Properties of whistler mode waves in Earth's plasmasphere and plumes

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Key points

1. Whistler mode waves are statistically analyzed both inside the plasmasphere and in the plumes based on Van Allen Probes observations.

2. The occurrence rate and amplitudes of whistler mode waves inside the plasmasphere and plumes show dependence on L, MLT and geomagnetic activity.

3. The majority of whistler mode waves in plumes are suggested to be locally amplified due to energetic electron injection.

Abstract

Whistler mode wave properties inside the plasmasphere and plumes are systematically investigated using five-year data from Van Allen Probes. The occurrence and intensity of whistler mode waves in the plasmasphere and plumes exhibit dependences on magnetic local time (MLT), *L* and *AE*. Based on the dependence of the wave normal angle and Poynting flux direction on *L* shell and normalized wave frequency to electron cyclotron frequency (f_{ce}), whistler mode waves are categorized into four types. Type I: ~0.5 f_{ce} with oblique wave normal angles mostly in plumes; Type II: 0.01–0.5 f_{ce} with small wave normal angles in the outer plasmasphere or inside plumes; Type III: <0.01 f_{ce} with oblique wave normal angles mostly within the plasmasphere or plumes; Type IV: 0.05–0.5 f_{ce} with oblique wave normal angles deep inside the plasmasphere. The Poynting fluxes of Type I and II waves are mostly directed away from the equator, suggesting local amplification, whereas the Poynting fluxes of Type III and IV are directed either away from or towards the equator, and may originate from other source regions. Whistler mode waves in plumes have relatively small wave normal angles with Poynting flux mostly directed away from the equator, and are associated with high electron fluxes from ~30 keV to 100s keV, all of which support local amplification. Whistler mode wave amplitudes in plumes can be stronger than typical plasmaspheric hiss, particularly during active times. Our results provide critical insights into understanding whistler mode wave generation inside the plasmasphere and plumes.

1. Introduction

Plasmaspheric hiss is an electromagnetic whistler mode wave that exists inside the plasmasphere or high-density plumes in the inner magnetosphere (*Thorne et al.*, 1973; *Summers et al.,* 2008), and plays a vital role in the loss of energetic electrons within these regions (*Lyons et al.*, 1972; *Lyons and Thorne*, 1973; *Albert*, 2005; *Summers et al.*, 2008; *Ni et al.*, 2013; *Breneman et al.*, 2015; *Li et al.,* 2015a; *Ma et al.,* 2016). Plasmaspheric hiss waves are believed to be incoherent and unstructured. However, recent studies have shown that hiss intensification can be modulated by the variation of plasma density (*Chen et al*., 2012b) or the variation of electron flux (*Shi et al.*, 2018) and whistler mode waves in the plume region exhibit a high level of coherency (*Tsurutani et al.*, 2015; *Su et al.*, 2018). These studies (*Tsurutani et al.*, 2015; *Shi et al.*, 2018; *Su et al.*, 2018) indicate that the observed hiss emissions are locally amplified through wave-particle interaction with anisotropic electron populations (*Kennel and Petschek*, 1966; *Thorne et al.*, 1979). The external origin of hiss emissions from whistler mode chorus, which is excited in the plasmatrough region outside the plasmasphere (*Bortnik et al*, 2008, 2009), is another possible generation mechanism of hiss emissions. Chorus waves are typically observed as a series of coherent bursts of wave power in the frequency range spanning 0.1-0.8 f_{ce} with a gap at 0.5 f_{ce} (*Burtis and Helliwell*, 1969; *Tsurutani and Smith*, 1974; *Koons and Roeder*, 1990), where f_{ce} is electron cyclotron frequency. *Li et al.* (2015b) provided direct evidence that hiss originates from chorus with a remarkable correlation between the chorus observed outside the plasmasphere and the hiss emissions inside the plasmasphere. Results of a statistical study based on multiple satellites (*Meredith et al.*, 2013) and ray tracing simulations (*Chen et al.*, 2012a) also support chorus as the origin of plasmaspheric hiss. Lightning generated waves from low altitudes (*Green et al.*, 2005) can also be a possible source of hiss emissions, although the geographic distribution of lightning is inconsistent with that of hiss wave intensity in the major frequency range, which is below 2 kHz.

Properties of plasmaspheric hiss emissions have been extensively studied (*Meredith et al.*, 2004, 2013; *Li et al.*, 2015a; *Spasojevic et al.*, 2015; *Tsurutani et al.*, 2015; *Malaspina et al.*, 2016; *Hartley et al.,* 2018). *Meredith et al*. (2004) illustrated a pronounced dependence of the plasmaspheric hiss wave intensity on geomagnetic activity, *L* shell, MLT and MLAT. The hiss amplitudes show a clear day-night asymmetry and have higher values during high levels of geomagnetic activity. Comparisons between the distribution of energetic electrons and the observed hiss emissions suggested a possible local excitation of hiss in the outer plasmasphere due to electrons with energies from tens to hundreds of keV (*Meredith et al.*, 2004). *Li et al.* (2015a) analyzed the dependence of hiss on frequency and suggested that low frequency (below 100 Hz) hiss, which was missing in the previous radiation belt models, should be included in modeling hiss-driven electron dynamics. The importance of the relative location with respect to the plasmapause of hiss emissions was raised by *Malaspina et al*. (2016), which revealed important features of the frequency-dependent spatial distribution of hiss power. Most of the above statistical studies mainly focus on the wave power and its dependence on frequency, spatial location and geomagnetic activity. However, other wave properties, such as wave normal angle (WNA) and direction of Poynting flux, also provide important information, especially regarding the generation mechanisms of hiss emissions. In the present study, we thoroughly analyze and evaluate these wave properties.

Moreover, the whistler mode waves in plasmaspheric plumes have not been systematically evaluated, although their properties are important to understand the generation of plasmaspheric hiss. *Laakso et al*. (2015) presented an observation of hiss emissions, suggesting that the waves are generated in the equatorial region of the plasmaspheric plumes in the dusk sector. The hiss emissions propagate poleward in the plasmaspheric plume, whereas in the plasmasphere, the waves propagate toward the equator in both hemispheres. Therefore, it was proposed that the plasmaspheric hiss inside the plasmasphere partly originates from the plume region (*Laakso et al*. 2015; *Tsurutani et al*., 2015). *Su et al*. (2018) provided clear evidence of local generation of hiss emissions in the plume region. They observed intense hiss emissions in association with electron injections at tens of keV. The plume hiss emissions exhibited rising tones in frequency-time spectrograms at frequencies around 0.5 f_{ce}. The WNA and the direction of Poynting flux of these waves also support the scenario of local generation caused by wave-particle interactions with anisotropic injected electrons (*Su et al*., 2018).

The present study systematically investigates the wave properties of whistler mode waves, including wave power, WNA and direction of Poynting flux, both inside the plasmasphere and in the plasmaspheric plumes. The dataset and criteria of identifying whistler mode waves are described in Section 2. Two typical observations of whistler mode waves in the plume and inside the plasmasphere are analyzed in Section 3. The statistical results of wave properties are presented in Section 4, followed by a summary and discussion in Section 5.

2. Data and Methodology

The data from the twin Van Allen Probes (RBSP-A and B), with an altitude of ~600 km at perigee and geocentric distance of ~5.8 R_E at apogee (*Mauk et al.*, 2012), are used for the present study. The wave amplitude and spectra are provided by the Waves waveform receiver (WFR) on the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS), which measures wave power spectral density from 10 Hz to 12 kHz at 6 s time resolution (*Kletzing et al.*, 2013). The WFR also provides continuous-burst waveforms with a 35 kHz sampling rate. Wave properties (e.g., wave normal angles, planarity of polarization, ellipticity and direction of Poynting flux) calculated using the Singular Value Decomposition method (*Santolik et al.,* 2003) are routinely available. Plasma density can be derived based on the high-frequency receiver (HFR) data (*Kurth et al.,* 2015) or be inferred from the spacecraft potential measured by the Electric Field and Waves (EFW) instrument (*Wygant et al.,* 2013). High resolution electron flux measurements over the energy range of ~30 keV to 4 MeV are provided by the Magnetic Electron Ion Spectrometer (MagEIS) instrument (*Blake et al.*, 2013; *Spence et al.*, 2013). We utilize the level 3 MagEIS dataset which includes particle pitch angle distribution to calculate the linear growth rate of the whistler mode waves.

The location of plasmapause is determined when the density increases (decreases) by more than a factor of 5 within 0.5 *L* from lower (higher) to higher (lower) *L* shells (*Malaspina et al*., 2016). If there are multiple density structures satisfying the definition in one leg of the orbit (either inbound or outbound), the one closest to the Earth is chosen to be the plasmapause. If there is no plasmapause crossing in one leg, the whole leg is considered to be inside the plasmasphere. The plume region is identified after the plasmapause is determined. More specifically, between the apogee and the plasmapause crossing, the plume region is defined when $N > 1.2 \times \min(N_{\mathrm{lower}\ L})$ and $N > 2.5 \times \min(N_{\mathrm{lower}\ L}) \times L_{n6}/L_6$. Here min ($N_{\mathrm{lower}\ L}$) is the minimum density between the plasmapause crossing and the satellite location (outside the plasmapause) where the density is N, and L_n is the L shell where the minimum density ($N_{\mathrm{lower}\ L}$) is recorded. We utilized the data from the EMFISIS Waves instrument for the density profile. We further validated the identified plume regions through visual inspection to ensure that the selected plume regions are reasonable. Whistler mode waves are identified by selecting waves with planarity larger than 0.3 and ellipticity larger than 0.7 with wave frequency between 20 Hz and 7 kHz. We collected all the selected waves inside the plasmasphere and in the plumes separately. Each data point (with 6 s resolution) is regarded as a sample and a sample satisfying the above criteria is identified as a whistler mode wave event.

3. Event Study

Figure 1 presents a typical example of whistler mode wave emissions in the plasmaspheric plume (Case I) observed by Van Allen Probe B on Nov 6, 2012. The satellite was located in the dawn sector (MLT over 4.7 – 7.7) from 12:00 UT to 18:00 UT. The *AE* index (black) and *AE** (blue) are shown in Figure 1a, where *AE** is the maximum of *AE* index in the preceding 3 hours. Figure 1b shows the HFR spectra. The density profile is shown in Figure 1c, where the identified plume regions are highlighted with magenta lines. The vertical black lines at 14:42 UT and 18:40 UT correspond to the plasmapause crossings (L = 5.93 and L= 4.12). The whistler mode emissions are observed from 30 Hz up to 0.5 f_{ce} (magenta dashed line) in the plume region (Figures 1d and 1e) in association with the enhancement of anisotropic electron flux at tens of keV (Figure 1i). Figure 1f shows a flag indicating plasmaspheric hiss inside the plasmasphere (yellow), whistler mode waves in the plumes (orange), whistler mode chorus in the low-density plasmatrough (cyan), and magnetosonic waves (red). It is worthwhile to note that there exist whistler mode waves with frequencies larger than 0.5 f_{ce} in the plumes, albeit with a much weaker intensity. The whistler mode waves in plumes have Poynting fluxes directed antiparallel to the ambient magnetic field (Figure 1h). Considering that Van Allen Probe B was in the southern hemisphere (MLAT < 0°), the Poynting flux of the whistler mode emissions was directed away from the magnetic equator. Just below 0.5 f_{ce}, a portion of the whistler mode waves propagates obliquely (Figure 1g) in the plumes, which is similar to the property of oblique chorus waves in the low-density plasmatrough region (e.g., *Santolik et al.,* 2009; *Agapitov et al.,* 2016; *Li et al.,* 2016). At lower frequencies, the whistler mode waves in the plumes propagate quasi-parallel to the ambient magnetic field. The continuous-burst waveforms are shown on the bottom of Figure 1 for three occasions at 14:13 UT (Figures 1j-1k) inside the plasmasphere, 16:06 UT (Figures 1l-1m) in the plume and 17:42 UT (Figures 1n-1o) outside the plasmasphere in the plasmatrough region (N < 10 cm^{-1}). Inside the plasmasphere, the hiss emissions appear to be unstructured (Figure 1j-1k). In contrast, clear rising tone structures are embedded in broadband waves in the plume (Figure 1l-1m), where the plasma density is around 40 cm^{-3}. The rising tones sweep from 100 Hz up to more than 1 kHz just below 0.5 f_{ce} and propagate quasi-parallel to the background magnetic field (Figure 1m). These are direct evidence indicating that the nonlinear wave-particle interaction process was operating in the plasmaspheric plume. Figures 1n-1o show typical rising tone chorus waves in the low-density region. Compared to the typical chorus elements (Figure 1n-1o), interestingly, the duration of rising tones in plumes is longer (Figure 1l-1m).

Figure 2 shows a typical event of hiss emissions inside the plasmasphere (Case II) observed by Van Allen Probe B on November 23, 2013. The satellite was in the afternoon sector (MLT over 13.4-18.7) from 8:00 UT to 14:00 UT. The intensification of the observed hiss emissions is associated with injected anisotropic electrons (Figures 2f and 2g) probably due to local amplification (*Shi et al*., 2017) at higher L shells (L > 5.5). The anisotropy is calculated following equation (2) of *Chen et al*. (1999). However, at lower L shells (L < 5.5) the calculated linear growth rate based on *Summers et al*. (2009) (Figure 2k) becomes inconsistent with the observed wave power spectrum (Figures 2c and 2d) at low frequency (circled by orange dashed lines). This discrepancy can be explained if we take into account the direction of Poynting flux (Figure 2i) and the WNA (Figure 2j). The black curve in Figure 2i roughly depicts the frequency boundary which separates the Poynting flux directed away from the equator (anti-parallel to the magnetic field) from that towards the equator (quasi-parallel to the magnetic field). Note that the satellite was in the southern hemisphere during this period (MLAT < -9°). The frequency boundary, which is drawn with a black line in Figures 2c-2e and 2j-2k, is estimated by the empirical function f_{est}= $(4_7/L_7)$ kHz. Above this frequency, the Poynting flux is directed mostly away from the equator, which is consistent with the scenario of local amplification. However, below this frequency the Poynting flux was directed mostly towards the equator, suggesting that the waves originate from other source regions. The calculated linear growth rate (Figure 2k), based on *Summers et al*. (2009), is consistent with the wave emissions that have a Poynting flux away from the equator (above f_{est}). The minimum resonant energy corresponding to the estimated frequency boundary is shown in Figures 2f and 2g as black curves, which agrees very well with the upper energy of injected energetic electrons, especially over *L* shells of 4.5–6.5. Note that due to the limited energy coverage of the MagEIS instrument (>~30 keV), the linear growth rates above several hundred Hz are not shown in Figure 2k. However, since the minimum resonant energy for the estimated frequency boundary (f_{est}) of the observed hiss is above ~30 keV (black line in Figure 2f), MagEIS contains the crucial electron data to calculate the linear growth rates of hiss near the estimated frequency boundary. It is also important to note that the linear growth rate was calculated based on the local pitch angle distributions of electrons, thus may have underestimated the growth rate compared to the calculation using the equatorial electron distributions.

We discussed two examples of whistler mode wave emissions both in the plume region (Figure 1) and inside the plasmasphere (Figure 2) above. The observed whistler mode emissions in plumes are likely due to local amplification, whereas inside the plasmasphere the observed hiss waves may be locally amplified at higher frequency above a critical frequency. This critical frequency is related to the energies of injected electrons through the wave-particle resonance condition and is dependent on *L* shell, with higher values at a lower *L* shells. The following section will focus on the statistical features of whistler mode wave properties inside the plasmasphere and in the plumes separately.

4. Statistical Results

The number of samples inside the plasmasphere, regardless of existence of hiss, is plotted in the *L*-MLT domain (Figure 3a) for three different levels of *AE**. The number of hiss wave events and the occurrence rate of hiss (the ratio between the number of hiss events and the number of samples), are shown in Figures 3b and 3c, respectively. There is a clear day-night asymmetry of the occurrence rate, with a minimum on the night-side. With increasing of *AE**, the occurrence rate decreases on the night side, and the dawn-dusk asymmetry of occurrence rate becomes evident, with a higher occurrence rate on the dawn side during more active times. Figure 3d shows the root mean square (RMS) of the magnetic wave power from 30 Hz to 7 kHz. The wave power exhibits a clear day-night asymmetry and is dependent on geomagnetic activity, which is consistent with the previous studies (*Meredith et al.*, 2004; *Li et al.*, 2015a). It is worthwhile to note that the EMFISIS data were collected near the equatorial inner magnetosphere mostly within 20° of the magnetic equator, while *Meredith et al.* (2004) investigated the global distributions of hiss emissions in the equatorial and mid-latitude (up to 30°) region using the CRRES data.

Figure 4 shows the statistical distribution of whistler mode waves in plumes in the *L*-MLT domain. The occurrence rate of the plumes (Figure 4b), which is the ratio between the number of samples in the plumes and the total number of samples outside the plasmapause regardless of plumes (Figure 4a), highly depends on *L*, MLT, and *AE**. The plumes are more frequently observed in the dusk sector (MLT over 15–21) during active geomagnetic times (*AE** > 500 nT). During moderate times (200 < *AE** < 500 nT), the plumes are often observed from 17 to 23 MLT. However, the occurrence rate of plumes decreases with increasing *AE** on the dawn-side. This statistical distribution of the plume occurrence, particularly at relatively large *L* shells (>~5), is overall consistent with the previous statistical results (*Chappell et al.,* 1974; *Lee et al.,* 2016), where the occurrence rate of plumes is typically high from the afternoon to the dusk sector during moderate-to-disturbed geomagnetic activity. This statistical result also agrees with the physical picture of the formation and evolution of plumes due to the combined effect of the corotation electric field and the convection electric field during moderate-to-disturbed activities (*Chappell et al.,* 1974). The occurrence rate of whistler mode waves in plumes (Figure 4d), which is the ratio between the number of the whistler mode wave events (Figure 4c) and the total number of samples outside of the plasmapause (Figure 4a), has a similar spatial distribution as the occurrence of plumes. The amplitudes of whistler mode waves (Figure 4e) increase with increasing AE^*, particularly from the noon to the dusk sector. Interestingly, from the midnight to the dawn sector, although the occurrence rate of the whistler mode waves is low (Figure 4d), the wave amplitude is intense at larger L shells ($>$ 5), probably due to the larger flux of energetic electrons on the nightside, which provide a source of free energy for whistler mode wave excitation (e.g. *Li et al.,* 2010).

For comparison, Figure 5 illustrates the statistical distribution in the ΔL-MLT domain, where ΔL is the distance between the wave and the plasmapause. The negative ΔL corresponds to the region inside the plasmasphere while the positive value corresponds to the plume region. Figure 5a shows the distribution of the number of the samples inside the plasmapause and in plumes. The occurrence of the whistler mode waves inside the plasmapause or in plumes (Figure 5c) is defined as the ratio between the number of whistler mode wave events (Figure 5b) and the number of samples inside the plasmasphere or in plumes (Figure 5a). During modest-to-strong activity ($200 < AE^* < 500$ nT and $AE^* > 500$ nT), the occurrence rates of whistler mode waves in the plumes are typically large ($> \sim 0.7$) from the afternoon to the dusk sector. This value is in a similar range as the occurrence inside the plasmasphere on the dayside. It is important to note that the hiss occurrence rate is much higher just inside the plasmasphere ($\Delta L > \sim$-2), compared to that well inside the plasmasphere ($\Delta L < \sim$-2). Although the occurrence rates of whistler mode waves in plumes appear to be large during quiet times (Figure 5c), the RMS wave amplitudes are relatively weak. Interestingly, the whistler mode waves in plumes are more intense (particularly from the noon to the dusk sector and on the nightside), compared to the plasmaspheric hiss wave intensity.

Since the whistler mode waves in plumes are suggested to be locally generated due to wave-particle interaction, we show in Figure 6 the averaged electron flux as a function of L shell and electron kinetic energy in the plume region. The electron flux associated with strong wave intensity (RMS(B_w) > 30 pT) is clearly larger at L shells over 4–6 (Figure 6a) compared to the electron flux when the wave intensity is weaker (RMS(B_w) < 30 pT) (Figure 6b). The black lines in Figures 6a and 6b show the number of wave events as a function of L shell. The ratio between the electron flux with strong wave intensity (Figure 6a) and that with weak wave intensity (Figure 6b) is shown in Figure 6c. The peak ratio resides at $L \sim 5$ from several tens of keV to ~200 keV. It is interesting to note that the energy of peak ratio decreases with increasing L shell. The large ratio (>1) supports the local amplification scenario with more intense anisotropic electron fluxes leading to stronger whistler mode waves.

Figure 7 illustrates the frequency dependence of the whistler mode wave properties inside the plasmasphere and plumes. Figure 7a shows the distribution of the number of whistler mode wave events as a function of ΔL and normalized frequency (f/f_{ce}). The vertical dashed lines represent the location of the plasmapause. Inside the plasmasphere, the normalized frequency of peak number of events decreases with increasing distance from the plasmapause. The accumulative magnetic wave spectral density (Figure 7b) inside the plasmasphere shows a similar trend, which is consistent with *Malaspina et al*. (2016) where the absolute frequency of peak number almost remains constant as a function of *L* inside the plasmasphere. The accumulative magnetic wave spectral density is calculated by the summation of the magnetic spectral density of all whistler mode wave events. The wave power is strongest just inside the plasmasphere. The normalized wave frequency of the peak number of event and peak accumulative wave power (Figure 7b) remains almost constant inside the plumes, where both the number of wave events and the accumulative wave power are much lower than those inside the plasmasphere. However, the average electric spectral density and magnetic spectral density in the plume (Figure 7c and 7d), when there exist whistler mode wave emissions, are stronger than those inside the plasmasphere.

Figures 7e and 7f show the distribution of median wave normal angle and direction of Poynting flux power-weighted by the wave magnetic intensity, respectively. The higher value (~ 1) in Figure 7f means that the Poynting flux of the waves is directed away from the equator while the lower value (~ 0) indicates that the Poynting flux is directed towards the equator. Four types of whistler mode waves with different properties (WNA and Poynting direction) are identified. Type I waves, around $0.5\, f_{ce}$, circled by the yellow lines (Figures 7e and 7f), propagate in a relatively oblique direction to the ambient magnetic field, and the Poynting flux of the waves is directed away from the equator. These features are similar to the oblique chorus waves that are locally generated in the low-density plasmatrough region. Type II waves, below $0.5\, f_{ce}$ (surrounded by magenta box), propagate quasi-parallel to the ambient magnetic field with the Poynting flux directed away from the equator. Case I and II (Figure 1 and Figure 2) indicate that this part of waves can be locally generated (or amplified) in association with the anisotropic injected electrons. It is important to note that the lower frequency boundary of Type II is dependent on the *L* value, with a higher value at a lower *L* shell inside the plasmasphere. Type III waves have a higher WNA (~40°) and their Poynting flux is directed towards or away from the equator with a slight preference towards the equator (grey box). These waves are likely to propagate from other source regions. The last type (Type IV) is at the frequency from ~0.05 f_{ce} to 0.5 f_{ce} and at lower *L* shells (blue box), where the waves propagate obliquely and the Poynting flux is directed towards or away from the equator. These waves might originate from lightning generated whistlers due to their high frequency and low *L* shell locations (e.g., *Green et al.*, 2005). In the plumes, the majority of the whistler mode waves belong to Type II, considering the distribution of the number of events (Figure 7a) and the accumulative wave power (Figure 7b). Only a small amount of wave power for Type I exists around 0.5 f_{ce} (Figures 7a and 7b). The median WNA of Type I is larger in the plumes (~ 40°) than that inside the plasmasphere (~ 15°). The Type III waves are also a minor part in the plumes, existing over the ΔL between 0 and ~2 below ~ 0.01 f_{ce}. Therefore, the majority of the whistler mode waves in plumes (Type I and Type II) may be locally amplified through cyclotron resonance with anisotropic electrons. Inside the plasmasphere, the majority of the hiss waves belongs to Type II and Type III, with Type II dominates at higher frequency while Type III dominates at lower frequency. Inside the plasmasphere, the accumulative wave power of Type III is relatively higher than that of Type II (Figure 7b), although the number of events appears to be similar (Figure 7a). It is also important to note that just inside the plasmapause, the waves with Poynting flux away from the equator extend to a lower frequency (~0.01 f_{ce}) (Figure 7f) and the wave power is also strong (Figure 7b). It is consistent with the scenario that whistler mode emissions are preferentially locally amplified just inside the plasmapause where the injected electrons can access lower L shells due to the dynamics of the plasmapause (*Li et al*., 2013; *Tsurutani et al*., 2015). The representative fractions of the sum of all magnetic spectral density for each type are 0.24% for Type I, 43.98% for Type II, 55.75% for Type III and 0.04% for Type IV, clearly indicating the dominant magnetic wave power of Type II and Type III.

Figure 8 shows the distribution of median wave normal angle and the Poynting flux direction in different L and frequency domains. Figures 8a and 8b show these properties in a ΔL - f/f_{ce} domain, exactly the same as Figure 7e and Figure 7f. Figures 8c and 8d show the distribution in the plume region in the L - f/f_{ce} domain. Most of the whistler mode waves in plumes propagate quasi-parallel to the magnetic field in the frequency range from 0.04 f_{ce} to 0.4 f_{ce}, which is almost independent of L shell. Figures 8e and 8f show the wave distribution inside the plasmasphere in the L- f domain. The magenta curves in Figures 8e and 8f depict the estimated frequency boundary used in Figures 2j and 2k (f_{est}= ($4_7/L_7$) kHz). Above this frequency, the waves have a Poynting flux mainly away from the equator, and propagate quasi-parallel to the magnetic field (WNA < 10°) except for the kHz waves (corresponding to the waves around 0.5 f_{ce} in Figure 8a).

The WNA dependence of the number of hiss events and accumulative electric spectral density is shown in Figure 9 for whistler mode waves in plumes (Figures 9a and 9c) and inside the plasmasphere (Figures 9b and 9d). The black solid and the black dashed lines represent the resonance cone angle ($\theta_{res}= \cos^{-1}(f/f_{ce})$) and the Gendrin angle ($\theta_g = \cos^{-1}(2f/f_{ce})$), respectively. The majority of the waves reside in the low WNA (< 20°) at frequencies from 0.01 f_{ce} to 0.5 f_{ce}, both inside the plasmasphere and in the plume region, consistent with *Hartley et al.* (2018), while whistler mode waves in plumes tend to be more quasi-parallel to the ambient magnetic field line compared to the waves inside the plasmasphere. It is worthwhile to note that there exists a minor peak at wave normal angles between the resonance cone angle and the Gendrin angle (Figures 9a–9d), which are similar to the distribution of the oblique lower band chorus (*Li et al.*, 2016).

5. Summary and Discussion

In the present study, we have systematically evaluated the properties of whistler mode waves inside the plasmasphere and in plumes separately through focusing on the wave normal angles and the Poynting flux, based on the extensive data collected by Van Allen Probes from September 2012 to June 2017. The principle findings of this study are summarized as follows:

1. An interesting event observed by Van Allen Probes shows that rising tone structures can exist in the main frequency range (100 Hz – 1 kHz) of whistler mode waves in plumes, which suggests local generation of the observed emissions. These rising tone structures are

distinct from the unstructured plasmaspheric hiss, and each rising tone element lasts longer than the typical chorus waves observed outside the plasmapause.

2. The occurrence rates and wave amplitudes of whistler mode waves in plumes show a clear dependence on MLT and geomagnetic activity. The whistler mode waves in plumes occur in a broad range of L and MLT, while the occurrence rate peaks near the dusk sector during active times. The whistler mode waves in plumes intensify with increasing AE index, similar to the hiss waves inside the plasmasphere. However, the wave amplitudes of whistler mode waves in plumes are often stronger than those of the hiss inside the plasmasphere, particularly during active times.

3. The intensification of whistler mode waves in plumes are associated with higher electron flux from ~30 keV to a few hundred keV, supporting the local amplification of these waves due to injected energetic electrons.

4. Based on the distinct wave properties (WNA and direction of Poynting flux), the whistler mode waves inside the plasmasphere and in plumes can mainly be categorized into four types. Type I waves, around 0.5 f_{ce} mostly in plumes, are similar to the oblique chorus waves. Type II waves over 0.01–0.5 f_{ce} propagate quasi-parallel to the magnetic field and the Poynting flux is directed away from equator. These two types of waves are likely to be locally generated or amplified. Type III waves at lower frequency (below the critical wave frequency which increases with decreasing L shells) have oblique WNA and propagate either away from or towards the equator. These waves may propagate from other source

regions. The last type (Type IV) of waves is distributed at lower *L* shells (< ~3) with higher frequencies (>100 Hz), and may originate from lighting generated whistlers.

5. The wave normal distribution of whistler mode waves both inside the plasmasphere and in plumes exhibit two peaks, with a major peak in the quasi-parallel direction and a minor peak close to the resonance cone. The wave normal angles of whistler mode waves in plumes are typically smaller than those inside the plasmasphere.

The investigation of whistler mode waves based on Cluster observations (*Laakso et al.*, 2015) showed that almost all hiss emissions propagate away from the magnetic equator in plumes. Our statistical results based on the Van Allen Probes, which operate mainly close to the equatorial plane, demonstrate a similar trend showing that most of the whistler mode waves in plumes propagate away from the equator. Moreover, the whistler mode wave intensifications in plumes were associated with the injection of the energetic electrons at tens of keV (Figure 1i and Figure 6). *Woodrofee et al*. (2017) investigated whistler mode waves in plumes observed by Van Allen Probes, which exhibit rising tone structures, indicating the potential presence of nonlinear wave growth mechanism. Furthermore, a recent study (*Su et al.*, 2018) provided clear evidence of internal excitation of plume hiss by a combination of linear and nonlinear instability of hot electrons. Different from the observation shown in *Su et al.* (2018) where the rising tones exist at frequencies around 0.5 f_{ce} (1 kHz), the whistler mode waves in plumes in the present study (Case I) exhibited a series of rising tones in the main frequency range from 100 Hz to more than 1 kHz. Moreover, the wave coherency of whistler mode waves detected in plumes was shown to be quite high (*Tsurutani et al*., 2015), also supporting the local generation of whistler mode waves in plumes. Our statistical results of Poynting flux of whistler mode waves in plumes and their association with energetic electron flux increase suggest that the whistler mode waves in plumes are likely locally amplified and might serve as one possible source of hiss waves observed inside the plasmasphere.

Li et al. (2013) provided evidence that low-frequency hiss emissions were excited by local amplification through the cyclotron resonance instability due to the injection of plasma sheet electrons into the plasmasphere in the prenoon sector. In their study, however, the calculated linear growth rate was inconsistent with the observed hiss intensity at lower L shells. When the Poynting flux (away from equator) is taken into account, the discrepancy can be well explained (local growth can only account for the wave amplification at higher frequency at $L < \sim 4.5$), which is similar to our Case II shown in Figure 2. The ray tracing of low frequency hiss by *Chen et al.* (2014) supported local wave amplification and demonstrated that cyclic amplification due to wave propagation could account for sufficient net wave gain (> 40 dB) to excite low frequency hiss emissions from the thermal noise to the observable level. The systematic evaluation of low frequency hiss also supported the scenario of local amplification of hiss waves (*Shi et al.*, 2017). However, in the present study we provide credible evidence through a systematic statistical analysis that the hiss waves at higher frequency can also be generated or amplified through the same local amplification processes by interacting with energetic electrons. This is due to the fact that the frequency of the waves in resonance with electrons at a fixed energy increases with decreasing *L* shell due to the decreasing ratio (between the plasma and electron cyclotron frequency) with decreasing *L* shell inside the plasmasphere (*Sheeley et al.*, 2001). At lower frequencies, which cannot be explained by local amplification, the hiss waves may propagate from other sources. These sources may include the seed wave signals from the whistler mode chorus waves outside the plasmasphere, the whistler mode waves in the plumes or the hiss emissions inside the plasmasphere at higher *L* shells. Over the main frequency range (50-1000 Hz), the Poynting flux of the hiss waves inside the plasmasphere propagates away from the magnetic equator at higher *L* shells, while they propagate either away or towards the equator at lower *L* shells, which is consistent with *Kletzing et al.* (2014).

Our statistical results provide critical insights into understanding the generation of whistler mode waves at various frequencies inside the plasmasphere and plumes separately. It is important to note that whistler mode waves are extensively present inside the plumes, often with even higher wave intensity than that inside the plasmasphere. Since whistler mode waves in plumes could be very effective in electron scattering loss (*Summers et al.,* 2008; *Zhang et al.,* 2018), we suggest that the effect of whistler mode waves in plumes should be properly incorporated into radiation belt modeling.

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Figure Captions

Figure 1. An example of whistler mode waves in plumes in association with electron injection. (a) *AE* index (black) and *AE** (blue), which is the maximum *AE* in the preceding 3 hours; (b) frequency-time spectrogram for the HFR channel; (c) plasma density, where the magenta line corresponds to the density in plume regions. (d) Frequency-time spectrogram of wave electric field and (e) wave magnetic field spectral density in the WFR channel; (f) identification of the observed plasma waves: hiss waves inside the plasmasphere (yellow), whistler mode waves inside plumes (orange), chorus waves (cyan) and magnetosonic waves (red); (g) wave normal angle of whistler mode waves; (h) angle between the Poynting vector and the background magnetic field for whistler mode waves; (i) energy spectrum of spin-averaged electron flux measured by MagEIS. The bottom panels show the waveform data including magnetic field spectra and the WNA of plasmaspheric hiss (j-k); whistler mode waves in the plume region (l-m), and typical chorus waves in low-density plasmatrough (n-o). The vertical red dashed lines correspond to these three occasions.

Figure 2. An example of hiss waves inside the plasmasphere in association with electron injection. (a) *AE* index (black); (b) frequency-time spectrogram for the HFR channel; (c) frequency-time spectrogram of wave electric field and (d) wave magnetic field in the WFR channel, where the two magenta lines represent f_{ce} (solid) and 0.5 f_{ce} (dashed). (e) Identification of the observed plasmaspheric hiss; (f) energy spectrum of spin-averaged electron flux measured by MagEIS; (g) electron anisotropy; (h) plasma density, where the

black dashed line corresponds to a density of 100 cm^{-3}. (i) Angles between the Poynting vector and the background magnetic field; (j) wave normal angles; (k) convective linear wave growth rates calculated for various frequencies. The black lines in Figures 2c-2e and 2i-2k are the estimated frequency boundary of waves (f_{est}= ($4^7/L^7$) kHz) separating Poynting flux directed away from the equator from that towards the equator. The orange circles in Figures 2c, 2d, 2i, 2j, and 2k represent the regime where the calculated linear growth rates are inconsistent with the observed hiss intensification.

Figure 3. Global distribution of hiss inside the plasmasphere in the *L*-MLT domain. (a) Number of data samples, (b) number of hiss events, (c) occurrence rate of hiss, and (d) root mean square (RMS) of hiss magnetic wave amplitude, during quiet ($AE^* < 200$ nT), modestly disturbed ($200 < AE^* < 500$ nT), and active times ($AE^* > 500$ nT).

Figure 4. Global distribution of whistler mode waves in plumes in the *L*-MLT domain. (a) Number of data samples outside the plasmasphere (including the plasma trough and plume regions), (b) occurrence of plumes outside the plasmapause, (c) number of whistler mode wave events in plumes, (d) occurrence of whistler mode waves in plumes (the ratios between the values in Figure 4c and those in Figure 4a), and (e) RMS wave amplitudes of whistler mode waves in plumes.

Figure 5. Global distribution of whistler mode waves inside the plasmasphere and plumes categorized by the distance to the plasmapause. (a) Number of data samples inside the plasmasphere and plumes, (b) number of whistler mode wave events, (c) occurrence rate of whistler mode waves, and (d) RMS magnetic wave amplitude of whistler mode waves,

during quiet (AE^* < 200 nT), modestly disturbed (200 < AE^* < 500 nT), and active times (AE^* > 500 nT).

Figure 6. Averaged electron fluxes measured by MagEIS when the magnetic amplitude of the whistler mode waves in plumes is (a) greater than 30 pT and (b) less than 30 pT. (c) The ratio between the averaged electron flux when the magnetic amplitude greater than 30 pT and less than 30 pT. The black line in Figure 6a (Figure 6b) represents the number of whistler mode wave events with wave amplitudes larger (smaller) than 30 pT as a function of L shell.

Figure 7. Whistler mode wave properties in the ΔL-f/f_{ce} domain. (a) Number of wave events, (b) accumulative magnetic spectral density (summation of the magnetic spectral density of whistler mode waves), (c) mean value of wave electric spectral density, (d) wave magnetic spectral density, (e) median WNA, and (f) direction of Poynting flux weighted by wave magnetic power. The vertical dashed lines represent the location of the plasmapause. Four types of whistler mode waves are highlighted by four different colors in Figures 7e and 7f.

Figure 8. Whistler mode wave properties in the ΔL-f/f_{ce} domain or L-f/f_{ce} domain. (a) and (b) are the same as Figures 7e and 7f. (c) Median WNA and (d) direction of Poynting flux of whistler mode waves in plumes in the L-f/f_{ce} domain. (e) Median WNA and (f) direction of Poynting flux of hiss waves inside the plasmasphere in the L-f domain, where the magenta dashed line is the estimated frequency boundary of waves (f_{est}= ($4_7/L_7$) kHz) separating Poynting flux directed away from the equator from that towards the equator.

Figure 9. Wave properties as a function of WNA and f/f_{ce} inside plumes and the plasmasphere separately. (a) Number of whistler mode wave events in plumes, (b) number of hiss events inside the plasmasphere. (c) Accumulative wave electric spectral density of whistler mode waves in plumes and (d) hiss waves inside the plasmasphere. The black solid and the black dashed lines represent the resonance cone angle ($\theta_{res}= \cos^{-1}(f/f_{ce})$) and the Gendrin angle ($\theta_g = \cos^{-1} (2f/f_{ce})$), respectively.