

A parametric study on how lightning-generated whistler waves propagate up into the magnetosphere

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Key Points:

- Lightning-generated whistler (LGW) waves with normal angles $>90^\circ$ launched at magnetic latitudes $>\sim 35^\circ$ can propagate into the magnetosphere.
- More LGW waves propagate into the magnetosphere when geomagnetic activity is enhanced.
- Simulations demonstrated that LGW waves are mainly distributed in the region of $L \sim 2\text{--}3$.

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Abstract: Lightning-generated whistler (LGW) waves leaking into the magnetosphere can efficiently scatter electrons into the atmosphere and produce a diffuse aurora. Here, we investigate the propagation of LGW waves by utilizing a numerical ray tracing model. The simulations indicate that the spatial distribution of an LGW wave exhibits two peaks: one in the ionosphere and the other within $L \sim 2\text{--}3$ in the magnetosphere. The ionospheric peak is due to the waves trapped in the ionosphere as they are emitted at low latitudes ($\lambda < \sim 15^\circ$) or as their initial normal angles are $\sim 90^\circ$. The magnetospheric peak is due to the waves propagating into the magnetosphere under the conditions of enhanced geomagnetic activity or at higher emission latitudes ($\lambda > \sim 35^\circ$). Moreover, the LGW waves propagating into the magnetosphere are finally confined to specific magnetic shells because the wave normal angle increases to the Gendrin angle near the reflection point, subsequently leading to field-aligned propagation. These findings refine current characterization of the propagation and distribution of LGW waves in the magnetosphere, contributing to quantifying the precipitation losses of electrons.

Keywords: lightning-generated whistler; ray tracing model; ionosphere; magnetosphere

1. Introduction

Lightning-generated whistler (LGW) waves are very low frequency electromagnetic emissions excited by lightning discharges on Earth (Santolík et al., 2009; Fiser et al., 2010; Graf et al., 2013; Starks et al., 2020). They generally propagate within the plasmasphere with right-hand circular polarization, and their frequencies are significantly below the local electron gyrofrequency along the propagation path (Guo MY et al., 2020). The magnetospheric plasma environment imparts strong dispersion to the LGW wave, causing higher frequency components to propagate much faster than their lower frequency counterparts. This characteristic manifests as a hook-shaped waveform in time–frequency spectrograms

(Wold et al., 2024).

Recent studies (Němec et al., 2010; Zheng H et al., 2016; Ripoll et al., 2020) have reported correlations between lightning activity and magnetospheric whistler waves, determined by combining Worldwide Lightning Location Network data with *in situ* satellite observations, such as DEMETER (Detection of Electro-Magnetic Emissions Transmitted from Earthquake Regions) in the top-side ionosphere and Van Allen Probes in the near-equatorial magnetosphere. These studies have consistently demonstrated that lightning activity significantly modulates electromagnetic wave intensity in the magnetosphere. The light energy not only is the primary driver of wave intensity above 2 kHz (Němec et al., 2010) but also strongly correlates with whistler-mode waves at low L shells ($L < 3$; Zheng H et al., 2016). Furthermore, a strong correlation exists between the spatial distribution of the lightning power and the amplitude of the LGW wave (Ripoll et al., 2020). The LGW wave amplitude attenuates in the $L < 2$ region owing to strong damping by the dayside ionosphere.

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The oblique whistler waves are reported to contribute to diffuse aurora precipitation (Ni BB et al., 2008; Thorne, 2010; Li T et al., 2023; Liu NG et al., 2023; Tripathi et al., 2023). For example, chorus waves can effectively scatter electrons into the loss cone, causing electron precipitation loss (Su ZP et al., 2009, 2010). As a branch of the whistler-mode waves, LGW waves have also been discovered to effectively scatter electrons into the loss cone via the cyclotron resonance mechanism (Jasna et al., 1992; Abel and Thorne, 1998; Blake et al., 2001; Bortnik et al., 2002; Rodger et al., 2003; Ripoll et al., 2015). These electrons precipitate along the geomagnetic field into the upper atmosphere, thereby producing lightning-induced electron precipitation (Jasna et al., 1992; Blake et al., 2001; Bortnik et al., 2002; Green et al., 2020). Rodger et al. (2003) has identified lightning-induced electron precipitation as an important mechanism responsible for the substantial loss of electrons in the inner radiation belt.

Lightning-generated whistler waves undergo a complex process to propagate from the ionosphere into the plasmasphere, fundamentally controlled by Snell's law. Previous simulations (Inan et al., 2007; Guo MY et al., 2020) have shown that LGW waves can be reflected at magnetic mirror points and will repeatedly traverse the magnetic equator in the absence of attenuation. The plasma-pause is a magnetospheric transition region characterized by a sharp gradient in cold plasma density, with its position and structure strongly controlled by geomagnetic activity. This boundary plays a decisive role in determining the propagation paths of whistler-mode waves (Guo MY et al., 2020). Lightning whistlers can be classified, based on their propagation paths in the magnetosphere, into ducted propagation, which is confined along the geomagnetic field lines (Carpenter, 1968), and nonducted propagation, which occurs under the influence of large-scale density gradients (Streltsov, 2021a, b, 2022; Xia ZY et al., 2024).

Because the LGW waves are a potential mechanism for scattering electrons in the inner magnetosphere, it is necessary to study their spatial distributions and propagation characteristics to deepen our understanding of the overall impact of LGW waves within the magnetosphere. In this study, we utilize a ray tracing technique to systematically examine the factors controlling LGW propagation.

2. Method and Model

We use a ray tracing program as in previous works (Horne, 1989; Xiao FL et al., 2007; Guo MY et al., 2020; Deng ZK et al., 2022, 2025; Zhang S et al., 2024). In this model, two right-handed orthogonal coordinate systems are defined. The Geocentric Coordinate System (OXYZ) is defined as a frame with its origin at the center of the Earth. Its Z-axis is aligned with the geomagnetic axis (positive northward), whereas the X-axis lies within the geomagnetic equatorial plane and is directed anti-sunward. The Y-axis completes the orthogonal triad, oriented in the dusk-to-dawn direction. The local magnetic field-aligned coordinate system (*pxyz*) is constructed as a frame at an arbitrary point *p*. Its z-axis is aligned parallel to the local geomagnetic field. The x-axis resides in the meridional plane (defined by the point *p* and the geomagnetic axis), directed anti-earthward. The y-axis completes the orthonormal basis through

the application of the right-hand rule. The propagation paths of the waves are determined by the Hamiltonian equations,

$$\frac{d\mathbf{R}}{dt} = -\frac{\partial D}{\partial \mathbf{k}} \bigg/ \frac{\partial D}{\partial \omega}, \quad (1)$$

$$\frac{d\mathbf{k}}{dt} = -\frac{\partial D}{\partial \mathbf{R}} \bigg/ \frac{\partial D}{\partial \omega}, \quad (2)$$

where $\mathbf{R}$ is the position vector of a point on the wave propagation path, ω is the wave frequency, $\mathbf{k}$ is the wave vector, *t* is the group time, and *D* denotes the dispersion relation of whistle. The dispersion relation formula used in the simulation is as follows:

$$\frac{c^2 k^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{\omega(\omega - \Omega_e \cos \theta)}, \quad (3)$$

where ω_{pe} is the plasma frequency, Ω_e is the cyclotron frequency, *c* is the speed of light, *k* is wavenumber and θ is the wave normal angle.

Some physically justified assumptions and parameters are used in ray tracing simulations. A dipole magnetic field model is adopted for the background magnetospheric configuration, maintaining validity within the inner magnetosphere, where the *L* shells are low. The background plasma density can significantly influence the propagation paths of LGW waves in the magnetosphere. A diffusive equilibrium (DE) plasma density model is adopted, and this model permits the superposition of an arbitrary number of magnetic field-aligned density structures, thereby enabling the simulation of diverse realistic density configurations (Angerami and Thomas, 1964; Kimura, 1966; Inan and Bell, 1977). In this model, the electron density is

$$N_e = N_b N_{de} N_{ii} N_{pl} \prod_{j=1}^k N_{d'}^j \quad (4)$$

where the coefficient N_b represents the reference density, typically $N_b = 3100 \text{ cm}^{-3}$, N_{de} represents the diffusive equilibrium model, N_{ii} models the ionosphere by creating a peak, N_{pl} models the plasmopause by creating the sharp density gradient, and N_d refers to the duct terms, which can be expressed as

$$N_d = 1 + d_d f_l f_r, \quad (5)$$

where d_d is the duct enhancement factor, the term f_l represents a one-sided duct and is used to roll off the density as a function of *L* beyond the duct center, and the term f_r controls the density gradient of the duct along the ambient magnetic field.

Specific mathematical formulations can be found in the work of Bortnik et al. (2011). In the DE model, we ignore the differences in electron distribution with magnetic local time as the reference, as in Angerami and Thomas (1964). Thus, the distribution of plasma density depends only on the temperature along the magnetic field line. Additionally, we focus on favorable conditions of the LGW (> 2 kHz) waves propagating upward without considering wave growth or damping, as in Thorne and Horne (1994). All propagation paths of the LGW waves we choose are launched in the ionosphere (*L* = 1.02 and magnetic local time [MLT] = 22), and the bottom of the ionosphere is defined as 90 km above the Earth's

surface. Calculation of the wave propagation path stops when it passes back through the ionosphere (height < 90 km) or out of the run time ($t > 10$ s).

In the following sections, we discuss the propagation characteristics of LGW waves at different levels of geomagnetic activity, which affect the position of the plasmopause. Therefore, the location of the plasmopause L_{pp} is estimated by an empirical formula $L_{pp} = 5.7 - 0.47 \times K_p$ in the DE model (Carpenter and Park, 1973). For the K_p indices of 2, 4, and 6, the plasmopause is located at $L = 4.76$, 3.82, and 2.88, respectively. The corresponding two-dimensional distributions of electron density in the magnetic meridian plane are shown in Figure 1. The dashed black line represents the plasmopause. With an increase in the K_p index and geomagnetic activity, the plasmopause shrinks toward the Earth and the range of high-density plasma obviously decreases.

3. Numerical Simulation

We perform the ray tracing simulations of the LGW waves with frequencies of 2, 3, and 6 kHz and initial normal angles of 90°, 150°, and 180° at the launched ionospheric latitudes of 15°, 35°, and 55°. The results are shown in Figure 1. The solid black line represents the ionopause determined by the DE model at 1.0981 R_E (Earth radii). The plasmopause typically located at $L = 4.5$ corresponds to the geomagnetic activity index $K_p = 2$. Emitted at low latitudes ($\lambda \sim 15^\circ$), most of the LGW waves with normal angles of 90°, 150°, and 180° cannot propagate out of the ionosphere, even when reflected repeatedly under the ionopause (Figures 2a, 2d, and 2g). Emitted at higher latitudes ($\lambda \sim 35^\circ$, $\lambda \sim 55^\circ$), the waves with a normal angle $\psi = 90^\circ$ remain trapped in the ionosphere; however, the waves with a normal angle $\psi = 150^\circ$ and 180° are capable of propagating into the magnetosphere. In addition, although the waves with a normal angle $\psi = 180^\circ$ launched at latitude $\lambda = 35^\circ$ can propagate into the magnetosphere, they are subsequently reflected back into the ionosphere (pink lines in Figures 2b, 2e, and 2h), unlike the propagation path of the waves launched at latitude $\lambda = 55^\circ$ (pink lines in Figures 2c, 2f, and 2i). Compared with the paths of 2, 3, and 6 kHz waves emitted at latitude $\lambda = 35^\circ$ and 55°, the waves with normal angles $\psi = 150^\circ$ and 180° are capable of propagating to the higher L shells as the wave

frequency becomes lower or the emitted latitude is higher. These results suggest that the propagation of LGW waves in the magnetosphere is determined not only by the refractive index but also critically by the emitted latitude and the initial wave normal angle.

To further quantify the path spatial distribution of LGW waves, we launch a number of LGW waves with normal angles ψ from 90° to 180° at three latitudes ($\lambda = 15^\circ$, 35°, and 55°) and subsequently track and count their propagation paths in the space. The spatial grids cover the magnetic latitudes from -60° to 60° and L shells from 1 to 5, with a resolution of 1° (magnetic latitude [Mlat]) $\times$ 0.1 (L). The path of a wave traversing the bins is counted only once. The statistical path spatial distributions of those waves are presented in Figure 3. The figure shows that the waves launched at a low latitude ($\lambda = 15^\circ$) concentrate within the vicinity of the ionosphere, with only a few of the waves with a frequency of 2 kHz leaking into the magnetosphere (Figures 3a, 3d, and 3g). However, the waves launched at middle ($\lambda = 35^\circ$) and higher ($\lambda = 55^\circ$) latitudes are mainly distributed in the magnetosphere (second and third columns). For those waves, the main distribution areas are covered in the L shell from ~ 2 to 3 and the Mlat from -60° to 60° (red patches in Figure 3). As the frequency increases from 2 to 6 kHz, the main distribution area is located at lower altitudes from the Earth but covered in wider L shells in the magnetosphere. Moreover, when launched at higher latitudes, those waves have wider spatial distributions; the main distribution areas are located at higher L shells in the magnetosphere as well. In addition, portions of the 2 kHz waves can propagate to regions of $L > 4$ owing to duct structures. In summary, the LGW waves can penetrate into the magnetosphere more efficiently as they are emitted at the middle and higher latitudes, but their spatial distributions present distinctions as the wave frequency varies from 2 to 6 kHz.

We further investigate the influence of geomagnetic activity on the propagation of LGW waves. By performing the wave path simulations and counting the propagation paths of the LGW waves, we obtain the spatial distributions of LGW waves with different frequencies at the three levels ($K_p = 2, 4, 6$) of geomagnetic activity. In this simulation run, the waves are launched at latitudes from 15° to 60°, and all propagation paths of those waves are

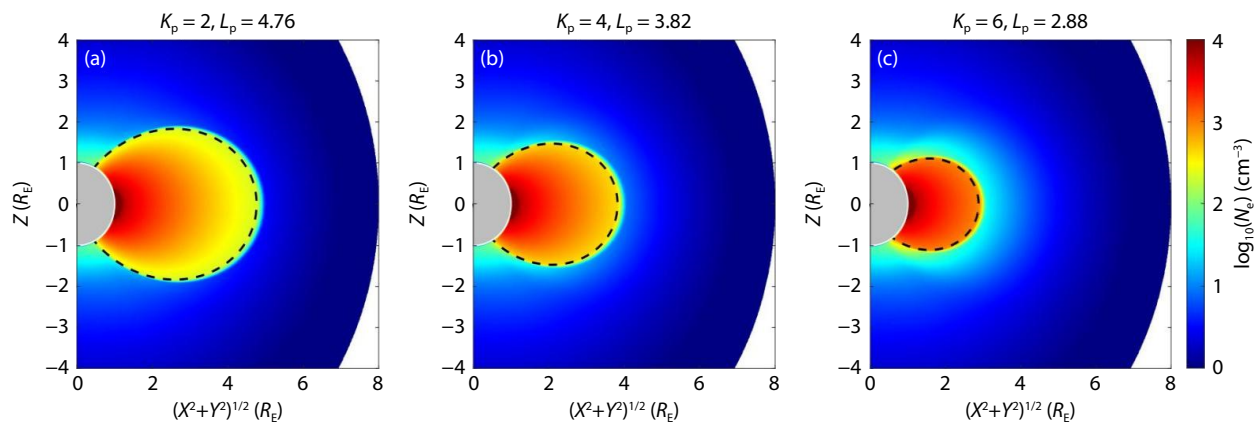


Figure 1. Distributions of electron density in the magnetic meridian plane for (a) $K_p = 2$, (b) $K_p = 4$, and (c) $K_p = 6$.

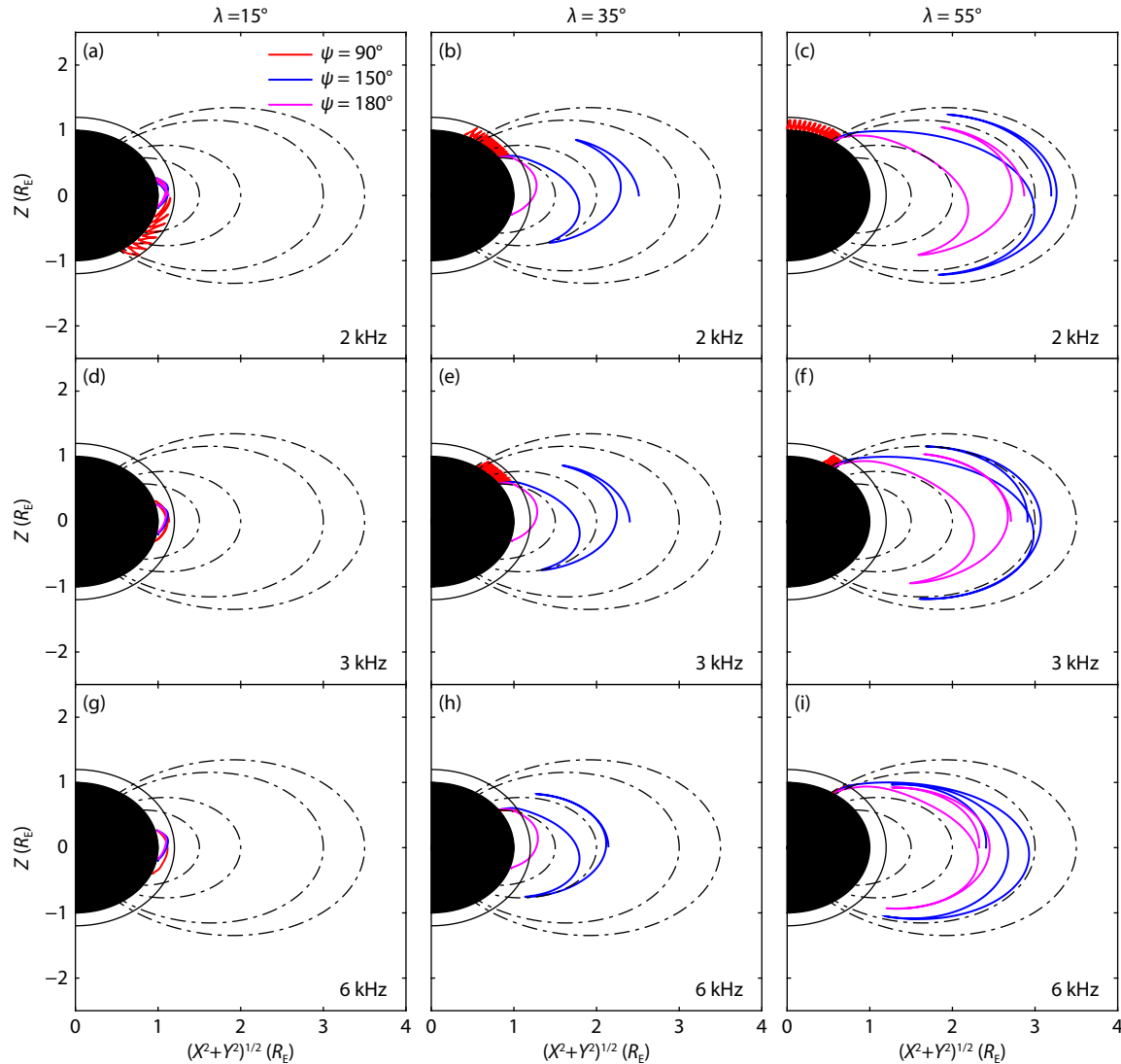


Figure 2. The propagation paths of LGW waves with frequencies of 2 kHz (first row), 3 kHz (second row), and 6 kHz (third row) launched at the three magnetic latitudes of 15° (first column), 35° (second column) and 55° (third column) in the ionosphere. The initial wave normal angles are 90° (red line), 150° (blue line), and 180° (pink line). The ionopause at 1.0981 R_E is shown by the solid black line. The dotted and dashed lines represent different L shells.

counted in the L -Mlat bins. The results are displayed in Figure 4, which illustrates that the LGW waves are predominantly distributed within two regions: one in the ionosphere (red patches near the Earth) and the other in the magnetosphere (red patches at $L \sim 2$ –3). As the K_p index increases from 2 to 6, more LGW waves propagate from the ionosphere into the magnetosphere at the middle and high latitudes. This result indicates that the LGW waves are capable of propagating into broader L shells in the magnetosphere as the geomagnetic activity is enhanced. However, the corresponding main distribution areas of the LGW waves are located at lower L shells, which is attributed to the plasmopause at lower L shells when geomagnetic activity is enhanced. As the wave frequency increases from 2 to 6 kHz, a similar variation trend can be observed. The 2, 3, and 6 kHz LGW rays exhibit similar propagation characteristics. However, their spatial distributions present a remarkable difference: the 2, 3, and

6 kHz LGW waves peak at $L = 2.5$ –3.0, 2.0–2.5, and 1.5–2.0, respectively. In the inner region ($L < 1.5$), the 2 kHz LGW shows a broader latitudinal spread (up to $\sim 60^\circ$) than that of the 3 and 6 kHz LGW waves.

To better understand the effect of geomagnetic activity on the distribution of LGW waves within the magnetosphere, the probability distribution of the propagation paths of the LGW waves observed in the L -Mlat bins is displayed in Figure 5. The figure presents the ratio of propagation paths observed within the bins to the total number of wave propagation paths. As shown in the figure, the LGW waves are primarily distributed in two distinct spatial areas: an asymmetric arc-shaped region near the boundary and a nearly symmetric fan-shaped structure confined to a range of L shells. The asymmetry of the arc-shaped structure is primarily attributed to the LGW waves emitted in the northern hemisphere. The waves observed in the symmetric fan-shaped regions make

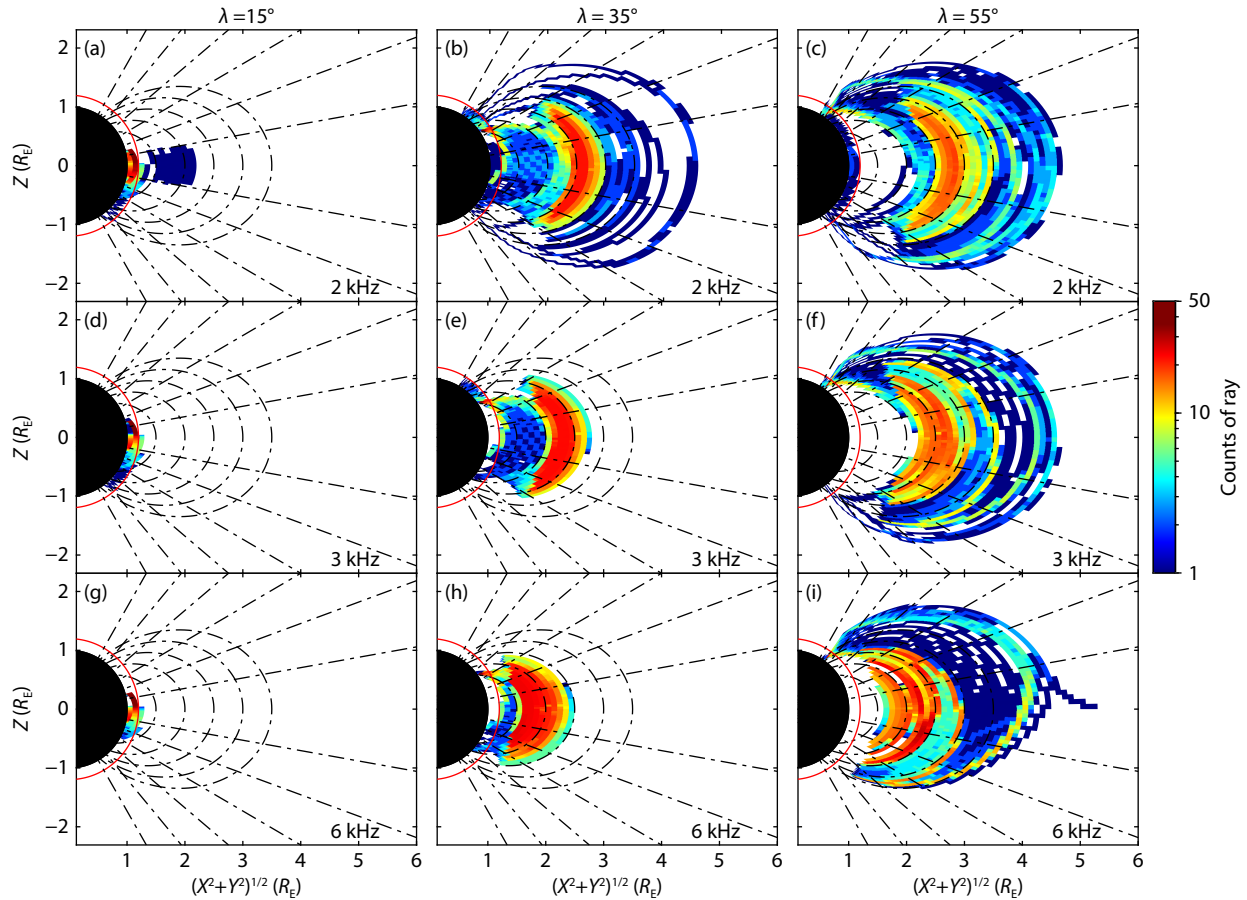


Figure 3. The propagation path distributions of LGW waves with frequencies of 2 kHz (first row), 3 kHz (second row), and 6 kHz (third row) launched at latitudes of 15° (first column), 35° (second column), and 55° (third column).

up ~90%. The locations and widths of the fan-shaped regions for the waves with different frequencies at three levels of geomagnetic activity vary as trends similar to the results in Figure 4.

The wave paths in Figure 2 first cross the magnetic field at large scales and finally are confined to the magnetic field-parallel structures in the magnetosphere. The waves mainly distributed in the fan-shaped regions in Figure 5 are also attributed to that propagation characteristic. To explain those features, we take the propagation path of a 2 kHz wave (Figure 6a) into the magnetosphere as an example to examine the path angles in two turning regions: In case 1, the path crosses the magnetic field at a large scale after the reflection in the magnetosphere, whereas in case 2, the path becomes nearly parallel to the magnetic field direction after the reflection. Theoretically, the turning behavior of the wave propagation path is governed by the ratio of the wave frequency (f) to the lower hybrid resonance frequency (f_{LHR} ; Kuzichev and Shklyar, 2013). The wave frequency f and lower hybrid resonance frequency f_{LHR} normalized to the f_{ce} are displayed in Figure 6b. This figure shows that $f < f_{\text{LHR}}$ at the first of several reflection points in the magnetosphere. Specifically, the first magnetospheric reflection corresponds to case 1, in which the refractive index surface remains closed (Figure 6c). Because the wave path direction is determined by the normal direction of the refractive index surface, the path direction of the wave maintains a substantial

angle with the background magnetic field, resulting in the crossing of the magnetic field on a large scale. Figure 6b also presents that $f \sim f_{\text{LHR}}$ after the first several reflection points, which corresponds to case 2. In case 2, as the wave frequency f approaches f_{LHR} , the refractive index of LGW tends toward infinity, resulting in the refractive index surface becoming open (Figure 6d). As shown in Figure 6d, as the wave propagates to the turning point, the wave normal angle increases to the Gendrin angle (Agapitov et al., 2011; Li W et al., 2011; Chen LJ et al., 2013) and the wave path becomes quasi-parallel to the magnetic field. In summary, local plasma conditions and the wave normal angle are important factors determining whether waves can cross the magnetic field at large scales. The features observed in the simulations (Figures 4 and 5) can be explained by the LGW wave propagation behavior described above.

The two-dimensional DE model utilized in this study successfully captures the primary propagation features of LGW waves in the meridional plane, as evidenced by the agreement with the statistical observations of He ZG et al. (2025). Nevertheless, it is worth noting that the underlying assumptions of the DE model (Angerami and Thomas, 1964) present certain limitations. For example, electron distributions on different field lines are independent, precluding any exchange of plasma across L shells. Neglecting loss processes other than field-aligned diffusion may

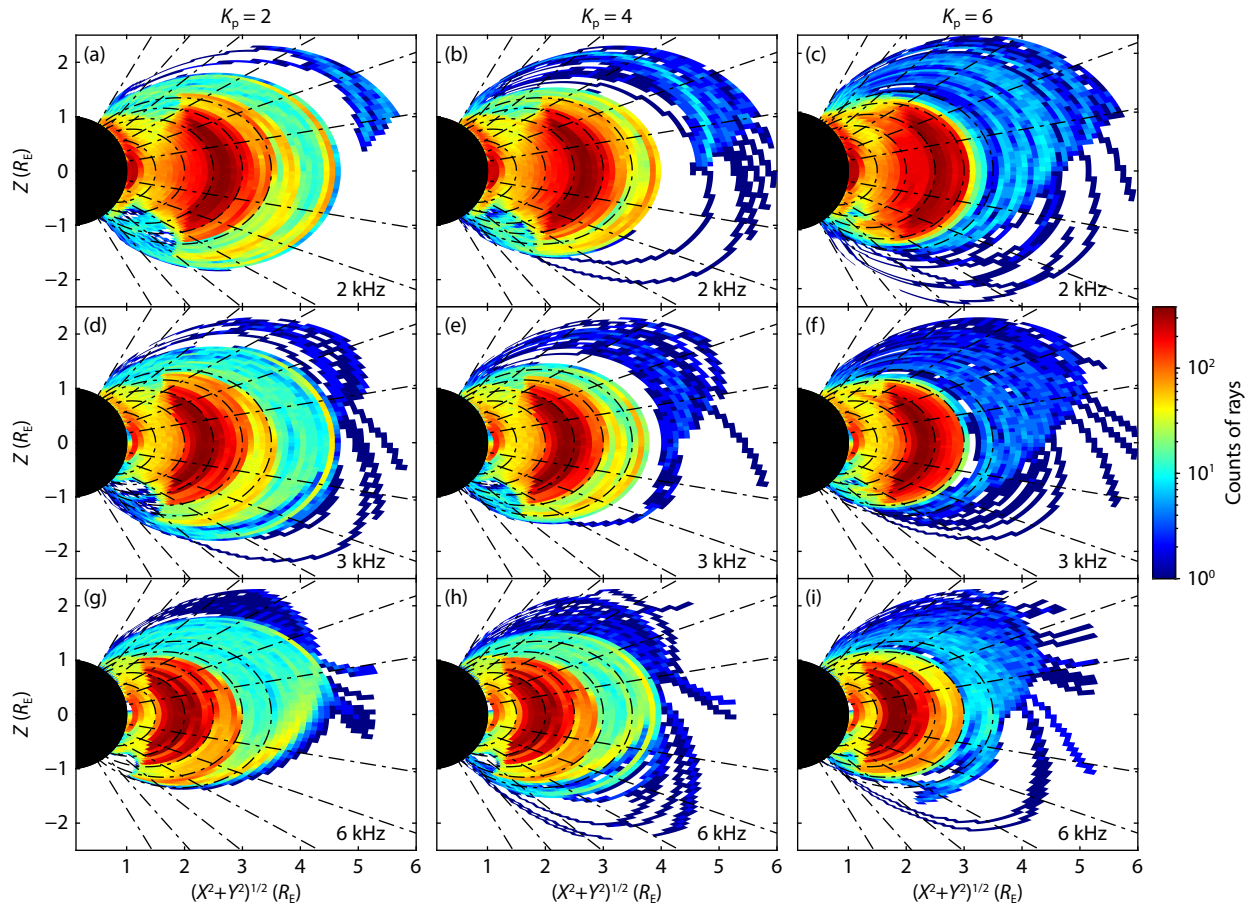


Figure 4. The propagation path distributions of LGW waves with frequencies of 2 kHz (first row), 3 kHz (second row), and 6 kHz (third row) at three levels of geomagnetic activity: $K_p = 2$ (first column), 4 (second column), and 6 (third column), respectively.

overestimate the electron density in certain regions. Consequently, the model does not account for MLT variations and cannot describe the full three-dimensional structure of the cold plasma density. Therefore, our results may not fully capture the complexities of the three-dimensional geophysical environment, which could potentially influence the distribution characteristics of LGW waves. For example, the plasmasphere often develops complex, nonaxisymmetric structures such as plumes (Su ZP et al., 2018; Wu ZY et al., 2022, 2024). In addition, we did not consider the effect of wave damping on the propagation path of LGW waves during the simulation, which may overestimate the spatial distribution of LGW waves and the probability of wave presence.

4. Conclusions

In this study, we investigated the propagation characteristics of LGW waves with different frequencies and wave normal angles in the magnetosphere. Considering the conditions of different emission magnetic latitudes and geomagnetic activity, we performed the ray tracing simulations of the LGW waves and obtained the results summarized below:

(1) The ray tracing simulations indicate that most of the LGW waves emitted at lower magnetic latitudes ($\lambda < 15^\circ$) are trapped in the ionosphere, whereas those waves launched at higher magnetic latitudes ($\lambda < 35^\circ$) are capable of propagating into the

magnetosphere, provided that the wave normal angles are greater than 90° . These results suggest that the propagation of LGW waves in the magnetosphere is determined not only by the refractive index but also critically by the emitted magnetic latitude and the initial wave normal angle.

(2) Numerical results of the path spatial distribution of the LGW waves suggest that those waves propagating into the magnetosphere are mainly distributed in the L shell from ~ 2 to 3 and the magnetic latitude from -60° to 60° . Moreover, as the wave frequency increases from 2 to 6 kHz, the main distribution areas are probably located at lower L shells but covered in wider L shells. Furthermore, the waves emitted at higher magnetic latitudes have wider spatial distributions, and the main distribution area is located at higher L shells in the magnetosphere. These results suggest that the LGW waves can penetrate into the magnetosphere more efficiently as they are emitted at higher magnetic latitudes or as their frequencies are relatively lower.

(3) The LGW waves are capable of propagating into broader L shells in the magnetosphere as the geomagnetic activity is enhanced. However, the corresponding main distribution area of the waves is located at relatively lower L shells, which is attributed to the plasmopause at lower L shells when geomagnetic activity is enhanced.

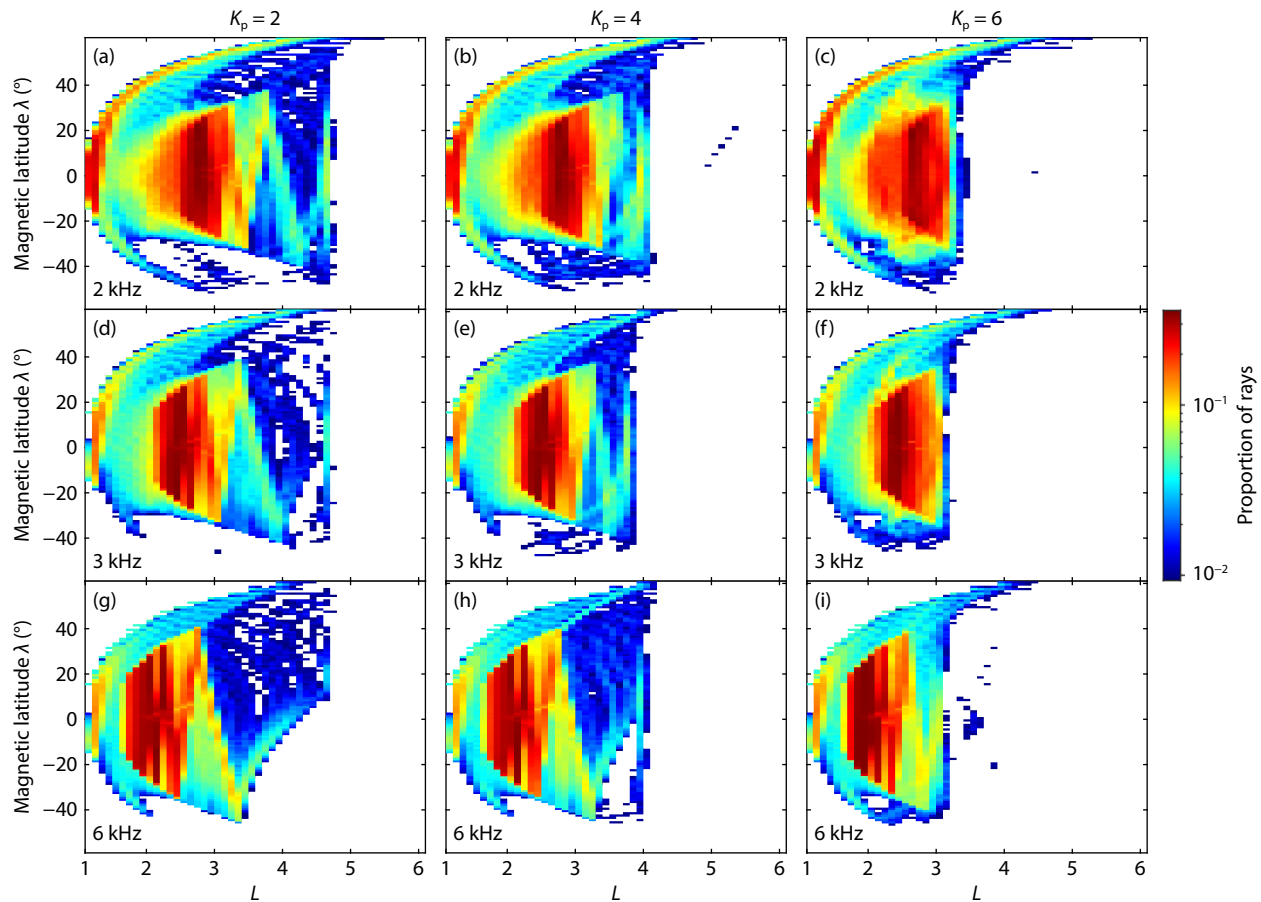


Figure 5. Probability distribution of the wave propagation paths at three levels of geomagnetic activity as described in Figure 4. The wave frequencies are the same as those in Figure 4.

The current results provide new insights into the propagation and distribution of LGW waves in the magnetosphere, which is helpful for quantifying the precipitation loss of electrons into the atmosphere and the contribution of LGW waves to a diffuse aurora.

Acknowledgements

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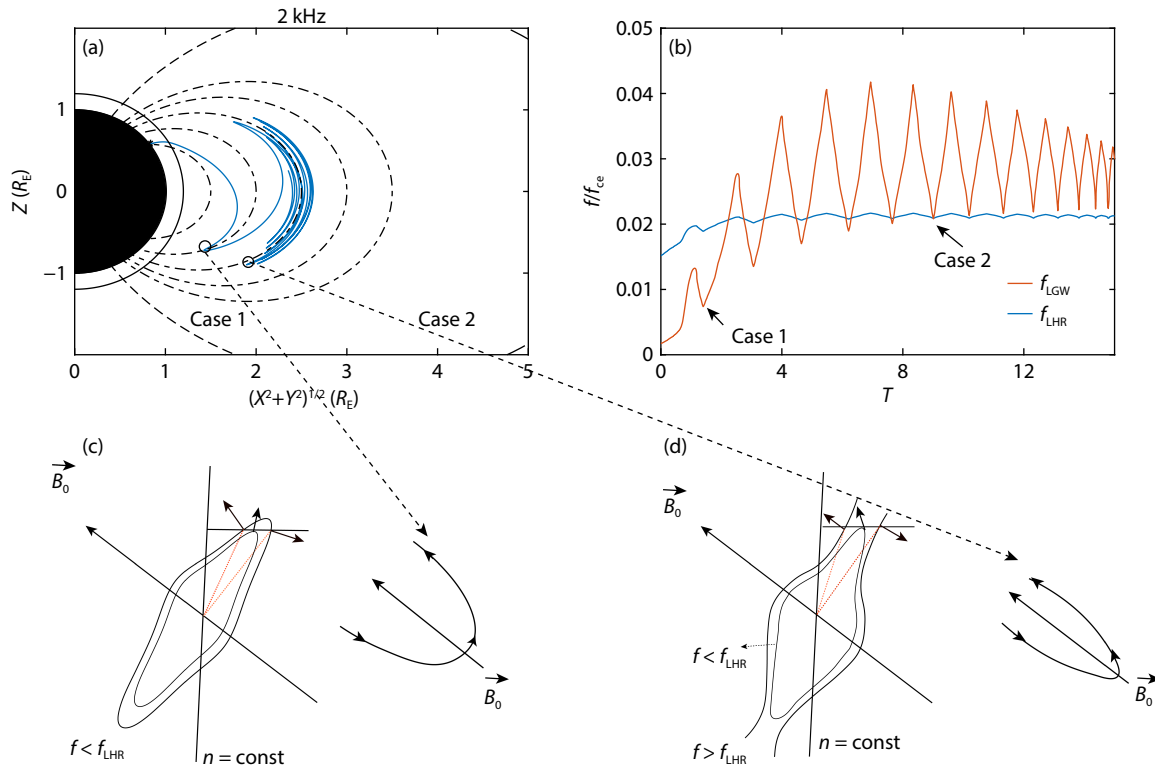


Figure 6. The propagation path of a 2 kHz wave emitted at magnetic latitude 40° is presented in (a). The wave frequencies f and f_{LHR} are normalized by the local electron cyclotron frequency f_{ce} (b). The schematic diagrams illustrate two distinct propagation behaviors: cases 1 (c) and 2 (d) of the path shown in (a). The curves without arrows depict refractive index surfaces, whereas the arrows represent directions of the path at different turning points. The red lines indicate wave normal angles.

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