Properties of Lightning Generated Whistlers Based on Van Allen Probes Observations and Their Global Effects on Radiation Belt Electron Loss

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Key Points

- Lightning generated whistlers (LGWs) are preferentially observed between 100s Hz and 10 kHz with the majority of wave power below f_{LHR}.
- Wave amplitudes of LGWs typically range from a few to tens of pT, peaking at $L < 3$ on the nightside with an occurrence rate of up to ~30%.
- The newly constructed statistical properties of LGWs are adopted to evaluate their global effects on the radiation belt electron loss.

Abstract

Lightning generated whistlers (LGWs) play an important role in precipitating energetic electrons in the Earth's inner radiation belt and beyond. Wave burst data from the Van Allen Probes are used to unambiguously identify LGWs and analyze their properties at $L < 4$ by extending their frequencies down to ~100 Hz for the first time. The statistical results show that LGWs typically occur at frequencies from 100s Hz to 10 kHz with the major wave power below the equatorial lower hybrid resonance frequency, and their wave amplitudes are typically strong at $L < 3$ with an occurrence rate up to ~30% on the nightside. The lifetime calculation indicates that LGWs play an important role in scattering electrons from tens of keV to several MeV at $L <$ ~2.5. Our newly constructed LGW models are critical for evaluating the global effects of LGWs on energetic electron loss at $L < 4$.

Plain Language Summary

After initial lightning strikes, a type of plasma wave is generated, typically referred to as a lightning generated whistler (LGW), a portion of which can propagate into near-Earth space. These waves can interact with the trapped energetic electron population in the Earth's radiation belts, causing pitch angle scattering, and thus play an important role in energetic electron loss into the Earth's upper atmosphere. Using high-resolution wave burst data from the twin Van Allen Probes over the entire Van Allen Probes era (2012–2019), we evaluate the typical properties and global distributions of LGWs. The newly constructed LGW models are used to quantify their global effects on energetic electron loss in the near-Earth space and indicate that LGWs play an important role in scattering electrons over a broad energy range (tens of keV to several MeV) in the inner radiation belt and beyond.

1 Introduction

Lightning-generated whistlers (LGWs) are coherent waves spanning the Extremely-Low-Frequency (ELF) and Very-Low-Frequency (VLF) band, that are injected from the troposphere after lightning strikes (Norinder and Knudsen, 1959). After generation, LGWs can propagate into the Earth's magnetosphere, either in the ducted mode (with wave vectors pointing nearly along the geomagnetic field lines) or unducted mode (with oblique wave normal angles), to form magnetospherically reflected (MR) whistler trains (e.g., Bortnik et al., 2003a; Edgar, 1976; Lauben et al., 2001; Smith and Angerami, 1968). After propagating out to the magnetosphere, these LGWs are known to migrate to a preferred L-shell region and subsequently settle on a particular L-shell where the wave frequency is approximately equal to the equatorial lower hybrid resonance frequency (f_{LHR}) (Bortnik et al., 2003a; Ristic-Djurovic et al., 1998; Thorne and Horne, 1994). LGWs are mostly contained within the plasmasphere with much weaker wave power outside the plasmapause (e.g., Bortnik et al., 2003b; Oike et al., 2014). Moreover, since the ionospheric attenuation of LGWs is much stronger on the dayside due to the collisional D-region (Helliwell, 1965), LGW wave power is known to be stronger on the nightside than on the dayside in the Earth's magnetosphere (e.g., Colman and Starks, 2013; Nemec et al., 2010; Ripoll et al., 2020).

Statistical analyses have been performed to reveal the global distributions of LGWs either from ground-based observations (Smith et al., 2010), or from satellites (Agapitov et al., 2014; Oike et al., 2014; Ripoll et al., 2020; Zahlava et al., 2018, 2019), or inferred from a proxy based on lightning flash rates (Colman and Starks, 2013). However, since LGWs often coexist with hiss, which is primarily observed at < 2 kHz (e.g., Li et al., 2015; Meredith et al., 2004, 2018), previous statistical studies only analyzed the LGW properties above ~2 kHz by assuming that wave power in this frequency band mainly comes from LGWs (e.g., Colman and Starks, 2013; Meredith et al., 2007; Nemec et al., 2010; Ripoll et al., 2020). However, LGW wave power is often observed to extend below 2 kHz, down to a few hundred Hz (e.g., Santolik et al., 2009; Zahlava et al., 2018, 2019). Therefore, to achieve a complete understanding of LGW spectral properties, it is critical to include wave power over a broad frequency range (~100 Hz to a few tens of kHz).

LGWs have been demonstrated to play an important role in precipitating radiation belt electrons through pitch angle scattering in the inner belt and beyond (e.g., Abel and Thorne, 1998; Albert et al., 2020; Blake et al., 2001; Bortnik et al., 2002, 2006a, b; Inan et al., 2007, 2010; Rodger and Clilverd, 2002; Voss et al., 1984, 1998). Direct observations of lightning-induced electron precipitation measured by VLF sensing, satellites and rockets have been reported in case studies (Goldberg et al., 1986; Inan et al., 2007; Johnson et al., 1999; Rycroft, 1973; Voss et al., 1984). While the effects of LGWs on energetic electron scattering have been evaluated based on the wave power above a few kHz (Abel and Thorne, 1998; Albert et al., 2020; Starks et al., 2020), their accurate global effects based on the realistic wave properties (e.g., by including the wave power down to ~100 Hz) need further investigation.

In the present study, by analyzing high-resolution waveform data from the Van Allen Probes, we are able to unambiguously identify LGWs over a broad frequency range from 100 Hz to 10 kHz, and thus provide the detailed LGW wave properties on a global scale in the near-equatorial magnetosphere. We also use the newly constructed wave properties of LGWs to calculate electron pitch angle diffusion coefficients and lifetimes, which are critical to quantify their global effects on energetic electron loss in the inner belt and beyond.

2 Detection of LGWs Using the Van Allen Probes Wave Observation

To evaluate typical wave properties of LGWs, we analyze the wave burst data from the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) wave instrument (Kletzing et al., 2013) onboard the twin Van Allen Probes, which were orbiting in the near-equatorial plane with the apogee of ~5.8 Earth Radii (Mauk et al., 2013). The wave burst data provide full waveforms in both electric and magnetic fields with a sampling rate of ~35 kHz, with each wave burst lasting for ~6 s (Kletzing et al., 2013).

Figure 1 shows two representative examples of LGWs with decreasing wave frequency with time observed within 15° of the magnetic equator. Figure 1 (left) shows LGWs with the peak wave power at a few kHz and a duration of ~1 s at L ~ 1.9 and 2.9 h in magnetic local time (MLT), and Figure 1 (right) shows LGWs with the peak wave power occurring below 1 kHz at L ~ 1.9 and MLT ~ 15.6. For the waveform data, we performed the Fourier transform for each 1024 data points (~0.029 s) and used a sliding window with 512 data points to calculate wave electric and magnetic spectra, which have the time resolution of ~0.0145 s and the frequency resolution of ~34.1 Hz. Wave polarization properties (panels d and j: wave normal angle; e and k: ellipticity) were calculated using the Singular Value Decomposition method based on the three components of wave magnetic fields described by Santolík et al. (2003). The wave normal angles of most LGWs, shown in Figure 1d, were relatively small (< ~30°), indicating that they were in the ducted mode. However, LGWs shown in Figure 1 (right) were in the unducted mode with large wave normal angles (> ~70°). All LGWs exhibited the ellipticity close to 1 (Figures 1e and 1k), which is expected for right-hand polarized LGWs.

Since plasmaspheric hiss is often observed from tens of Hz to several kHz (Li et al., 2015; Meredith et al., 2004, 2018), it naturally often overlaps with LGWs. We thus identified the LGWs, which typically exhibit discrete structures in contrast to broadband hiss using the following criteria at $L < 4$.

1) Exclude the regions outside the plasmapause to remove chorus waves. Since $L < 3$ resides mostly inside the plasmasphere over the Van Allen Probes era, we exclude the regions outside the plasmapause over $3 < L < 4$, where the electric wave amplitude of electrostatic electron cyclotron harmonic (ECH) waves integrated from electron cyclotron frequency (f_{ce}) to 50 kHz is larger than 0.0005 mV/m (e.g., Meredith et al., 2004).
2) Calculate the median magnetic spectral density and median electric spectral density for each frequency band (which is achieved after performing the Fourier transform for the magnetic/electric waveform data) over each 6 s duration of wave burst data.
3) Select the time-frequency bins in which both magnetic spectral density and electric spectral density are at least 8 times of the median spectral density at that frequency band.
4) Among the selected time-frequency bins, further identify the bins with ellipticity ≥ 0.7.

After applying the above criteria, the identified LGW bins are shown in Figures 1c and 1i, indicating reasonable detections of LGWs. We further calculated the magnetic wave amplitude of LGWs by integrating the filtered magnetic wave spectral density from 100 to 10,000 Hz, indicating a variation from a few pT to several hundred pT (Figures 1f and 1l). It is important to note that compared to the statistically averaged LGW wave amplitude of a few pT (e.g., Agapitov et al., 2014; Ripoll et al., 2020), the wave amplitude of the LGWs could be very large, up to several hundred pT (Figures 1f and 1l). It is also noteworthy that the third criterion may cause our algorithm to identify bins with LGW wave power significantly above the noise floor or coexisting hiss wave power, and thus exclude very weak LGWs. In particular, this algorithm may work less well at lower frequencies due to the higher background noise floor. Nevertheless, the advantage of this algorithm is being able to unambiguously identify LGWs from hiss and other waves. After automatic detection, we further removed events which are misidentified as LGWs (e.g., a small portion of hiss and chorus) by visual inspection for all identified LGW events.

3 Statistical Results: Global Distribution and Wave Properties of LGWs

Using the above criteria, all LGWs events were identified based on the wave burst data from both Van Allen Probes A and B during the entire Van Allen Probes era of 2012–2019 at $L < 4$. Due to the near-equatorial orbits of the Van Allen Probes, the collected data were naturally restricted to be within 20° of the magnetic equator.

Figure 2 shows the statistical results of LGWs sorted by L-shell and MLT (0.1 L × 1 h MLT). Note that the L-shell and MLT values were obtained using the IGRF magnetic field model (Thebault et al., 2015), which is reasonable at $L < 4$. Figure 2a presents the total observation time of wave burst data collected by both Van Allen Probes. The particularly high values at $L < 1.5$ in the premidnight sector are related to the combination of planned activities including a lighting campaign, a spread F campaign, and conjunctions with the ERG (or Arase) satellite (Miyoshi et al., 2018), where many long-duration continuous wave burst data were collected. The root-mean-square (RMS) magnetic wave amplitudes of LGWs were calculated during all intervals when wave burst data were available (assuming 0 pT for the time intervals when LGWs were not detected). The global distribution of LGW wave amplitudes (Figure 2b) indicates that LGWs are typically strong up to $L \sim 3$ peaking at $L < 2$. The wave intensity is stronger on the nightside than that on the dayside, which is consistent with the previous results (e.g., Colman and Starks, 2013; Nemec et al., 2010; Oike et al., 2014; Ripoll et al., 2020). The occurrence rate of LGWs is defined as the ratio between the duration of the time intervals when LGWs are detected and the duration of the entire time intervals when wave burst data are available regardless of the presence of LGWs. The occurrence rate of LGWs (Figure 2c) is larger on the nightside at $L < 3$ with the peak occurrence rate of ~30%. Figures 2d, 2e, and 2f show the occurrence rate of weak (2–10 pT), modest (10–50 pT), and strong (> 50 pT) LGWs. Weak LGWs (Figure 2d) occur up to ~20% at $L < 2.5$; modest LGWs (Figure 2e) occur up to ~10% at $L <$ ~2; large amplitude LGWs (Figure 2f) are mostly observed at $L < 2$ with an occurrence rate up to a few %. It is noteworthy that the global distribution of the RMS wave amplitudes (particularly the *L*-MLT bins with the strong amplitudes), as shown in Figure 2b, is similar to that of the occurrence rate for the modest (Figure 2e) and the large amplitude LGWs (Figure 2f), likely due to the significant contribution of wave power from relatively strong LGWs.

Figure 3 shows the statistical LGW wave properties as a function of *L*-shell and frequency after merging wave data from all MLTs. The distribution of satellite time, when Van Allen Probes recorded spectral bins as LGWs in the frequency-*L* domain (Figure 3a), indicates that the majority of LGWs are observed at $L < 3$, with frequencies between a few hundred Hz and 10 kHz. Figure 3b shows median values of LGW wave normal angles, which typically range between 20° and 75°. Interestingly, LGWs between 0.25 f_{LHR} and 0.1 f_{ce} are observed to be highly oblique (60°–75°) at $2 < L < 4$, where f_{ce} is the equatorial electron cyclotron frequency calculated using the dipole magnetic field. Wave normal angles show intermediate values (30°–50°) at $L < 2$ and at frequencies below 0.25 f_{LHR} over $2 < L < 4$, where f_{LHR} represents the equatorial lower hybrid resonance frequency, which is approximately equal to $f_{ce}/43$ in this region where the electron plasma frequency is larger than the electron cyclotron frequency. Overall, the majority of LGWs show oblique wave normal angles, indicating that they propagate preferentially in the unducted mode, consistent with the previous statistical results of oblique wave normal angles over 40°–90° (Jacobson et al., 2019). However, wave normal angles tend to be small at frequencies above 0.1 f_{ce}, although not many LGWs are detected in this frequency range (Figure 3a). Figures 3c and 3d show the average magnetic and electric spectral densities, respectively. It is important to note that we used zero values to fill in the spectral bins, which were not identified as LGWs, and used all spectral bins during the periods when waveform data were available (regardless of the presence of LGWs) to calculate the average values shown in Figures 3c and 3d. Both magnetic and electric spectra show that the majority of wave power is concentrated below f_{LHR} with decreasing wave frequency with increasing *L*-shell, the trend of which is consistent with previous studies (e.g., Bortnik et al., 2003a; Ristic-Djurovic et al., 1998; Thorne and Horne, 1994; Zahlava et al., 2019). At low *L*-shells (< ~2.3), the peak magnetic wave power (Figure 3c) spreads over a broad frequency range from several hundred Hz to several kHz. However, it is important to note that the peak magnetic wave power is observed below 1 kHz over *L*-shells of 2.3–3, which is likely due to the much longer lifetime of low-frequency LGWs than that of high-frequency ones (Bortnik et al., 2003b). The pattern of wave spectra appears to be shifted to the higher frequencies for the electric spectra (Figure 3d) compared to the magnetic spectra (Figure 3c), since the wave normal angles of the lower-frequency LGWs tend to be smaller than the higher-frequency ones (Figure 3b). For the constructed magnetic spectra and wave normal angle distribution of LGWs at various *L*-shells, we fitted them using analytical functions, as shown in Figures S1 and S2 and Tables S1 and S2 in the

Supporting Information. These newly constructed statistical wave properties are helpful for evaluating the global effects of LGWs on energetic electron dynamics at $L < 4$.

4. Calculation of Electron Pitch Angle Diffusion Coefficients and Lifetimes

Electron pitch angle diffusion coefficients are calculated based on the newly constructed spectral properties and wave normal angle distribution of LGWs using the Full Diffusion Code (Ma et al., 2016; Ni et al., 2008), by considering the cyclotron resonances up to ± 10 and including the Landau resonance. To evaluate the relative importance of LGWs for energetic electron loss, the calculated pitch angle diffusion coefficients of LGWs are further compared to those of plasmaspheric hiss and VLF transmitter waves, both of which are known to be important for energetic electron dynamics in the slot region and beyond (Abel and Thorne, 1998; Claudepierre et al., 2020a; Lyons and Thorne, 1973; Meredith et al., 2007). When calculating pitch angle diffusion coefficients, we use the total electron density model based on Ozhogin et al. (2012) and a dipole magnetic field model. The detailed MLT-averaged wave parameters used to calculate pitch angle diffusion coefficients are listed in Table S3 of the Supporting Information.

Figure 4 shows drift- and bounce-averaged pitch angle diffusion coefficients ($\langle D_{\alpha\alpha}\rangle$) for LGWs (a–c), hiss (d–f), and VLF transmitter waves (g–i) at three different L-shells. At L = 1.5, LGWs are efficient for scattering electrons from several hundred keV to several MeV (Figure 4a). The modest values of $\langle D_{\alpha\alpha}\rangle$ at low energies (~1–10 keV) are due to the Landau resonance caused by the oblique component of LGWs. At L = 1.5, hiss pitch angle scattering rates are rather weak below a few MeV (Figure 4d), while VLF transmitter waves scatter electrons from several hundred keV to a few MeV. At L = 2.5, LGWs are capable of scattering lower energy electrons down to a few tens of keV, but with lower values of $\langle D_{\alpha\alpha}\rangle$ than those at L = 1.5. At L = 2.5, LGWs are still more efficient in pitch angle diffusion of electrons with energies from tens of keV to ~200 keV (Figure 4b); hiss plays a dominant role in scattering electrons above ~200 keV (Figure 4e); and VLF transmitter waves play a dominant role in scattering electrons below a few tens of keV (Figure 4h). At L = 3.5, hiss scatters electrons much more efficiently than LGWs in a broad energy range (> 10 keV) except at lower energies (< 10 keV), where LGWs play a dominant role (Figure 4c). At L = 3.5, VLF transmitter waves are too weak (e.g., Ma et al., 2017; Meredith et al., 2019) to play any role in electron pitch angle scattering, and thus are not included here (Figure 4i).

Based on the above pitch angle diffusion coefficients, we further calculate the electron lifetime (τ) due to pitch angle scattering driven by LGWs, hiss, and VLF transmitter waves using equation (1) from Albert and Shprits (2009), where α_{LC} represents the bounce loss cone, and $\langle D_{\alpha\alpha}\rangle$ is the drift- and bounce-averaged pitch angle diffusion coefficients, as shown in Figures 4a–4i.

$$\tau \approx \int_{\alpha_{LC}}^{\pi/2} \frac{1}{2\langle D_{\alpha\alpha}\rangle tan\alpha} d\alpha \quad (1)$$

Figures 4j–4l show the calculated electron lifetimes due to pitch angle scattering by hiss alone (blue), hiss and VLF transmitter waves (black), and the combination of hiss, VLF transmitter waves and LGWs (red) at three different L-shells. The integration in Equation (1) is performed over the pitch angle from α_{LC} to 88.5° due to the potential lack of scattering close to 90°. At L = 1.5 (Figure 4j), hiss alone plays a role in scattering electrons above a few MeV with a relatively long lifetime (> ~1000 days), whereas VLF transmitter waves play an important role in scattering electrons from several hundred keV to a few MeV with the shortest lifetime of several thousand days. By further including the effect of LGWs, the electron lifetimes are significantly reduced, particularly above several hundred keV with the shortest lifetime of ~200 days at several MeV.

However, for the electrons with energies below ~1 MeV, the calculated lifetimes of > 1000 days are still longer than the observed lifetime of 100s days (e.g., Claudepierre et al., 2020b), suggesting that other physical processes are operating in this region. At L = 2.5 (Figure 4k), hiss alone is effective for scattering electrons above several hundred keV with the shortest lifetime of ~10 days; VLF transmitter waves play a dominant role from a few keV to ~100 keV with the shortest lifetime of ~30 days; LGWs become important from tens of keV to ~1 MeV by further reducing the lifetime by a factor of up to ~6. At L = 3.5 (Figures 4l), hiss plays a dominant role in scattering electrons above ~10 keV with the shortest lifetime down to ~1 day at a few hundred keV, while LGWs play a minor role except for scattering electrons from a few to a few tens of keV with a long lifetime (> ~100 days). Overall, LGWs are relatively important for scattering electrons from several hundred keV to several MeV at L = 1.5, and from tens of keV to ~1 MeV at L = 2.5, but have a minor effect for electrons at L = 3.5.

5 Summary and Discussion

Using the Van Allen Probes waveform data throughout the entire Van Allen Probes era (2012–2019), we analyzed the typical properties and global distribution of LGWs at L < 4 and evaluated their global effects on radiation belt electron loss in the Earth's inner radiation belt and beyond. The high-resolution waveform data in an extensive period allow us to unambiguously distinguish LGWs from other types of waves (e.g., hiss) in a comprehensive manner. The principal findings of the present study are summarized below.

(1) Magnetic wave amplitudes of LGWs range from a few pT to a few tens of pT, and are typically stronger at L < 3, peaking at L < 2 on the nightside. The occurrence rate of LGWs is also larger from the dusk to the dawn sector at L < 3 with an occurrence rate of up to ~30%.

(2) The majority of LGW wave power is observed with frequencies between a few hundred Hz and 10 kHz at L < 3, and is concentrated below the equatorial f_{LHR} with decreasing wave frequency with increasing L-shell. Although the peak wave power spreads from several hundred Hz to several kHz at L < 2.3, it shifts to several hundred Hz over 2.3 < L <3, which is likely due to the much longer lifetime of low-frequency LGWs than that of high-frequency ones.

(3) Wave normal angles of LGWs show intermediate values (30°–50°) at L < 2 and below 0.25 f_{LHR} over 2 < L < 4, suggesting the mixture of ducted and unducted LGWs, while the wave normal angles tend to be more oblique (60°–75°) over 0.25 f_{LHR}–0.1 f_{ce} over 2 < L < 4, suggesting the dominance of unducted LGWs.

(4) To evaluate the relative role of LGWs in the inner belt and beyond, electron lifetimes due to pitch angle scattering by LGWs, VLF transmitter waves, and plasmaspheric hiss are calculated based on their pitch angle diffusion coefficients. Their comparisons indicate that LGWs are relatively important for scattering electrons from several hundred keV to several MeV with a lifetime down to ~200 days at L = 1.5 and from tens of keV to ~1 MeV at L = 2.5, but have little impact on energetic electron dynamics at higher L-shells (~3.5). Moreover, VLF transmitter waves play a role in scattering electrons from several hundred keV to a few MeV at L = 1.5 and from a few keV to ~100 keV at L = 2.5; hiss becomes important for scattering electrons at higher L-shells (> ~2.5) from tens of keV to a few MeV.

It is important to note that compared to the previous statistical analyses (e.g., Colman and Starks, 2013; Meredith et al., 2007; Nemec et al., 2010; Ripoll et al., 2020), which assume that wave power of LGWs is mostly above ~2 kHz, our time-averaged statistical results using waveform data (distinguishing LGWs from other types of waves) indicate that although LGWs are indeed strong at > ~2 kHz at L < 2.5, the wave power can extend down to several hundred Hz, mostly below f_{LHR}. This is likely due to the fact that although the initial wave power of LGWs is strong at ~kHz at low L-shells, after generation, MR whistlers tend to migrate toward higher L-shells and settle at frequencies near f_{LHR} having decreasing peak frequencies with increasing L-shells (Bortnik et al., 2003a), and these low-frequency LGWs tend to have much longer lifetimes than the high-frequency components (Bortnik et al., 2003b).

In the present study, we evaluated the electron lifetimes due to LGWs based on the quasilinear theory, where the effects of waves on electrons are treated as a diffusive process (Schulz & Lanzerotti, 1974). However, for large-amplitude coherent LGWs, as an example shown in Figure 1a with a wave amplitude of several hundred pT, the quasilinear treatment may not be applicable, and nonlinear effects will need to be considered (e.g., Albert, 2002; Inan et al., 1978). Evaluation of the nonlinear effects of LGWs is beyond the scope of the present study, and is left as future investigations.

Acknowledgments and Data

This research is supported by the NSF grants AGS-1723588 and AGS-1847818, NASA grants 80NSSC17K0231 and 80NSSC20K0196, and the Alfred P. Sloan Research Fellowship FG-2018-10936. QM and JB are grateful for RBSP-ECT and EMFISIS funding provided by JHU/APL Contract 967399 and 921647 under NASA's Prime Contract NAS5-01072. We acknowledge R. Shi for the helpful discussion. The Van Allen probes data from the EMFISIS instrument were obtained from http://emfisis.physics.uiowa.edu/Flight/. The data used to produce figures in the present study are publicly available at https://doi.org/10.6084/m9.figshare.12580385.

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Figure 1. Two typical examples of LGWs based on the wave burst data from Van Allen Probe B at L = 1.9 & MLT = 2.9 (left) and at L = 1.9 & MLT = 15.6 (right). (a) Time-frequency spectrogram of wave electric spectral density, and (b) magnetic spectral density over 6 s time interval near 09:32:42 UT on 9 April 2015. Here the red solid (dashed) line indicates equatorial lower hybrid resonance frequency f_{LHR} (0.5 f_{LHR}). (c) Time-frequency spectrogram of magnetic spectral density, (d) wave normal angle, (e) ellipticity, and (f) magnetic wave amplitude of LGWs for the bins identified as LGWs, shown as the filtered magnetic spectra in panel (c). (g)–(l) The same format as panels (a)–(f), but showing LGWs with major wave power below 1 kHz during a different time interval at ~06:58:45 UT on 02 April 2015.

Figure 2. Global distribution of LGWs in the L-MLT domain. (a) Satellite time during which wave burst data are available regardless of the presence of LGWs in each 0.1 L × 1 h MLT bin. (b) Root-mean-square (RMS) magnetic wave amplitude of LGWs. (c) Occurrence rate of LGWs for all detected LGWs. (d) Occurrence rate of LGWs with weak amplitude ($2 < B_w < 10$ pT), (e) modest amplitude ($10 < B_w < 50$ pT), and (f) large amplitude ($B_w > 50$ pT).

Figure 3. Statistical results of LGW wave properties as a function of L-shell and frequency. (a) Satellite time during which Van Allen Probes recorded spectral bins identified as LGWs; (b) median wave normal angles for the identified LGW spectral bins; (c) average magnetic spectral density, and (d) average electric spectral density of LGWs. Here the white dashed (dash-dotted) line represents equatorial 0.5 f_{ce} (0.1 f_{ce}); red solid (dashed) line represents equatorial f_{LHR} (0.5 f_{LHR}); and the black solid line represents equatorial proton cyclotron frequency (f_{cp}).

Figure 4. Theoretical calculations to evaluate the relative role of LGWs in energetic electron loss, compared to hiss and VLF transmitter waves. (a–c) Drift and bounce-averaged pitch angle diffusion coefficients ($\langle D_{\alpha\alpha} \rangle$) of LGWs, (d–f) hiss, and (g–i) VLF transmitter waves at L = 1.5 (left), 2.5 (middle) and 3.5 (right). The vertical dashed magenta lines represent the bounce loss cone at the given L-shell. MLT-averaged RMS wave amplitude of each wave used to calculate $\langle D_{\alpha\alpha} \rangle$ is listed in the bottom left of each panel. (j–l) Calculated electron lifetimes color-coded for pitch angle scattering due to various combinations of plasma waves.