Simulating Electron Distribution Function in the Pulsating Aurora Using Particle and Wave Data of ARASE Satellite

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Abstract

Decades lasting research on the pulsating aurora suggested that this phenomenon forms as result of interactions between the magnetospheric keVs electrons and whistler-mode chorus waves. Arase satellite observation reported the direct evidence for this process confirming in situ measurement of highly correlated precipitated electrons and chorus wave activity. This paper presents the theoretical analysis of this observational event based on the SuperThermal Electron Transport (STET) code that simulates the highly dynamic environment of measured waves and particle data. Specifically, the STET code simulated results confirms the delicate loss-cone observation results of this mission and further reveals the broader energy range of precipitated electron fluxes that was not measurable by Arase satellite.

Keywords: Pulsating aurora; magnetosphere-ionosphere coupling; electron precipitation; whistler-mode chorus wave

Key points:

- Applying Arase satellite observations for the kinetic simulation of pulsating aurora.
- STET code simulated precipitated electron fluxes driven by whistler-mode chorus waves.
- Revealing hidden pulsating aurora dynamics in Arase observation using STET code.

1. Introduction

It was widely accepted for the past several decades that pulsating auroras are the result of interactions between the high-energy magnetospheric electrons and whistler-mode chorus waves (Johnstone, 1978, Davidson, 1990, Lessard, 2012, and Jaynes et al., 2013). Whistler-mode chorus waves are more effective in pitch angle scattering at geocentric distances $r \leq 8\ R_E$ (Ni, Thorne, Horne, et al., 2011; Ni, Thorne, Meredith, et al., 2011; Thorne et al., 2010; Miyoshi, et al., 2015, Li et al., 2013) and they are also associated with the electron precipitation processes in the region of diffuse aurora (Ma et al., 2020). Nishimura et al. (2010) have suggested that chorus waves interact with equatorial electrons to produce pulsating auroras, while Mozer et al. (2017) examined the role of time domain structures in the formation of this phenomenon. The rocket-borne measurements of electron modulations within pulsating aurora by Yau et al. (1981) provided a clear indication that electrons of different energies were being injected with temporal variability from the near-equatorial plane.

The direct Arase spacecraft observations of magnetospheric electrons and chorus waves presented by Kasahara et al. (2018a), with associated observation of auroral pulsations observed by the ground based All-Sky Imagers (ASIs) of the THEMIS mission, provided the clear evidence that the pulsating aurora was formed via interaction of modulated chorus wave activity with magnetospheric electrons. This is, however, not the end of the story because the case study by Samara et al. (2017) of a pulsating auroral event imaged optically at high time resolution presented observational evidence of the role of atmosphere in the formation of additional time dependent pulsating aurora structures. Specifically, for the first time, Samara et al. (2017) demonstrated that a certain type of pulsating aurora is caused by electrons bouncing back and forth between the two hemispheres.

The theoretical studies of aurora, as atmospheric phenomena, we mentioned above were focusing on the magnetospheric driver of electron precipitation into the atmosphere. However, as was suggested by Khazanov et al. (2017a, 2021a), aurora is not only driven by pure magnetospheric processes. Magnetosphere-Ionosphere-Atmosphere (MIA) coupling of the precipitated electrons and their interplay between the northern and southern hemispheres is also an additional mechanism that proves to be an important contributor in the formation of different kinds of auroras (Khazanov et al., 2020; Khazanov et al., 2021b). Such kind of processes also play an important role in the pulsating aurora studies. Recently, using the time dependent SuperThermal Electron Transport (STET) code, Khazanov et al. (2023a) successfully modeled the event presented by Samara et al. (2017) and achieved perfect agreement between the data and simulated results.

The Arase spacecraft observations (Kasahara et al., 2018a) that are mentioned above, provide the detailed data of the chorus waves and associated high-energy electron environment, including the delicate measurements of loss-cone precipitated electron fluxes. They used the following criterion for loss-cone measurements: when the angle between the center of the field of view of their detector and the magnetic field is smaller than 2°, the detected electrons are inside the loss cone. The instrument field of view angular width is 3.5°. As Kasahara et al. (2018a) mentioned, “This approach needs caution regarding contamination from electrons outside the loss cone, because a fraction of the field of view can extend outside the loss cone.” Kasahara et al. (2018a) carefully evaluated the effects of the field of view angular range, and found that the contamination from fluxes outside the loss cone was insignificant, although not negligible, during this event. Such a careful examination of the precipitated electron data leads to the restricted energy range of measured loss-cone electrons. This obstacle, however, does not diminish the importance of the study by Kasahara et al. (2018a) and opens an additional venue for further analysis of Arase spacecraft observations using STET model based kinetic capabilities.

This paper is organized into the following sections. Section 2 describes the Arase satellite observations. STET code setting and simulation results are presented in the Sections 3 and 4. Follow-up Section 5 summarizes studies that are presented in this manuscript.

2. Arase Satellite Observations

2.1.Geomagnetic Storm on 27 March 2017

The chorus-induced electron precipitation and pulsating aurora event analyzed by Kasahara et al. (2018a) occurred during the main phase of a geomagnetic storm on 27 March 2017. The two-day variations of Sym-H, Kp and AE indices are presented in Figures 1a-c. The geomagnetic storm commenced at ~00 UT on 27 March, and Sym-H reached minimum at ~12:30 - 12:40 UT on 27 March (Figure 1a). This storm is classified as a moderate storm because the minimum Sym-H is about -85 nT. However, the Kp index reached high values of 6+ shortly after the Sym-H minimum (Figure 1b), and the AE index reached above 1500 nT during 10 - 11 UT and 18 - 19 UT on 27 March (Figure 1c). The high Kp and AE indices suggests strong plasma convection and injection activities, which may favor the chorus wave generation (Li et al., 2009, 2010; Meredith et al., 2020).

2.2. Instrumentation

We use the waves and electron measurements by Arase satellite (Miyoshi, Shinohara et al., 2018) to analyze the formation of pulsating aurora during this event. The Arase satellite has an orbital perigee at ~400 km, apogee at ~32000 km and inclination of ~31°. The background magnetic field is measured by Magnetic Field Experiment (MGF) at 8-s resolution (Matsuoka et al., 2018). The local electron gyrofrequency ($f_{\mathrm{ce,local}}$) is calculated using the measured magnetic field, and the equatorial electron gyrofrequency (f_{ce}) is estimated using $f_{\mathrm{ce,local}}$ and the scaling of a dipole field geometry. The Plasma Wave Experiment (PWE) measures the wave electric and magnetic power spectral densities over a broad frequency range (Kasahara, Kasaba et al., 2018c). We use the Onboard Frequency Analyzer (OFA) of the Low-Frequency Wave Receiver (Matsuda et al., 2018) to obtain the chorus wave frequency spectrogram from 0.05 f_{ce} to f_{ce} frequencies. The OFA instrument also provides the data product of wave properties, including the wave normal angle, ellipticity and Poynting flux angle, inferred using the Singular Value Decomposition method (Santolik et al., 2003). The High Frequency Analyzer (HFA) of the High-Frequency Wave Receiver measures the wave electric power spectral densities from 2 kHz to 10 MHz (Kumamoto et al., 2018). We use the total electron density provided in the data products of HFA instrument, inferred by identifying the upper hybrid emissions.

The Low-Energy and Medium-Energy Particle Experiments - Electron Analyzer (LEP-e and MEP-e) measure the electron fluxes for different pitch angles at ~19 eV – 19 keV and ~7 keV – 90 keV energies, respectively (Kazama et al., 2017; Kasahara, Yokota et al., 2018b). We use the electron fluxes measured by LEP-e at energies below 7 keV and MEP-e at energies from 7 keV to 90 keV, and the measurements from the first and last energy channels are excluded. We estimate the local pitch angle of loss cone at the Arase location assuming a dipole magnetic field geometry and identify the observed precipitating electron fluxes as the electrons with pitch angles smaller than the loss cone pitch angle using MEP-e measurements. This method relies on the dipole assumption and does not account for the look-direction width of the electron detectors, so some electron fluxes outside the loss cone may be included. However, as will be shown in Section 2.3, our method captures the major features of the precipitating electron fluxes obtained by Kasahara et al. (2018a).

2.3. Particle and Wave Data

The Arase measurements during 08 – 13 UT on 27 March 2017 are presented in Figures 1d-g. Arase was travelling from the southern hemisphere (-26.3° magnetic latitude) to the northern hemisphere (6.5° magnetic latitude), from L = 2.8 to L = 6, and over the nightside (23.5 h to 4.4 h magnetic local time, MLT). Figure 1d shows the waves measurement at 2-500 kHz frequencies overplotted with the local electron gyrofrequency and the upper hybrid resonance frequency (f_{UH}). The plasmapause crossing is identified at ~08:20 UT, after which the electron cyclotron harmonic (ECH) waves were observed at frequencies between $f_{\mathrm{ce,local}}$ and f_{UH}. The ECH waves are significantly intensified after ~09:30 UT.

Figure 1e shows the whistler-mode wave observation at frequencies from 50 Hz to 20 kHz. Lower band chorus (LBC) waves were observed during 09:20 - 13:00 UT over 0.05 - 0.5 f_{ce} frequencies, and upper band chorus (UBC) waves were observed during 10:30 – 12:30 UT over 0.5 - 1 f_{ce} frequencies. The LBC wave intensity reached the high values of 100 $\mathrm{pT}^2/\mathrm{Hz}$. The waves were highly bursty during 10:00 – 12:20 UT, showing fast temporal variation of wave power within a few minutes or less. After 12:20 UT, the LBC waves present less significant short-time variation but still have high wave intensity. Figure 1f shows the chorus wave Poynting flux angle at 0.05 – 1 f_{ce} frequencies for the wave intensities higher than 0.01 $\mathrm{pT}^2/\mathrm{Hz}$. The Poynting flux angle shows that the lower and upper band chorus waves propagate from equator to high latitudes towards the Earth; i.e., the waves in the southern hemisphere propagate in the direction opposite to the field line before 11:35 UT, and the waves in the northern hemisphere propagate along the field line after 11:35 UT. The wave propagation property suggests that the waves are generated at the equator.

Figure 1g shows the electron flux measurements by the LEP-e and MEP-e instruments. Some electron injections at 0.1 – 10 keV energies were observed after 09:20 UT, and higher energy (> 10 keV) electron flux enhancements were observed during 10:10 – 11:10 UT. The energetic electrons from injections may interact with the chorus waves and be scattered into the loss cone.

We analyze 40-min period of 10:40 – 11:20 in Figure 2, when Arase was close to the equator at $5.7 < L < 6$, and strong chorus waves were observed. Figure 2a shows the total electron density inferred using the upper hybrid line (black), and the partial electron density calculated using the electron flux measurements by LEP-e and MEP-e instruments. The total electron density is about 3 – 4 cm^{-3}, and the density for electrons at > 19 eV energies is $\lesssim 50\%$ of the total density.

Figure 2b shows the bursts of chorus waves with strong intensity below 0.5 f_{ce}. The wave normal angle of LBC is primarily field aligned (below 30°) (Figure 2c), and the wave normal angle of UBC is larger although the magnetic intensity is much lower than that of LBC. Figure 2d shows the integral wave amplitude of LBC and UBC at ~1 sec time cadence. The peak of LBC wave amplitude is higher than 500 pT, and the majority of the wave amplitudes are in the range of 50 – 500 pT. The amplitude of UBC wave amplitude is mostly below ~50 pT.

Figures 2e-f show the electron fluxes measured by MEP-e instrument at pitch angles outside the dipole loss cone and inside the dipole loss cone, respectively. The precipitating electron fluxes measured during 10:45 – 11:15 UT overall agree with the features reported by Kasahara et al. (2018a). Although the measurements inside the loss cone are not always available for the full energy range of 7 – 90 keV during this period, some high electron fluxes are correlated with the LBC wave bursts (e.g., during 10:47 – 10:49 UT, 10:52 – 10:57 UT, and 11:11 – 11:16 UT). The UBC waves during 11:10 – 11:12 UT may be associated with the precipitating electron fluxes at energies below 10 keV despite the limited measurements at low energies. Simulations are required to produce the full energy spectrum of precipitating electron fluxes due to the observed chorus waves.

Figure 3 shows the processed data of waves and electron fluxes which are used in the STET simulations. Because the time resolution of electron flux measurements by MEP-e is about 8 s, we averaged the chorus waves measurements in every ~8 s time window to unify the time cadence between waves and particles. The wave amplitude in ~8 s cadence is smoother in time and still shows the modulation of chorus wave bursts (Figure 3a). The electron flux measured outside the loss cone ("Trapped Flux") are interpolated in energy with a step of 1 eV (Figure 3b), which will be used as simulation input. The electron flux measured inside the loss cone ("Precipitating Flux") are also interpolated in energy with a step of 1 eV (Figure 3c), which will be used as comparison to the simulated electron fluxes in the loss cone. Considering the limitations of particle measurements inside the loss cone, data interpolation is performed to fill in the gaps of the measured precipitating flux as a function of energy (e.g., for ~15 – 45 keV energies during 0 – 2 min after 10:40 UT) to obtain a better coverage of precipitating electron measurements.

3. STET Code Setting

3.1 Time-dependent STET code

The Time-Dependent STET code to be used in this paper solves the gyro-average kinetic equation for electron energies above 1 eV and is well documented (Khazanov, 2011; Khazanov et al., 2021b). Applying this kinetic equation for the study of superthermal electron (SE) transport in the pulsating aurora this equation can be presented as

$$\frac{1}{v}\frac{\partial \Phi}{\partial t} + \mu\frac{\partial \Phi}{\partial s} - \frac{1-\mu^2}{2}\left(\frac{1}{B}\frac{\partial B}{\partial s} - \frac{F}{E}\right)\frac{\partial \Phi}{\partial \mu} + EF\mu\,\frac{\partial}{\partial E}\left(\frac{\Phi}{E}\right) = Q + \langle S\rangle\,, \qquad (1)$$

where the electron number flux $\Phi=2Ef/m^2$ is a function of time (t), s is the distance along the magnetic field, μ is the cosine of the pitch angle, E is the electron energy, and F is the electric field force. The right-hand side represents the source term Q due to photoionization and the loss terms $\langle S\rangle$ due to the various electron collisional processes. The collision terms in STET code include elastic collisions between charged and neutral particles, all non-elastic collisions between electrons and neutrals for the electron energies above of 1 eV, and wave-particle interaction (WPI) between the electrons and the whistler-mode chorus using the data presented in the Section 2. STET code can provide the full energy and pitch-angle distribution of SE along the closed magnetic field lines without interruption between the magnetosphere and the ionosphere, thus providing a useful tool to understand the MIA coupling dynamics in the auroral regions. STET is a well-established code developed and improved in the past few decades. A detailed derivation of these collisional and WPI terms is given in Khazanov (2011) and Khazanov et al. (2015) and all of them are explicitly presented in the recent papers by Khazanov *et al.* (2020, 2021b).

The multiple dissipation processes of magnetospheric electrons in aurora are associated with the cascading of high-energy electrons toward smaller energies and the production of secondary, tertiary, and further resultant electrons. Such ionization cascades can be treated with just a single kinetic equation that takes all the collisional processes into account and seamlessly propagate the solution of Equation (1) along the nonhomogeneous geomagnetic field lines in the presence of WPI processes and with participation of two magnetically conjugate regions of northern and southern hemispheres.

As it was discussed in the book by Khazanov (2011), it is convenient to change variables in (1) from (μ, s) to (μ_0, s), where

$$\mu_0(s) = \frac{\mu}{|\mu|}\sqrt{1 - {}^{B_0}\!/\!{}_{B(s)}\left(1-\mu^2\right)} \tag{2}$$

with B_0 and μ_0 denoting the magnetic field strength and the cosine of the pitch-angle at the magnetic equator of the flux-tube. After the change of variables, the mirror force in the equation of (1) disappears, and $\Phi(\mu_0, s)$ now becomes a slowly varying function with s that greatly reduces computational effects associated with approximating errors in the derivatives (see Khazanov (2011) for the details). Figure 4, adapted from the paper by Khazanov et al. (2015), represents the regions for the solution of kinetic equation (1) using different pitch angle variables connected by (2).

As we further discuss in Subsection 3.3, initiated electron precipitations from the magnetosphere to ionosphere-atmosphere region are driven by chorus wave activity presented in Figures 2, via their interactions with the trapped electrons that are shown in Figure 5. The boundary conditions were set up in velocity space above 19 eV (low energy limit of electron distribution function by Arase satellite observations) at the loss-cone (see red lines, μ_{LC} and μo_{LC} in the Figure 4). As time progresses, electron fluxes at this boundary change. As it was discussed by Khazanov et al. (2015), here we allow the communication between the initially trapped magnetospheric electrons (yellow region in Figure 4) and the electrons with the same energies that initially scattered by chorus waves to the atmosphere and return to magnetospheric equatorial plane through the loss-cone (blue region in Figure 4) after multiple backscatter and degradation precipitated electrons in both magnetically conjugated regions. In another word, we allow (as it's supposed to be) the magnetospheric electrons scattered by the atmosphere to communicate back and forth between the loss cone and trapped zones as they travel back to the magnetosphere and to the magnetically conjugate ionospheric regions, iterating the solution of (1) in (μ_0, s) variables at the lines of $\mp\mu_{ob}(s) = \sqrt{1 - B_0/B(s)}$ as discussed by Khazanov et al. (2015). The quantitative analysis of these effects for the different energies and pitch-angles was presented by Khazanov et al. (2017b) in their Figures 3-5.

The demonstration of this communication between the loss-cone and trapped regions also is presented below, in the Subsection 3.4, in the vicinity of Arase satellite location. In the presence of the strong chorus wave activity measured by Arase spacecraft (Figure 2), such an approach naturally includes the multiple atmospheric electron backscatter in magnetically conjugate atmospheric regions and an exchange between the loss-cone and trapped regions. Further, we assume that trapped electron fluxes presented in Figure 3, measured for the pitch-angles outside the loss cone, are isotropic and their energy distribution change in time and space as is shown at this figure.

The simulations that are presented below were performed in the tilted dipole magnetic field geometry as it is shown in Figure 5 and used the following inputs to the STET model. The neutral atmospheric model used is the MSIS-90 (Hedin, 1991). The plasma density structure in the ionosphere is based on the International Reference Ionosphere (IRI-2016) model (Bilitza et al., 2017), and extended into the magnetosphere based on electron density measurements presented in

Section 2. Cross sections for elastic collisions, state-specific excitation and ionization were taken from Solomon et al. (1988).

3.2 Quasi-Linear Modeling of Electron Diffusion

To describe the interaction of chorus waves with the trapped energetic electron population, we use quasi-linear (QL) diffusion collision term that is symbolically included in the kinetic equation of (1) as $\langle S \rangle$, as all others collisional processes of precipitated electrons with the cold plasma and the neutral atmospheric components. All these specific collisional processes are described in all details in the book by Khazanov (2010) and will not be repeated here. The only term that we must mention here is an *applicability* of QL theory in the description of trapped magnetospheric electron interaction with such a strong chorus wave activity measured by Arase satellite and presented in Figures 2b-d and 3a.

The QL theory assumes that the wave magnetic field is much weaker than the background magnetic field and the waves are broadband and incoherent (Kennel and Englemann, 1966). Following these assumptions, the particle phase space density evolution could be described as diffusive processes in the pitch angle and momentum spaces. The QL modeling is useful to evaluate the long-term (> 10 min) particle dynamics due to resonant interaction with plasma waves.

Large amplitude LBC waves in a broad frequency spectrum are observed during 10:40 – 11:20 UT (Figures 2b-c). The peaks of 8-sec average wave amplitude are about 500 pT, although the high amplitudes lasted for short timescales (Figure 3a). Gan et al. (2022) suggested that the difference between test-particle simulation which includes nonlinear effects and the quasilinear modeling is small for a broad band chorus with a wave amplitude less than 300 pT at $L = 6$, assuming that the wave normal angle is 0°. The threshold of wave amplitude may be higher than 300 pT if we consider a range of wave normal angle or the concurrent UBC wave activities. During this event, nonlinear interaction may have potential effects as the wave amplitude in 1-sec resolution reaches higher than 500 pT (Figure 2c), or at the times of 4 peak wave amplitudes (~500 pT) in 8-sec resolution (Figure 3a). However, the wave magnetic fields are much smaller than the background magnetic field (100 - 200 nT). In addition, the duration of the large amplitude chorus is very short. During the majority of the 40-min interval, the wave amplitudes are below 300 pT (Figure 3a), suggesting that the quasilinear theory is still applicable to simulate the overall features for most of the times.

To account for the potential variation of wave frequency spectrum and background parameters (total magnetic field strength at the equator B_0 and electron density N_e), we calculate the electron diffusion coefficients in every 10 min time interval of observations. Figure 6 shows the 10-min averaged observations of wave frequency spectrum, B_0, N_e, and wave amplitudes of LBC ($B_{\mathrm{w,LBC}}$) and UBC ($B_{\mathrm{w,UBC}}$). The 10-min averaged wave amplitudes are below the threshold of nonlinear effects by Gan et al. (2022). The wave frequency spectrum of LBC is relatively stable, and the UBC wave appears during the last interval. The observed wave amplitudes (Figure 3a) will be used to scale the diffusion coefficients to account for the temporal variation of LBC wave bursts and the UBC wave activity.

Using the wave frequency spectrum and parameters in Figure 6, we calculate the local diffusion coefficients from 0° to 20° magnetic latitude using the UCLA Full Diffusion Code (Ni et al., 2011;

Ma et al., 2018). Ten orders of harmonic resonances and Landau resonance are included in the calculation. The total electron density is assumed to be a constant from equator to 20° magnetic latitude. The diffusion code uses a dipolar magnetic field model with the magnetic field strength scaled to the observation at the Arase latitude. The wave normal angle (θ) is assumed to be quasi-field aligned. The wave magnetic power is assumed to be proportional to exp $(-(\frac{\tan\theta - \tan\theta_m}{\tan\theta_w})^2)$ with $\theta_m = 0°$ and $\theta_w = 30°$. The quasi-field aligned wave normal angle assumption is consistent with the observation in Figure 2c. Oblique chorus waves have been observed in the previous studies (e.g., Li et al., 2016), and their precipitation effects (Goyal et al., 2017, 2018) and the subsequent MIA energy interplay will be an interesting future study.

We computed the computed local diffusion coefficients which are inputs to the STET code. Figure 7 shows the pitch angle diffusion coefficients at selected latitudes (0°, 5°, 10° and 20°), representative for the major features of pitch angle scattering effects. The pitch angle scattering rates due to chorus waves at lower latitudes are higher for low energy electrons than the waves at higher latitudes. The waves at higher latitudes could be the dominant source of electron scattering at high energies. For example, the waves at 0° latitude are less efficient in scattering > 20 keV electrons than the waves at 20° latitude. The < 30 keV electron scattering rates by chorus waves at latitudes higher than 20° are much smaller than the waves within 10° latitude. The electron scattering by LBC slightly shifts to lower energies as time evolves from the first interval (10:40 – 10:50 UT) to the last interval (11:10 - 11:20 UT). The UBC effects are most evident during the last interval for the energies below 2 keV and pitch angles below 40° (Figure 7d). The diffusion coefficient variations during each 10-min interval will be incorporated in the STET simulations using the relation that $D_{\alpha\alpha} \propto B_w^2$.

3.3 The Simulation Scenario

The simulation scenario that is used below in the analysis of Arase satellite observation is like our previous STET code setting of aurora precipitation phenomena that, besides the chorus waves other magnetospheric waves were considered: electron cyclotron harmonics waves (Khazanov et al., 2015); time domain structures (Khazanov et al., 2021c), and hiss waves (Khazanov et al., 2022b). In the analysis presented in these papers chorus waves were also considered and their relative role in electron precipitation phenomenon was examined focusing on steady-state conditions.

Presented in Figures 1d-g and Figure 2 Arase satellite data are very dynamical, and their analysis requires the usage of a non-steady STET code formalism (Khazanov, 2011). This code was recently validated to analyze the electron precipitation temporal dynamics during two substorms on 16 February 2010 (Khazanov et al., 2022a), simulate the electron thermal heat fluxes during the Saint Patrick's Days 2013 and 2015 geomagnetic storms (Khazanov et al., 2023b), and explain the pulsating aurora event that was imaged optically at high time resolution by Samara et al. (2017). This measurement provided direct observational evidence of the interhemispheric electron bouncing phenomena, previously predicted by STET code (Khazanov et al., 2015) and now quantitatively explained by Khazanov et al. (2023a) using these high time resolution optical observations.

Figure 5, adapted from our previous studies, presents the simulation scenario of STET code in the analysis of Arase satellite observations on the time scale of 40 minutes as are shown in Figures 2-

3. Strong chorus waves (Figure 3a) in the equatorial plane of magnetosphere interact with the trapped electron fluxes measured outside the loss cone (Figure 3b) and create the electron precipitation into the loss cone. These fluxes are denoted in this figure as the *Precipitating Primary Fluxes* (large red and yellow arrows in Figure 5), have pure magnetospheric origin, and deliver their energy to both northern and southern magnetically conjugate regions at the same time. As it was discussed in our previous studies, some of the primary electrons that precipitate into the atmosphere are backscattered into the magnetosphere and are denoted as the *Primary Reflected Flux* in Figure 5. Impact ionization and collisions with neutrals cause the energy degradation of the primary electrons and the production of secondary electrons. The mixed population of primary and secondary (denoted as *Escaping Secondary Flux* (blue arrows in Figure 2)) electrons cascade toward lower energies and escape to the magnetospheric altitudes.

When these primary reflected and escaping secondary electrons move back inside the loss-cone to the magnetosphere, passing the region of intense chorus wave activity, some of these electrons are scattered back to the trap zone (yellow region in Figure 4), become trapped by the magnetic field, and move between the magnetic point of reflections while continually losing their energy colliding with the thermal electron populations, forming so-called *Returned Thermal Flux* that is shown in Figure 5 by purple arrow. Some of these primary reflected and escaping secondary electrons that ended up in the geomagnetic trap can be scattered back to the loss-cone and travel back and forth between the two magnetically conjugate regions, repeating these passes in the velocity and configurational spaces multiple times till they completely lose their energy.

All these processes that we discuss above are hidden in the experimental data and can be only revealed during the specific setting of the STET code. We used such an approach in the past to reveal the role of multiple backscatter atmospheric processes in the formation of electron precipitation in the diffuse aurora (Khazanov et al., 2017; 2021a). In these two studies, we were setting the specifically designed simulation scenarios of the STET code to clearly distinguish between the magnetospheric and ionospheric contributions to the precipitating electrons in the region of diffuse aurora. As it was demonstrated in these papers, atmospheric collisional processes, and the overall MIA energy circulation dynamics, with the participation of two magnetically conjugate hemispheres, play a very important role in the formation of electron energy fluxes that are coming from the magnetosphere. We refer readers to these studies in the connection with results presented in this manuscript.

Applying this simulation scenario to the analyses of Arase satellite observations, one should always keep in mind that trapped electron population presented in Figure 2e and used below in their interaction with strong chorus waves as shown in Figure 2b, already accounted for all above-mentioned processes. By using these data, one only hopes to verify the precipitated loss-cone electron fluxes that are shown for some of the energies in Figure 2f and have not been used in the setting of STET simulation scenario. These data only capture the electron precipitation when the angle between the center of the field of view of Arase satellite detector and the magnetic field is smaller than the local pitch angle of loss cone (~2°). STET code, however, has no restriction in the representation of precipitated electron fluxes and can reveal all precipitated fluxes entering upper ionospheric altitudes at all considered energies.

Proceeding to the STET simulated results presented in this manuscript that are associated with Arase satellite pulsating aurora observations we will return to this discussion above regarding the connection between the experimental and theoretical results.

3.4 Electron Dynamics in the Vicinity of Arase Satellite Location

To demonstrate some of our points presented in the previous subsection, let us discuss electron flux formation dynamics near the magnetospheric equatorial plane where Arase satellite was located. As we mentioned in Section 2 of this manuscript the chorus wave data (Figure 2b) were measured with time resolution of ~1 second. On the other hand, the particle measurement had the time resolution of ~8 seconds. Apparently, because of this, in the correlation analysis presented by Kasahara et al. (2018a), wave and particle observations do not always coincide. That is why for the consistency between the wave and particle data in all STET simulation presented below, we average wave data over the time interval of 8 seconds to match the time resolution of electron fluxes (Figure 3).

As we mentioned in the previous subsection, any particle experimental data include all these processes that are associated with the pulsating aurora formation we presented in Figure 5. Because the major focus in our manuscript is electron precipitation studies provided by Arase satellite observations, let us reveal the initial stage of particle as an exchange between the loss-cone and trapped zones as was shown and discussed in the Figure 4 in the vicinity of this satellite at the beginning of the measurements presented in Figure 3, at the time of 10.40.

Figure 8 shows three loss-cone energy-time spectral windows at pitch-angles of 0^o, 1.4^o, 2.11^o, along with the pitch-angle of 2.81^o located in the trapped zone, in proximity from the loss-cone boundary that is indicated in Figure 4 by red line. This figure represents an artificial STET run scenario when electrons that are driven to the loss-cone area via WPI processes stay in this region (blue area in Figure 4) bounce back and forth between the two of magnetically conjugate regions, without an exchange with the magnetospheric trapped population located in the yellow region of Figure 4. Previously such case was analyzed using steady state STET code simulations (Khazanov et al., 2017b) where all electron distribution function peculiarities that characterize pulsating aurora were completely missing.

Analyzing the dynamics in Figure 8, it is interesting to note that for 10s eV electrons, simulation results show that electron fluxes at 90-degree pitch-angles are smaller than those at lower ones inside the loss cone. The mechanism of such electron distribution function behavior is the following: the initially trapped high-energy electrons driven by WPI processes enter the loss cone, precipitate to the atmosphere and produce the secondary electrons in the energy range below 100 eV. As shown in Figure 5, these electrons precipitate to both magnetically conjugate regions and travel back and forth inside the loss cone, elevating initially smaller fluxes in this zone. The effect of elevated upward-moving electrons has been seen in our previous kinetic studies (Khazanov et al., 2014, 2017b, 2021a) and is consistent with FAST (Fast Auroral SnapshoT explorer) observations by Dombeck et al. (2018).

When precipitated magnetospheric electrons reach atmospheric altitudes in both magnetically conjugate regions, they lose some energy experiencing nonelastic collisions with atmospheric population and partly backscatter back to the magnetosphere from the northern and southern hemispheres (see Figure 5). As they travel back and forth between these two regions and cross the geomagnetic equatorial plane, the chorus wave activity that created electron precipitation to begin with to the atmosphere, partly scatter returning to the magnetosphere electrons back to the trap zone that represent the yellow region in Figure 4. Figure 9 that has the similar notation with Figure 8 represents the non-steady STET code simulation when an exchange between the loss cone and trapped zones are naturally considered. As we mentioned in the Section 3.1, the quantitative analysis of these effects for the different energies and pitch-angles was presented by Khazanov et al. (2017b) in their Figures 3-5.

Compared to the Figure 8, the latest plot shows the complexity in the electron precipitation dynamics that is one of the features of the pulsating aurora. It also shows returning from the atmosphere electrons that are trapped back to the magnetosphere. Apparently, some of the modulation of trapped magnetospheric electrons presented in Figures 3b and 9 partly represent the dynamics of magnetospheric electrons in the velocity space that corresponds to their multiple atmospheric backscatters in the magnetically conjugate regions (Khazanov et al., 2023a) as well as an exchange between the loss cone and trapped zones.

4 STET Code Simulated Results

Transitioning to the Arase satellite based non-steady state STET simulations, we note that all these results were obtained based on complete scenario of electron precipitation dynamics that we outlined in the Subsection 3.3 and presented in Figure 5. We also made time resolution of wave activity consistent with particle measurements by averaging wave data over the time interval of 8 second and restricted the upper energy range of simulated results to the auroral electron energies of 30 keV (Figure 3).

4.1 Precipitated Fluxes

The lower energy electron observations in the Arase satellite data that correspond to the trapped magnetospheric electrons starts with energies of 19 eV (Figure 1g). Based on the results of analysis by Khazanov et al. (2021a), this is the energy flux of ionospheric origin. In fact, as presented in the above-mentioned reference, the transitional energy between the electrons of ionospheric and magnetospheric origins depends on the shape of the distribution function of magnetospheric electrons and lies in the range of 200-400 eV. This fact confirms the electrons traveling in the velocity space and the exchange between the loss cone and trapped zones as was demonstrated in Subsection 3.4.

Now, let now us consider the electron precipitation that we mentioned in Section 2, organizing them in the logical loop of their formation as presented in the Figure 5. Figure 10a shows the experimental electron data outside of the loss-cone that are labeled as *Trapped Flux Observations*. These fluxes are presented for the time interval of 40 minutes with time resolution of 8 seconds from the beginning of this observational event, 2017-03-27/10:40, at the locations that are labeled on the bottom of Figure 2. Below Figure 10a, we show the corresponding to this time interval observations of wave data, Figure 10b, that were averaged over the 8 seconds to be consistent with particle observations and labeled as *Arase Waves Observations*.

Both Figures 10a,b represent the inputs to the STET code that initiate the *precipitating primary fluxes* and the follow-up electron precipitation dynamics and energy interchange in the velocity and configuration spaces as is shown in Figure 5 and described in details in Subsections 3.3 and 3.4. Because the electron and wave data before the time of 2017-03-27/10:40 are unavailable, the initial condition in the solution of (1) is assumed to be zero. Corresponding to the Figures 10ab measured by Arase satellite loss-cone energy fluxes are presented in Figure 10c on the same time interval with time resolution of 8 seconds and labeled as *Loss Cone Observations*.

Compared to the trapped electron flux observations shown in Figure 10a, the loss-cone fluxes presented in Figure 10c have restricted electron energy and time ranges. Here the hidden electron precipitated fluxes are attributed to the fact that they are only measured when the angle between the center of the field of view of the electron detector and the magnetic field is smaller than 2° (Kasahara et al., 2018a). These authors found good correlation between the chorus waves and loss-cone electron flux at the energy of 24.5 keV. This indicates that wave–particle interaction is indeed taking place, and it was concluded that combination of electron energy and wave frequency of 0.38–0.64 kHz satisfies the cyclotron resonance condition.

Kasahara et al. (2018a), in Figure 4 of their manuscript, discussed the variability in the quasi-parallel electron flux (pitch-angles 20^o-40^o) outside the loss cone and found it nearly stable compared to the dynamic modulation of the loss-cone fluxes and chorus waves power. This conclusion, however, regarding near stable electron flux variations in the trap zone is relevant only for the high energy electron fluxes above of about approximately 1 keV. Below these energies, as is shown in the Arase based data in Figure 2f, one also can see the strong modulated electron fluxes. We cannot to explain the dynamical nature of this low energy trapped electrons modulation and only speculate that such a temporal variability of these electrons is not only because of changes in the chorus wave activity presented in Figure 10b. The electron energy exchange between the loss-cone and trapped zones, that was discussed in Subsection 3.4 of this manuscript, in combination with their MIA coupling between the two of magnetically conjugate regions (Khazanov et al., 2023a) also can be involved in such a modulation of lower energy electrons.

Compared to the slow high energy electron viability in the trap zone, the precipitated electrons presented in Figure 10c follow the dynamic of chorus wave activity and their intensity visually correlate with the power of chorus waves that are shown in Figure 10b. For example, sharp drop of chorus wave intensity in the vicinity of 5 mins data (Figure 10b) leads to the corresponding drop of electron precipitated fluxes that covers the broad energy range of keV electrons. Also, the intensification of the wave activity in the vicinity of 25 minutes correspondingly leads to the increase the precipitated electron fluxes. Such tendencies in wave activity and precipitated high energy electrons remain to be the same when the loss-cone precipitations that are shown in Figures 10bc are available. The correlation between the chorus wave activity and precipitated electron fluxes is nicely demonstrated in the original study by Kasahara et al. (2018a) in their Figure 4, and our simulations results seems consistent with this data.

Finally, in this subsection we show the results of STET code simulation that are driven by the particle and wave data of Arase satellite measurements presented in Figures 10ab. Figure 10d presents loss-cone STET simulated results of electron precipitated fluxes. For convenience, these data are shown at the time and energies corresponding to the actual measurement of electron precipitation in Figure 10c when the angle between the center of the field of view of the electron detector and the magnetic field is smaller than 2°.

Note, as we discussed in the Section 2, here, in Figure 10c, we show electron precipitating fluxes that include their interpolation in small time areas of 0-4 mins and around 32 mins after simulation were started. This has been done for two reasons: 1. To validate interpolation technique presented in the Section 2 and provide to experimentalists the guidance of revealing some of the uncertain observational data, and 2. Find additional simulation scenario for STET code validation.

The general qualitative tendency of STET electron precipitation is in line with the experimental results and well correlated with behavior of chorus wave activity in Figure 10b. For example, sharp drop of chorus wave intensity in the vicinity of 5 mins data (Figure 10b) leads to the corresponding drop of electron precipitation fluxes, and the intensification of the wave activity in the vicinity of 25 minutes correspondingly leads to the increase the precipitated electron fluxes. These are very similar to the experimental results shown in Figure 10c. Quantitatively, however, the experimental and theoretical loss-cone fluxes have some differences. For example, one can observe in Figure 10d smaller fluxes (compared to Figure 10c) at the beginning of the simulation, that are related to the selected prehistory of electron fluxes which are assumed to be zero. This was done intentionally to demonstrate the electron flux precipitation development in the vicinity of the main phase of this magnetic storm. We also should not exclude the fact that the loss-cone at the altitudes of Arase satellite is very small, and the loss-cone measurement technique requires a very delicate analysis. As we discussed above, Kasahara et al. (2018a) mentioned that this "approach needs caution regarding contamination from electrons outside the loss cone, because a fraction of the field of view can extend outside the loss cone."

Interestingly to note here that the data presented in Figure 10c around 0-4 mins and 32 mins after simulation started, as results of interpolating loss-cone observational electron fluxes compare well with corresponding STET simulated fluxes in Figure 10d. The latter verifies the accuracy of interpolation procedure of these electron fluxes presented in the Section 2.

Continue with electron precipitation analysis, Figure 10e presents electron fluxes in time-energy domain that were "hidden" in Arase satellite experiment because the angle between the center of the field of view of the electron detector and the magnetic field was apparently *bigger* than 2°, that is required for the registration of loss-cone fluxes. Electron fluxes in this figure are also seen at the very low energies down to 1 eV. These fluxes are below the lowest measurable energy in the trapped fluxes, 19 eV, presented in Figure 10a and resulted from MIA energy interplay as was shown and discussed in Figure 5. One can see the clear correlation of this "missing" fluxes with the activity of chorus waves in Figure 10b; at the times of about 3, 6, 20, 27, and 35 observational minutes, when wave activity drops, the intensities of electron precipitation are dropping for all presented energies and at the same time.

The preliminary analysis of temporal variability of precipitated electron fluxes presented in Figures 10de shows the consistency of their periods with the auroral pulsations ranging from a few seconds to a few tens of seconds (e.g., Johnstone, 1978; Samara et al., 2017). In this manuscript, we do not consider any optical time-dependent emissions generated by the STET code simulations and assume that the electron energy flux, the major focus of our analysis, is roughly proportional to the total optical intensity of the aurora (Stenbaek-Nielsen et al., 1998).

As was discussed by Ozaki et al. (2018), coordinated Arase and Ground-based network observations (PWING) of a pulsating aurora provide the observational evidence that pulsating auroras reflect the rapid spatiotemporal evolution of the wave-particle interaction region on timescales of less than 1 s. As follows from their study the "intensity modulations of a pulsating aurora are clearly related to successive discrete chorus elements and also possibly associated with chorus subpacket structures at a time scale of tens of milliseconds". Another time scale that relates to the optical emission in the pulsating aurora is associated with the bouncing time of precipitated electrons between the northern and southern hemispheres (Khazanov et al., 2023a).

4.2 Global View of Electron Distribution Function

Continuing the discussion of Arase experiment, Figure 11 shows the global view of SE fluxes as a function of distance along the magnetic field line, and their velocity space characteristics associated with Arase experiment at three different selected times after the time of 2017-03-27/10:40. The first column presents SE omnidirectional fluxes along the magnetic field line from 150 km to the magnetic equator. The second column demonstrates pitch-angle/energy configurations at the magnetic equator, and the third column shows equatorial energy distribution for the pitch angles of 0º – 90º.

The simulation output and some plotting scales in Figure 11 are chosen in a way to survey and to show prominent features of electron distribution function. This includes irregular distance grids for the first column (y-axis) with finer spacing at lower distances, finer grids at lower energies in the second column (x-axis) and irregular pitch-angle intervals in the third column (x-axis). This, however, shows pretty accurate representation of the line plots that were created for the comparison of these results but not shown here. We refer reader to the similar approach that was used by Khazanov et al. (2022b) to verify similar representation of simulation results.

Figure 12 is very similar to the second and third columns in Figure 11, but instead of showing 2D pitch-angle-energy spectrogram, illustrates the 3D representation of electron distribution function. This figure shows the sharp gradients in the velocity space that are an indication of the potential sources of plasma instabilities (Mishin, 2019; Mishin and Streltsov, 2021) that are out of the scope of this manuscript.

Electron fluxes presented in Figures 11 and 12 are clearly modulated by activity of chorus waves presented in Figure 10b. Close to the energies of 10's eV such a modulation is less pronounced because electrons with these energies are of ionospheric origin (Khazanov et al., 2021a) coming to the magnetospheric altitudes after they experienced multiple collisional processes with the charged and neutral atmospheric populations.

4.3 Particle and Energy Fluxes Entering Upper Ionosphere

The STET simulated results presented in Figures 8-12 were focusing on the magnetospheric dynamics of electron distribution function, revealing some of its features that were hidden from the Arase satellite observations. The only results that are comparable with the data were loss-cone electron precipitated fluxes in Figures 10cd that covered a very restricted time-energy domain. As we discussed in the Subsection 4.1, qualitative tendency of loss-cone STET electron precipitation presented in Figure 10d are in line with the corresponding experimental results shown in Figure 10c, and well correlated with the behavior of chorus wave activity in Figure 10b. Quantitatively, however, the experimental and theoretical loss-cone fluxes have slight differences that could be related to the imperfection of selected theoretical approach that we used in our manuscript as well as the difficulties in the analysis of Arase satellite observations outside the trapped zone.

Now we present particle and electron energy fluxes that enter upper ionospheric altitude in the northern hemisphere at the altitude of 800 km. Figure 13 shows the time-energy spectrograms of directional downward (a), upward (b) particle fluxes, and their ratios (c). Downward fluxes, Figure 13a, are clearly modulated by equatorial wave activity presented in Figure 10b, and the upward fluxes, Figure 13b, generated well below 800 km via different kind of collisional processes, respond to this electron precipitation correspondingly, with the intensities proportional to the values of precipitated electrons.

In the energy region of about 100 eV and below, with the chosen upper limit of the bar in Figure 13c at 1.2, the saturation of the color of this plot indicates domination of upward flux over the corresponding downward one. Depending on the time and energy, the UP/DN ratio in this area vary from 1.2 to 7 (not shown here). This is consistent with previous theoretical (Khazanov et al., 2021a) and experimental (Dombeck et al., 2017) studies in the region of diffuse aurora and has a simple explanation (Khazanov et al., 2014) that is based on the collisional redistribution of precipitated electron fluxes that we discussed in the Section 3 and illustrated in Figure 5. Upward electron flux in this energy range (below 100-200 eV), at the altitude of 800 km, builds up by escaping secondary electrons and degrades to these energies of precipitating electrons of magnetospheric origin (with participation of two magnetically conjugate regions) that contribute to the upward fluxes after they experience elastic collisions with the neutral atmosphere.

Looking at the ratio presented in Figure 13c, one also can notice that at some of simulation times, this parameter exceeds the value of 1 in the high energy range, indicating domination of the upward fluxes well above of 100 eV, reaching energies of 10s keV. Such a situation cannot be explained by the energy redistribution as in the case in the region of diffuse aurora that was mentioned above. To explain this phenomenon, let us look at Figure 13c during simulation times about of 6, 19.2, and 27.3 minutes where such a ratio behavior is the most pronounced, and pay attention to the chorus variability presented in Figure 10b. Right before these times, the wave intensity sharply drops at the corresponding times of 5.5, 18.7, and 27 minutes. Because the precipitating fluxes and chorus wave activity are highly correlated, this leads to the decrease of downward flux with follow up decrease, *but with some time delay* of upward fluxes. Such a situation does not exist in the region of diffuse aurora and is only in the feature of the pulsating aurora.

Here we want to remind the reader again that in this manuscript, we do not consider any optical time-dependent emissions generated by the STET code simulations and assume that the electron energy flux, the major focus of our analysis, is roughly proportional to the total optical intensity of the aurora (Stenbaek-Nielsen et al., 1998). That is why we are using *pulsating aurora* terminology applying it to the variability of precipitating electron fluxes that are the source of the *real* optical emissions that are observed in the sky of auroral region.

To conclude this subsection, Figure 14 presents the histograms of total particle (a), energy (b), electron thermal (c) fluxes, and electron temperature (d) at the different moments of Arase satellite observations. Total particle and energy fluxes integrated over the energy range of 1eV – 30 keV based on the directional fluxes are presented in Figures 13ab. Compared to the differential electron fluxes, the total downward particle and energy fluxes always dominate their counterparts, the total upward particle and energy fluxes, during entire simulation time presented in Figures 14ab. At the time of 26.8 mins, after simulations started, particle and energy fluxes dropped in both directions when the chorus wave activity that is shown in Figure 10b sharply went down.

Two places in the manuscript by Kasahara et al. (2018a) provide discussions regarding the total energy fluxes that cause the pulsating aurora. In the main body of their paper, they noticed: “when the loss cone is filled, the measured electron energy flux in the atmosphere is sufficient to excite visible aurorae. Specifically, it is several times 10^9 keV cm^{-2} s^{-1} or several erg cm^{-2} s^{-1}—comparable to, but above, the threshold for visible aurorae (Yahnin et al., 1997)”. Further, in the METHODS section they estimated precipitating electron energy flux around the energy of 20 keV and “obtain a downward electron energy flux of about $5x10^9$ keV cm^{-2} s^{-1}, or 8 erg cm^{-2} s^{-1}.”

Unfortunately, Kasahara et al. (2018a) did not indicate the exact time of these measurements in their 40 minutes observational window. Our calculations presented above estimated the average energy flux over the entire time domain to be about 23.5 ergs cm^{-2} s^{-1} and from the Figure 14b one can see the downward electron energy flux about 8 erg cm^{-2} s^{-1} in the simulation time domain between 3 and 8 minutes.

The electron heat fluxes in Figure 14c were calculated by STET code as it was described in Subsection of 4.1 of recent publication by Khazanov et al. (2023b). They visibly correlate with the total energy fluxes of high energy electrons presented in Figure 14c, but their intensities are about three orders of magnitudes less than these values. As we have described in the Section 3, they are generated by trapped secondary electron population, always directed toward the upper ionospheric altitudes. These heat electron thermal fluxes are the major sources of electron temperature, Te, that is an important parameter in the determination of total integrated content of the ionospheric plasma. The value of Te is presented for the same simulated times in Figure 14d. This parameter was calculated based on the analytical relation between electron temperature and electron heat flux developed by Khazanov (2011), and is recently validated using DMSP observations (Khazanov et al., 2023).

5 Concluding Remarks

Multi-years lasting studies on the pulsating auroras suggested that this phenomenon forms as result of interactions between the magnetospheric keVs electrons and whistler-mode chorus waves. Relatively recently, however, Arase satellite observation reported the direct evidence for this process confirming in situ measurement of highly correlated precipitated electrons and chorus wave activity (Kasahara et al., 2018a). As shown in Section 2 of this manuscript, the chorus waves and precipitated electrons observed by Arase are very dynamic, and the data analysis of this mission requires the time-dependent simulation technique as it was briefly presented in Section 3.

This STET code provides the full energy and pitch-angle distribution of SE along the closed magnetic field lines without interruption between the magnetosphere and the ionosphere, thus providing a useful tool to understand the MIA coupling and time-dependent dynamics in the region of pulsating aurora. As it was mentioned above in Subsection 3.3, this code was recently validated to analyze the electron precipitation temporal dynamics during two substorms on 16 February 2010 (Khazanov et al., 2022a), simulate the electron thermal heat fluxes during the Saint Patrick's Days 2013 and 2015 geomagnetic storms (Khazanov et al., 2023b), and explain the pulsating aurora event that was imaged optically at high time resolution (Khazanov et al. (2023a). These STET code validations results ensure the analysis of Arase satellite observations presented in this manuscript. Comparison with the available electron precipitated fluxes from Arase mission shows clear similarity to the corresponding results of STET code simulation that are shown in Figures 10c-d.

To conclude our study, we must emphasize again that applying STET code simulation scenario to the analyses of Arase satellite observation, presented in Subsection 3.3, one should always remember that trapped electron population presented in Figure 10a and used in their interaction with strong chorus waves as shown in Figure 10b, already accounted for all processes that are considered in equation (1) and illustrated by Figure 5. By using these data, we only hoped to verify the precipitated loss-cone electron fluxes that are shown for some of the energies in Figure 10c and succeed in doing this as illustrated in Figure 10d. These data, however, only capture the electron precipitation when the angle between the center of the field of view of Arase satellite detector and the magnetic field is smaller than 2°.

STET code has no restriction in the presentation of precipitated electron fluxes and can reveal all precipitated fluxes entering loss-cone domain at all considered times and energies that are not available from Arase satellite observation. These results were revealed in Figure 10e with notation of "Hidden LC Precipitation in ARASE Experiment". The same can be said about all other Figures 11-14 that simply demonstrate the peculiarities of electron fluxes at magnetospheric and ionospheric altitudes that reveal some of the *not measurable* electron distribution features in the region of pulsating aurora.

Additional studies would be required to understand the spatiotemporal evolution of electron fluxes in the pulsating aurora provided by Arase satellite observations and their connection with the modulation source of the chorus wave activity.

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Data Availability Statement

Science data of the 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)). This study uses Arase MGF-L2 8 sec spin-averaged data v03_04 (10.34515/DATA.ERG-06001), PWE-OFA-L2 power spectrum data v02_01 (10.34515/DATA.ERG-08000), PWE-OFA-L3 wave property data v01_03 (10.34515/DATA.ERG-08003), PWE-HFA-L2 spectrum data v01_02 (10.34515/DATA.ERG-10000), PWE-HFA-L3 electron density data v03_07 (10.34515/DATA.ERG-10001), MEP-e-L3 3-D flux data v01_01 (10.34515/DATA.ERG-02002), LEP-e-L3 pitch angle distribution data of electron flux data v03_01 (10.34515/DATA.ERG-04003), and Orbit L2 v03 data (10.34515/DATA.ERG-12000). The Arase data for simulations and the computed diffusion coefficients data are available at the data repository https://doi.org/10.6084/m9.figshare.23643615.

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Figure Captions

Figures 1. Overview of the Arase measurements during the geomagnetic storm on 27 March 2017. (a-c) Geomagnetic indices of Sym-H, Kp and AE. (d) Wave electric power spectrogram measured by HFA instrument at 2 – 500 kHz frequencies, where the white dashed and solid lines are the local upper hybrid resonance frequency and electron gyrofrequency. (e) Wave magnetic power spectrogram measured by OFA instrument at 0.05 – 20 kHz frequencies, where the white solid, dashed and dotted liens are equatorial electron gyrofrequency (f_{ce}), 0.5f_{ce} and 0.05f_{ce}, respectively. (f) Wave Poynting flux angle of whistler-mode chorus waves. (g) Spin-averaged electron flux at 19 eV – 90 keV energies measured by LEP-e and MEP-e.

Figures 2. Detailed observation of chorus waves and electrons during a 40-min interval. (a) Total electron density (black) inferred using the upper hybrid resonance frequency and integral electron density (blue) using electron measurements by LEP-e and MEP-e. (b) Wave magnetic power spectrogram, where the white solid, dashed and dotted liens are f_{ce}, 0.5f_{ce} and 0.05f_{ce}, respectively. (c) Wave normal angle. (d) Wave amplitudes of LBC (black) and UBC (blue), and total magnetic field strength (red). (e) Average electron flux outside the loss cone measured by MEP-e instrument. (f) Average electron flux inside the loss cone, where the white area indicates the energies and times where the measurements are not available inside the loss cone. The electron fluxes inside or outside the loss cone are identified by comparing the pitch angle of measurements with the local loss cone pitch angle modeled by a dipole field geometry.

Figures 3. Processed data for STET simulation. (a) Wave amplitudes of LBC (black) and UBC (blue) and total magnetic field strength (red), averaged in every 8 sec, which is the same time cadence as the electron measurements. (b) Electron flux measured outside the loss cone pitch angle interpolated in energy with a step of 1 eV. (c) Same as (b) but for electron flux measured inside the loss cone, where the gaps of electron measurements at ~15 – 45 keV energies during 0 – 2 min after 10:40 UT are also filled through interpolation.

Figure 4. Regions where we solve the kinetic equation (1) using different pitch angle variables (left) μ and (right) μo, which are connected by equation (2). The blue region corresponds to the loss cone and the yellow region to the trapped zone, where lines illustrate the trajectory of bouncing particles. The loss cone/trapped zone boundary is shown in red. This figure is adapted and modified for the manuscript by Khazanov et al. (2017b).

Figure 5. The physical scenario for this paper illustrating MIA exchange and WPI interaction processes. WPI (orange) causes primary precipitation (large red and yellow arrows) which can ionize the neutral atmosphere and produce secondary electrons. Secondary electron fluxes can also escape (blue) and precipitate into the conjugate region. This figure is adapted and modified for the manuscript by Khazanov et al. (2023b).

Figures 6. Wave frequency spectrum, total electron density, magnetic field strength, and wave amplitudes of LBC (black) and UBC (blue), averaged during each 10-min interval of Arase observation. These parameters are used as inputs to calculate the local diffusion coefficients in Figure 7.

Figures 7. Local diffusion coefficients due to LBC and UBC waves as a function of equatorial pitch angle and energy, for each magnetic latitude and each time interval. The wave amplitudes are shown in Figure 6. To be used as inputs of STET simulation, the diffusion coefficients will be scaled using the measured amplitudes in 8-sec cadence (Figure 3a).

Figure 8. An artificial STET run scenario when electrons that are driven to the loss-cone area via WPI processes stay in this region bounce back and forth between the two of magnetically conjugate regions, without an exchange with magnetospheric trapped.

Figure 9. The non-steady STET code simulation when an exchange between the loss cone and trapped zones was considered.

Figure 10. The comparison of the Arase satellite data with STET code simulation as discussed in Subsection 4.1.

Figure 11. 2D global view of SE fluxes as a function of distance along the magnetic field line (a,d,g) and their velocity space characteristics (b,e,h; and c,f,i) associated with Arase experiment at three different selected times after the date of 2017-03-27/10:40.

Figure 12. 3D representation of electron distribution function, showing it's sharp gradients in the velocity space at four different selected times after the date of 2017-03-27/10:40.

Figure 13. Time-energy spectrograms of downward (a), upward (b) particle fluxes, and their ratios (c).

Figure 14. Total particle (a), energy (b), electron thermal (c) fluxes, and electron temperature (d) at different covered energy ranges for different moments of Arase satellite observations.