}} + 2\sqrt{2}\sqrt{2}\ f$) and lower ($f_{\mathrm{m}} - 2\ \sqrt{2}\sqrt{2}\ f$) cutoffs, resembling typical LBC and UBC in the same manner as Shprits et al. (2006). The LBC and UBC wave amplitudes were assumed to be spatially uniform at MLAT 10° and set to zero at MLAT > 10°. Because there was a large ambiguity of the electron density in our observations outside the plasmapause, we calculated for two density values ($n_0 = 1$ and 5 cm^{-3}; cf. Sheeley et al., 2001). The peak frequency of the wave spectrum for ECH waves was assumed to be $1.5 f_{\mathrm{ce}}$ and the peak wavenumber was obtained by solving the dispersion relation using KUPDAP. The electron distributions explained in Subsection 2.1 were used. Only the total electron density was changed to $n_0 = 1$ and 5 cm^{-3}. We assumed the wave growth was centered at a propagation angle of $\psi = 89.5°$ and an angular width of $\Delta\psi = 0.5°$ (Horne & Thorne, 2000). The ECH wave amplitude was assumed to be spatially uniform at MLAT 3° and set to zero at MLAT > 3° (Gough et al., 1979; Meredith et al., 2009; Ni et al., 2017).

Figures 5c and 5d show calculated $\langle D \ \rangle$ for $n_0 = 1$ and 5 cm^{-3}, respectively. The energy ranges where the calculated $\langle D \ \rangle$ exceeded the strong diffusion level were almost consistent with those where the occurrence rates of strong diffusion were high for each wave. Notably, the occurrence rate of strong diffusion by LBC waves at energies below 1 keV was larger than those without simultaneous wave activity (Figures 5a and 5b). However, these energies were smaller than the typical cyclotron resonance energy of LBC waves, and the diffusion coefficient was smaller than the strong diffusion limit in these energies (Figures 5c and

5d). Although we excluded wave data that have typical-amplitude UBC and ECH waves in calculating the occurrence rates for LBC waves, UBC and ECH waves were often observed before and after LBC waves (Figures 1a–1e). The high occurrence rates by LBC waves in the low-energy range could be due to the PA scattering by UBC and ECH waves at different MLAT on the same field line.

In addition, the occurrence rate of strong diffusion with UBC waves was higher than that without simultaneous wave activity at energies above a few keV (Figures 5a and 5b), but the PA diffusion coefficient did not exceed the strong diffusion limit in these energies (Figures 5c and 5d). If we change the threshold value of wave amplitude to exclude ECH waves stricter from 0.1 to 0.01 mV/m, the occurrence rate with UBC waves in these energies becomes smaller than that without simultaneous wave activity (not shown), implying that the strong diffusion at energies above a few keV is not due to UBC waves.

3 Summary and Discussion

In this study, we revealed energy ranges where LBC, UBC, and ECH waves contribute to scattering electrons into loss cones based on *in situ* observations by LEPe and OFA onboard the Arase satellite. Based on the event study, we found that the loss cone filling ratios were enhanced in the cyclotron resonance energy ranges of LBC, UBC, and ECH waves with corresponding wave enhancements. As a result of the statistical analyses of wave and electron data obtained with the Arase satellite, the slopes of regression lines for wave amplitudes versus loss cone filling ratios were positive, and the correlation coefficients between them were statistically significant at energies above ~2 keV for LBC waves, at an energy of ~0.4 keV for UBC waves, and at energies below ~2 keV for ECH waves. The strong PA scattering commonly occurred in almost the same energy range for each wave. These energy ranges agreed with the energy ranges that PA diffusion coefficients exceeded the strong diffusion level based on the quasilinear theory.

Previous studies have shown that the contribution of ECH waves for strong diffusion is relatively small compared with LBC and UBC waves (Khazanov et al., 2015; Tao et al., 2011; Thorne et al., 2010; Tripathi et al., 2013). Recently, Kazama et al. (2021) identified that both LBC and UBC waves contribute to the electron PA scattering near the equator via Arase observations. On the othr hand, the PA scattering of keV electrons into a loss cone by ECH waves had been reported using ground-based all-sky imager and Arase satellite observations (Fukizawa et al., 2018, 2020). Although these previous studies are based on event studies, our study is based on the statistical analyses of the data obtained with the relatively high-angular resolution electron instrument onboard the Arase satellite. Our statistical analyses indicated that LBC waves commonly scattered electrons of energies above a few keV into loss cones near the inner magnetospheric magnetic equator ($L^* = 4$–6 and MLAT $< 5°$) and put electrons on strong diffusion. In addition, we showed that ECH waves scatter electrons into the loss cone at energies below ~1 keV and put ~0.1-keV electrons on strong diffusion with an occurrence rate of ~80%. Therefore, PA scattering by ECH waves contributes to loss of plasma sheet electrons as well as emissions of the diffuse aurora in the inner magnetosphere.

Acknowledgments, Samples, and Data

Science data of the ERG (Arase) satellite were obtained from the ERG Science Center operated by ISAS/JAXA and ISEE/Nagoya University (https://ergsc.isee.nagoya-u.ac.jp/index.shtml.en, (Miyoshi, Hori, et al., 2018)). In this study, we used the LEPe Level-1a v7 data (calibrated, identical to Level-2 v03_01 data), PWE/OFA L2-v02_01 data (Y. Kasahara, Kojima, et al., 2018), PWE/HFA L3-v03_05, v03_06, v03_07, v04_05, and v04_06 data (Y. Kasahara et al., 2021), and MGF L2-v03_04 and v04_04 data (Matsuoka, Teramoto, Imajo, et al., 2018) obtained by ERG. The ERG orbital data L2-v02 (Miyoshi, Shinohara, & Jun, 2018a) and L3-v02 (Miyoshi, Shinohara, & Jun, 2018b) were also used. The SPEDAS software (Angelopoulos et al., 2019) and ERG Plug-in tools were used for data analysis. The development and operation of LEPe are partly funded by Academia Sinica and National Cheng Kung University of Taiwan as well as supported by the Ministry of Science and Technology of Taiwan under contract 106-2111-M-001-011 and 105-3111-Y-001-042. The first author is a Research Fellow of the Japan Society for the Promotion of Science (DC). This study is supported by JSPS Bilateral Open Partnership Joint Research Projects (JPJSBP120192504), JSPS KAKENHI Grant Numbers JP15H05815, JP17H00728, JP18H03727, JP20H01959, and JP20J11829 and conducted by the joint research program of the Institute for Space–Earth Environmental Research (ISEE), Nagoya University.

References

Angelopoulos, V., Cruce, P., Drozdov, A., Grimes, E. W., Hatzigeorgiu, N., King, D. A., et al. (2019). The Space Physics Environment Data Analysis System (SPEDAS). *Space Science Reviews*. The Author(s). https://doi.org/10.1007/s11214-018-0576-4Ashour-Abdalla, M., & Kennel, C. F. (1978). Nonconvective and Convective Electron Cyclotron Harmonic Instability. *Journal of Geophysical Research*, *83*(A4), 1531–1543. https://doi.org/10.1029/JA083iA04p01531Fukizawa, M., Sakanoi, T., Miyoshi, Y., Hosokawa, K., Shiokawa, K., & Katoh, Y. (2018). Electrostatic electron cyclotron harmonic waves as a candidate to cause pulsating auroras. *Geophysical Research Letters*, *45*(12), 661–668. https://doi.org/10.1029/2018GL080145Fukizawa, M., Sakanoi, T., Miyoshi, Y., Kazama, Y., Katoh, Y., Kasahara, Y., et al. (2020). Pitch-angle scattering of inner magnetospheric electrons caused by ECH waves obtained with the Arase satellite. *Geophysical Research Letters*, *47*(23), 1–9. https://doi.org/10.1029/2020GL089926Fukizawa, M., Sakanoi, T., Ogawa, Y., Tsuda, T. T., & Hosokawa, K. (2021). Statistical Study of Electron Density Enhancements in the Ionospheric F Region Associated With Pulsating Auroras . *Journal of Geophysical Research: Space Physics*, *126*(12), 1–14. https://doi.org/10.1029/2021ja029601Gough, M. P., CHristiansen, P. J., Martelli, G., & Gershuny, E. J. (1979). Interaction of electrostatic waves with warm electrons at the geomagnetic equator. *Nature*, *279*(5713), 515–517. https://doi.org/10.1038/279515a0Horne, R. B. (1989). Path-integrated growth of electrostatic waves: The generation of terrestrial myriametric radiation. *J. Geophys. Res.*, *94*(A7), 8895–8909. https://doi.org/http://dx.doi.org/10.1029/JA094iA07p08895.Horne, R. B., & Thorne, R. M. (2000). Electron pitch angle diffusion by electrostatic electron cyclotron harmonic waves: The origin of pancake distributions. *Journal of Geophysical Research*, *105*, 5391–5402. https://doi.org/10.1029/1999JA900447Horne, R. B., Thorne, R. M., Meredith, N. P., & Anderson, R. R. (2003). Diffuse auroral electron scattering by electron cyclotron harmonic and whistler mode waves during an isolated substorm. *Journal of Geophysical Research: Space Physics*, *108*(A7), 1–12. https://doi.org/10.1029/2002JA009736Kasaba, Y., Ishisaka, K., Kasahara, Y., Imachi, T., Yagitani, S., Kojima, H., et al. (2017). Wire Probe Antenna (WPT) and Electric Field Detector (EFD) of Plasma Wave Experiment (PWE) aboard the Arase satellite: specifications and initial evaluation results. *Earth, Planets and Space*, *69*(1). https://doi.org/10.1186/s40623-017-0760-xKasahara, S., Yokota, S., Mitani, T., Asamura, K., Hirahara, M., Shibano, Y., & Takashima, T. (2018). Medium-energy particle experiments—electron analyzer (MEP-e) for the exploration of energization and radiation in geospace (ERG) mission. *Earth, Planets and Space*, *70*(1), 1–16. https://doi.org/10.1186/s40623-018-0847-zKasahara, S., Miyoshi, Y., Yokota, S., Mitani, T., Kasahara, Y., Matsuda, S., et al. (2018). Pulsating aurora from electron scattering by chorus waves. *Nature*, *554*(7692), 337–340. https://doi.org/10.1038/nature25505Kasahara, S., Miyoshi, Y., Kurita, S., Yokota, S., Keika, K., Hori, T., et al. (2019). Strong Diffusion of Energetic Electrons by Equatorial Chorus Waves in the Midnight-to-Dawn Sector. *Geophysical Research Letters*, *46*(22), 12685–12692. https://doi.org/10.1029/2019GL085499Kasahara, Y., Kasaba, Y., Kojima, H., Yagitani, S., Ishisaka, K., Kumamoto, A., et al. (2018). The Plasma Wave Experiment (PWE) on board the Arase (ERG) satellite. *Earth, Planets and Space*, *70*(1). https://doi.org/10.1186/s40623-018-0842-4Kasahara, Y., Kojima, H., Matsuda, S., Ozaki, M., Yagitani, S., Shoji, M., et al. (2018). The PWE/OFA instrument Level-2 power spectrum data of Exploration of energization and Radiation in Geospace (ERG) Arase satellite. https://doi.org/10.34515/DATA.ERG-08000Kasahara, Y., Kumamoto, A., Tsuchiya, F., Kojima, H., Matsuda, S., Matsuoka, A., et al. (2021). The PWE/HFA instrument Level-3 electron density data of Exploration of energization and Radiation in Geospace (ERG) Arase satellite. https://doi.org/10.34515/DATA.ERG-10001Kazama, Y., Wang, B. J., Wang, S. Y., Ho, P. T. P., Tam, S. W. Y., Chang, T. F., et al. (2017). Low-energy particle experiments–electron analyzer (LEPe) onboard the Arase spacecraft. *Earth, Planets and Space*, *69*(1). https://doi.org/10.1186/s40623-017-0748-6Kazama, Y., Kojima, H., Miyoshi, Y., Kasahara, Y., Usui, H., Wang, B. J., et al. (2018). Density Depletions Associated With Enhancements of Electron Cyclotron Harmonic Emissions: An ERG Observation. *Geophysical Research Letters*, *45*(19), 10,075-10,083. https://doi.org/10.1029/2018GL080117Kazama, Y., Miyoshi, Y., Kojima, H., Kasahara, Y., Kasahara, S., Usui, H., et al. (2021). Arase Observation of Simultaneous Electron Scatterings by Upper-Band and Lower-Band Chorus Emissions. *Geophysical Research Letters*, *48*(14), 1–10. https://doi.org/10.1029/2021GL093708Kennel, C. F., & Petschek, H. E. (1966). Limit on stably trapped particle fluxes. *Journal of Geophysical Research*, *71*(1), 1–28. https://doi.org/10.1029/JZ071i001p00001Khazanov, G. V., Tripathi, A. K., Sibeck, D., Himwich, E., Glocer, A., & Singhal, R. P. (2015). Electron distribution function formation in regions of diffuse aurora. *Journal of Geophysical Research: Space Physics*, *120*(11), 9891–9915. https://doi.org/10.1002/2015JA021728Kumamoto, A., Tsuchiya, F., Kasahara, Y., Kasaba, Y., Kojima, H., Yagitani, S., et al. (2018). High Frequency Analyzer (HFA) of Plasma Wave Experiment (PWE) onboard the Arase spacecraft. *Earth, Planets and Space*, *70*(1), 1–14. https://doi.org/10.1186/s40623-018-0854-0Liang, J., Uritsky, V., Donovan, E., Ni, B., Spanswick, E., Trondsen, T., et al. (2010). THEMIS observations of electron cyclotron harmonic emissions, ULF waves, and pulsating auroras. *Journal of Geophysical Research: Space Physics*, *115*(10), 1–24. https://doi.org/10.1029/2009JA015148Lyons, L. R. (1974). Electron diffusion driven by magnetospheric electrostatic waves. *Journal of Geophysical Research*, *79*(4), 575–580. https://doi.org/10.1029/ja079i004p00575Matsuda, S., Kasahara, Y., Kojima, H., Kasaba, Y., Yagitani, S., Ozaki, M., et al. (2018). Onboard software of Plasma Wave Experiment aboard Arase: instrument management and signal processing of Waveform Capture/Onboard Frequency Analyzer. *Earth, Planets and Space*, *70*(1). https://doi.org/10.1186/s40623-018-0838-0Matsuoka, A., Teramoto, M., Nomura, R., Nose, M., Fujimoto, A., Tanaka, Y., et al. (2018). The ARASE (ERG) magnetic field investigation. *Earth, Planets and Space*, *70*(1), 1–16. https://doi.org/10.1186/s40623-018-0800-1Matsuoka, A., Teramoto, M., Imajo, S., Kurita, S., Miyoshi, Y., & Shinohara, I. (2018). The MGF instrument Level-2 spin-averaged magnetic field data of Exploration of energization and Radiation in Geospace (ERG) Arase satellite. https://doi.org/10.34515/DATA.ERG-06001Meredith, N. P., Horne, R. B., Thorne, R. M., & Anderson, R. R. (2009). Survey of upper band chorus and ECH waves: Implications for the diffuse aurora. *Journal of Geophysical Research: Space Physics*, *114*(7), 1–11. https://doi.org/10.1029/2009JA014230Miyoshi, Y., Katoh, Y., Nishiyama, T., Sakanoi, T., Asamura, K., & Hirahara, M. (2010). Time of flight analysis of pulsating aurora electrons, considering wave-particle interactions with propagating whistler mode waves. *Journal of Geophysical Research: Space Physics*, *115*(10), 1–7. https://doi.org/10.1029/2009JA015127Miyoshi, Y., Oyama, S., Saito, S., Kurita, S., Fujiwara, H., Kataoka, R., et al. (2015). Energetic electron precipitation associated with pulsating aurora: EISCAT and Van Allen Probe observations. *Journal of Geophysical Research : Space Physics*, *120*, 2754–2766. https://doi.org/10.1002/2014JA020690.ReceivedMiyoshi, Y., Saito, S., Seki, K., Nishiyama, T., Kataoka, R., Asamura, K., et al. (2015). Relation between energy spectra of pulsating aurora electrons and frequency spectra of whistler-mode chorus waves. *Journal of Geophysical Research: Space*

Physics, 1–9. https://doi.org/10.1002/2015JA021562.Miyoshi, Y., Shinohara, I., Takashima, T., Asamura, K., Higashio, N., Mitani, T., et al. (2018). Geospace exploration project ERG. *Earth, Planets and Space*, *70*(1), 101. https://doi.org/10.1186/s40623-018-0862-0Miyoshi, Y., Hori, T., Shoji, M., Teramoto, M., Chang, T. F., Segawa, T., et al. (2018). The ERG Science Center. *Earth, Planets and Space*, *70*(1). https://doi.org/10.1186/s40623-018-0867-8Miyoshi, Y., Shinohara, I., & Jun, C.-W. (2018a). The Level-2 orbit data of Exploration of energization and Radiation in Geospace (ERG) Arase satellite. https://doi.org/10.34515/DATA.ERG-12000Miyoshi, Y., Shinohara, I., & Jun, C.-W. (2018b). The Level-3 orbit data of Exploration of energization and Radiation in Geospace (ERG) Arase satellite. https://doi.org/10.34515/DATA.ERG-12001Miyoshi, Y., Saito, S., Kurita, S., Asamura, K., Hosokawa, K., Sakanoi, T., et al. (2020). Relativistic Electron Microbursts as High-Energy Tail of Pulsating Aurora Electrons. *Geophysical Research Letters*, *47*(21). https://doi.org/10.1029/2020GL090360Miyoshi, Y., Hosokawa, K., Kurita, S., Oyama, S. I., Ogawa, Y., Saito, S., et al. (2021). Penetration of MeV electrons into the mesosphere accompanying pulsating aurorae. *Scientific Reports*, *11*(1), 1–9. https://doi.org/10.1038/s41598-021-92611-3Ni, B., Gu, X., Fu, S., Xiang, Z., & Lou, Y. (2017). A statistical survey of electrostatic electron cyclotron harmonic waves based on THEMIS FFF wave data. *Journal of Geophysical Research: Space Physics*, *122*(3), 3342–3353. https://doi.org/10.1002/2016JA023433Nishimura, Y., Bortnik, J., Li, W., Thorne, R. M., Lyons, L. R., Angelopoulos, V., et al. (2010). Identifying the driver of pulsating aurora. *Science*, *330*(6000), 81–84. https://doi.org/10.1126/science.1193186Ozaki, M., Yagitani, S., Kasahara, Y., Kojima, H., Kasaba, Y., Kumamoto, A., et al. (2018). Magnetic Search Coil (MSC) of Plasma Wave Experiment (PWE) aboard the Arase (ERG) satellite. *Earth, Planets and Space*, *70*(1), 1–13. https://doi.org/10.1186/s40623-018-0837-1Sheeley, B. W., Moldwin, M. B., Rassoul, H. K., & Anderson, R. R. (2001). An empirical plasmasphere and trough density model: VRESS observations. *Journal of Geophysical Research*, *106*(A11), 25631–25641. https://doi.org/http://dx.doi.org/10.1029/2000JA000286Shprits, Y. Y., Thorne, R. M., Horne, R. B., & Summers, D. (2006). Bounce-averaged diffusion coefficients for field-aligned chorus waves. *Journal of Geophysical Research: Space Physics*, *111*(10), 1–6. https://doi.org/10.1029/2006JA011725Sugiyama, H., Singh, S., Omura, Y., Shoji, M., Nunn, D., & Summers, D. (2015). Electromagnetic ion cyclotron waves in the Earth's magnetosphere with a kappa-Maxwellian particle distribution. *Journal of Geophysical Research A: Space Physics*, *120*(10), 8426–8439. https://doi.org/10.1002/2015JA021346Tao, X., Thorne, R. M., Li, W., Ni, B., Meredith, N. P., & Horne, R. B. (2011). Evolution of electron pitch angle distributions following injection from the plasma sheet. *Journal of Geophysical Research: Space Physics*, *116*(4), 1–8. https://doi.org/10.1029/2010JA016245Tesema, F., Partamies, N., Tyssøy, H. N., Kero, A., Smith-Johnsen, C., & Smith-Johnsen, C. (2020). Observations of electron precipitation during pulsating aurora and its chemical impact. *Journal of Geophysical Research: Space Physics*, *125*(6), e2019JA027713.

https://doi.org/10.1029/2019ja027713Thorne, R. M., Ni, B., Tao, X., Horne, R. B., & Meredith, N. P. (2010). Scattering by chorus waves as the dominant cause of diffuse auroral precipitation. *Nature*, *467*(7318), 943–946. https://doi.org/10.1038/nature09467Tripathi, A. K., Singhal, R. P., & Singh, K. P. (2011). Pitch-angle diffusion coefficients from resonant interactions with electrostatic electron cyclotron harmonic waves in planetary magnetospheres. *Annales Geophysicae*, *29*(2), 321–330. https://doi.org/10.5194/angeo-29-321-2011Tripathi, A. K., Singhal, R. P., Singh, K. P., & Singh, O. N. (2013). Diffuse auroral precipitation by resonant interaction with electron cyclotron harmonic and whistler mode waves. *Journal of Atmospheric and Solar-Terrestrial Physics*, *97*, 125–134. https://doi.org/10.1016/j.jastp.2013.01.013Tsyganenko, N. A., & Sitnov, M. I. (2005). Modeling the dynamics of the inner magnetosphere during strong geomagnetic storms. *Journal of Geophysical Research: Space Physics*, *110*(A3), 1–16. https://doi.org/10.1029/2004JA010798Turunen, E., Kero, A., Verronen, P. T., Miyoshi, Y., Oyama, S. I., & Saito, S. (2016). Mesospheric ozone destruction by high-energy electron precipitation associated with pulsating aurora. *Journal of Geophysical Research*, *121*(19), 11852–11861. https://doi.org/10.1002/2016JD025015

Figure 1. Summary plot of wave and particle data obtained with Arase from 20:00 UT on March 27, 2017 to 2:00 UT on March 28, 2017. Frequency–time spectrograms for the (**a**) wave electric field and (**b**) wave magnetic field. Black lines indicate $0.1f_{\mathrm{ce}}$, 0.5 f_{ce}, and integer multiple of f_{ce} from bottom to top. (**c**, **d**, and **e**) ECH, UBC, and LBC wave amplitudes in 1.00–$2.00f_{\mathrm{ce}}$, 0.50–$0.90f_{\mathrm{ce}}$, and 0.10–$0.45f_{\mathrm{ce}}$ frequency bands, respectively. Differential fluxes of loss cone electrons ((**f**) PA ranges of 0°–5° and (**g**) 175°–180°) and averaged bouncing electrons ((**h**) PA ranges of 5°–90° and (**i**) 175°–180°) in the unit of eV/s/cm^2/sr/eV. (**j** and **k**) Ratios of parallel flux $j(0^{\circ}$–$5^{\circ})$ / $\langle j(5^{\circ}$–$90^{\circ})\rangle$ and antiparallel flux $j(175^{\circ}$–$180^{\circ})$ / $\langle j(90^{\circ}$–$175^{\circ})\rangle$, respectively. Black solid lines denote CR energies of chorus waves with frequencies of $0.3f_{\mathrm{ce}}$, $0.5f_{\mathrm{ce}}$, and $0.7f_{\mathrm{ce}}$ from top to bottom. Black dashed lines denote CR energies of ECH waves with frequencies of $1.2f_{\mathrm{ce}}$ and 1.8 f_{ce} from bottom to top. (**l**) PA distribution of 180 eV electrons.

Figure 2. Occurrence rates of active (a) LBC waves, (b) UBC waves, (c) ECH waves, (d) LBC waves excluding UBC and ECH waves, (e) UBC waves excluding LBC and ECH waves, and (f) ECH waves excluding LBC and UBC waves in the L*–MLAT plane. The definition of the occurrence rate is given, where B_{LBC} and B_{UBC} is the wave magnetic field of LBC and UBC waves, respectively, E_{ECH} is the wave electric field of ECH waves, and n is (g) the sampling number.

Figure 3. Scatter plots of the LBC, UBC, and ECH amplitudes in logarithmic scales versus the loss cone filling ratios of 0.8-, 5-, and 16-keV electrons (black diamonds). Red filled and open circles show median values of loss cone filling ratios obtained with amplitude intervals of the logarithms of 0.1 pT, 0.05 pT,

and 0.2 mV/m for LBC, UBC, and ECH waves, respectively. Red open circles show the median value where the amount of data is 1% of the total amount of data. Red lines show regression lines determined by the least square method. The slope of a regression line, s, and its uncertainty, σ, as well as Kendall's rank correlation coefficient, , and the two-sided significance of its deviation from zero, p, are shown at the top of each panel. They were calculated using only red filled circles.

Figure 4. Energy dependence of (a) slopes of regression lines and (b) Kendall's rank correlation coefficients between loss cone filling ratios and LBC (black circles), UBC (blue squares), and ECH (red diamonds) wave amplitudes. Error bars in Figure 4a indicate the 2σ level. Filled and open symbols in Figure 4b indicate $p < 0.05$ and $p \geq 0.05$, respectively.

Figure 5. Energy dependence of occurrence rates of strong diffusion by (a) typical- and (b) high-amplitude LBC (black circles), UBC (blue squares), and ECH (red diamonds) waves. Amplitude ranges are shown at the top of each panel. Green shows occurrence rates of strong diffusion without simultaneous wave activity. Bounce-averaged PA diffusion coefficients ($\langle D_{\alpha\alpha} \rangle$) of LBC (black), UBC (blue), and ECH waves (red) as a function of the electron energy for the electron density of (c) 1 cm^{-3} and (d) 5 cm^{-3}. The upper and lower ends of the bands, respectively, represent $\langle D_{\alpha\alpha} \rangle$ for 10 and 100 pT (LBC), 10 and 30 pT (UBC), and 1 and 10 mV/m (ECH). The dashed line indicates the strong diffusion level.