

Properties of exohiss waves during different level of geomagnetic activity

HaiMeng Li¹, Xin Zhang^{1,2}, An Yuan^{1,2}, RongXin Tang^{1*}, ZhiHai Ouyang¹, BoPu Feng^{1,2}, and XiaoHua Deng¹

¹Institute of Space Science and Technology, Nanchang University, Nanchang 330021, China;

²School of Physics and Material Science, Nanchang University, Nanchang 330021, China

Key Points:

- The exohiss waves are mainly distributed on the dayside.
- The exohiss waves are obviously amplified in the afternoon during the intensification of geomagnetic activity.
- The amplitudes of exohiss waves with bidirection in the prenoon side increase very little during intense geomagnetic activity.

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Abstract: Exohiss are broadband, structureless whistler-mode waves outside the plasmopause. In our work, using the data sets detected by the EMFISIS suite aboard Van Allen Probe A, from 1st January 2013 to 30th June 2017, the exohiss waves are categorized among two types based on the direction of Poynting flux: unidirectional exohiss, and bidirectional exohiss waves. It seems that most exohiss waves are bidirectional, which are mainly distributed on the dayside. Compared to the hiss waves within the plasmasphere, the amplitude of bidirectional exohiss waves on the prenoon side increase very little with the enhancement of geomagnetic activity. Through the analysis of suprathermal electron flux associated with geomagnetic activity, this suggests that the waves may undergo very strong Landau damping during intense geomagnetic activity. On the other hand, the unidirectional exohiss waves are mainly distributed on the afternoon side, and the largest unidirectional exohiss waves are observed during the highest levels of substorm activity.

Keywords: Earth's radiation belts; whistler mode waves; exohiss; wave–particle interactions

1. Introduction

Whistler-mode wave is one kind of right-handed polarized electromagnetic wave that is widely observed in Earth's inner magnetosphere. Generally, there are three types of whistler-mode waves in the inner magnetosphere: plasmaspheric hiss, chorus, and exohiss. The whistler-mode waves can produce a pitch angle scattering of energetic electrons due to cyclotron resonance, thereby causing the precipitation of energetic electrons (Summers et al., 2008; Yuan ZG et al., 2011, 2012a, b; Li W et al., 2015). Because of this, they play important roles in the dynamic processes of both the ring current and radiation belt (Summers et al., 2002; Ni BB et al., 2014; Su ZP et al., 2014, 2016; Gao ZL et al., 2016; Yang C et al., 2016). Chorus waves are believed to bring about the enhancement of relativistic electron fluxes (Horne and Thorne, 2003; Horne et al., 2005; Xiao FL et al., 2009, 2010, 2014; Ni BB et al., 2011a, b, 2014; Thorne et al., 2013; Li W et al., 2014; Liu S et al., 2015). The amplitude modulation of chorus waves can cause de-trapping of some initially phase-trapped electrons (Tao X et al., 2012). Chorus waves are distributed mainly in the low-density trough outside of the

plasmopause (Burtis and Helliwell, 1969; Hayakawa et al., 1990), with a typical frequency range of $0.1 f_{ce}$ to $0.8 f_{ce}$, and a pronounced power minimum gap near $0.5 f_{ce}$, where f_{ce} indicates local cyclotron frequency (Tsurutani and Smith, 1974, 1977). The chorus wave power structure plays an important role in the evolution of electron pitch angle distributions after injection (Tao X et al., 2011). Using THEMIS data, Li W et al. (2009, 2011) show that chorus waves are mainly observed from midnight to the afternoon with $L \sim 5$ –10. Furthermore, in the low-latitude region ($|MLAT| < 10^\circ$), there is a strong positive correlation between chorus intensity and geomagnetic activity. Compared to the chorus waves on the dayside, the enhancement of chorus waves intensity on the nightside is more obvious with the enhancement of AE index. On the other hand, in the mid-latitude region ($10^\circ \leq |MLAT| < 25^\circ$), chorus waves are mainly observed on the prenoon side with $L \sim 5$ –10. These waves exhibit less of a positive correlation to AE (Li W et al., 2009). Plasmaspheric hiss is a wide, no structural ELF emission with a typical frequency band ranging from 100 Hz to several kilohertz (Meredith et al., 2006). The hiss waves are typically observed in the high-density regions ($L \sim 2$ –7) of the plasmasphere or plasmaspheric plume (Thorne et al., 1973; Yu J et al., 2017; Su ZP et al., 2018). The occurrence rate and amplitude of plasmaspheric hiss waves on the dayside is much higher than those on the nightside (Wang J et al., 2020). With the intensification of substorms, the amplitude of plasmaspheric hiss enhances on the dayside. Mean-

First author: H. M. Li, lihaimeng@ncu.edu.cn

Correspondence to: R. X. Tang, rongxint@ncu.edu.cn

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while, it may decrease on the nightside (Li W et al., 2015; Wang JL et al., 2020). This is probably because of the stronger Landau damping of whistler mode waves on the nightside, which is caused by greater injected suprathermal electron fluxes (Bortnik et al., 2008, 2009; Li W et al., 2015).

Another type of hiss-like wave observed outside of the plasma-pause is referred to as exohiss. Exohiss waves are wide, non-structural ELF emissions very similar to the plasmaspheric hiss waves. Using the data from Van Allen Probes, Zhu H et al. (2015) present a case study of exohiss waves within the low-latitude region. The Poynting fluxes of the exohiss waves on the prenoon side mainly present equatorward propagating components, while the waves present equivalent equatorward and poleward propagating components on the afternoon side. Combining the larger ratios of suprathermal electron fluxes to the cold electron densities j/n_e , the results suggest that exohiss waves with bidirectional Poynting fluxes are evolved from the plasmaspheric hiss waves leaking into the plasmatrail, suffering from strong Landau damping while propagating. Gao ZL et al. (2018) report two cases of exohiss waves during the observed period of substorms, suggesting that the exohiss waves, which exhibit poleward Poynting flux vector, can be amplified due to local electron cyclotron resonance. Based on the Van Allen Probe, Wang JL et al. (2020) indicate that exohiss waves have higher occurrence rates on the dayside (MLT = 8–20, $L = 3$ –6), and a positive correlation between the hiss waves and exohiss waves (correlation coefficient (cc) of more than 0.3). However, the relationship between exohiss waves (with different directional Poynting flux) and geomagnetic activity is still unclear.

In the present study, in order to explore the intensity of exohiss waves under different geomagnetic conditions, and according to the direction of Poynting flux vector, we categorize exohiss waves (observed by Van Allen Probe A from 1st January 2013 to 31st June 2017) into two types: unidirectional exohiss (unique poleward or equatorward exohiss), and bidirectional exohiss waves (poleward and equatorward exohiss waves that are mixed together). The statistical global distribution of exohiss waves (with both unidirectional and bidirectional vectors) associated with different level of geomagnetic activity are exhibited, respectively. Furthermore, in order to explain the variation of exohiss waves under different levels of geomagnetic activity, variations in hiss waves and Landau damping due to hot electrons are also investigated in this study.

In Section 2, we describe the data and methodology for identifying exohiss waves, and categorize them according to the vector of Poynting flux. Section 3 shows the statistical global distributions of both unidirectional exohiss and bidirectional exohiss at different levels of geomagnetic activity. In order to explain the relationship between exohiss waves and hiss waves (Landau damping due to hot electrons), the global distribution of corresponding hiss and Landau damping rate are shown in Section 4. Finally, we summarize the main conclusions in Section 5.

2. Data and Methodology

2.1 Data Sources

The Radiation Belt Storm Probes Mission is comprised of two

spacecraft launched in August 2012 by the National Aeronautics and Space Administration. These two spacecraft, also commonly known as Van Allen Probes A and B, operate in a highly elliptical orbit with a perigee of $\sim 1.2 R_E$ and an apogee of $\sim 5.8 R_E$ (Mauk et al., 2012). The apogee of Van Allen Probe satellites encircles the earth once every ~ 18 months. The Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrumentation suite aboard the Van Allen Probes provides measurements of DC magnetic fields, and a comprehensive set of wave electric and magnetic field with frequency range from 10 Hz up to 12 kHz (Kletzing et al., 2013). In the present study, the electron number density data is calculated from the trace of upper hybrid resonance frequency (Mauk, 2013), which is also detected by EMFISIS. The Level 4 data set of Van Allen Probe A provides wave power spectral density, ellipticity, wave normal angle (WNA), and planarity. In addition, the differential electron fluxes with energy from 0.1 keV to 10 keV are collected by the Helium Oxygen Proton Electron (HOPE) Mass Spectrometer aboard Van Allen Probe. Here, the data detected by Van Allen Probe A from 1st January 2013 to 31st June 2017 (54 months in total) are adopted to investigate the distribution of exohiss waves during different levels of geomagnetic activity.

2.2 The Method for Identifying Exohiss Waves

In order to clearly distinguish exohiss waves outside of plasma-pause from hiss waves inside the plasma-pause, first the outer edge of the plasma-pause is identified. In our study, the criterion to identify the plasma-pause is exhibited as follows, which is similar to the method mentioned in the study of Wang JL et al. (2020): (1) The central position of plasma-pause (L_{pp}) is identified as the innermost steep gradient of electron density, which demands the electron density to decrease by a factor >5 within $0.5 L$ shell (Moldwin et al., 2002; Malaspina et al., 2016; Zhang and Paxton, 2019); (2) To establish plasma-pause thickness, we consider $L_{pp} + 0.15L$ as the outer edge (L_{oe}) of the plasma-pause; (3) While the Van Allen Probes are operating outside the plasma-pause, the region where electron density exceeds the density value calculated by Sheeley plasmasphere model

$$n_e = 1390 \times \left(\frac{3}{L}\right)^{4.83} - 440 \times \left(\frac{3}{L}\right)^{3.60} - 5 \quad (1)$$

is interpreted as the plasmaspheric plume (Sheeley et al., 2001).

In our work, there are 2177 half-orbits in which the position of plasma-pause can be recognized during the interval from 1st January 2013 to 31st June 2017. The exohiss waves are then sought in these orbits using data from Van Allen Probe A. The waves beyond the plasmasphere and plasmaspheric plume that satisfy the following conditions are interpreted as the exohiss waves: (1) The magnetic power spectral densities are more than 10^{-8} nT²/Hz; (2) The frequencies are limited below $0.07 f_{ce}$; (3) In order to exclude the magnetosonic waves, the ellipticity of waves should be more than 0.5, the WNA should be less than 75° , and the planarity of waves should be more than 0.3; (4) The successive spectrum satisfying above conditions is more than 8 minutes; (5) The low-frequency choruses with frequencies below $0.07 f_{ce}$ are artificially excluded.

The mixed Poynting flux vector suggests that the hiss-like waves may simultaneously propagate from poleward and equatorial directions, and suffer from obvious Landau damping in the process (Zhu H et al., 2015; Laakso et al., 2015; Su ZP et al., 2018; Shi R et al., 2019). On the other hand, the energy of hiss-like waves with unidirectional Poynting flux vector is mainly from the amplification of local cyclotron resonance (Su ZP et al., 2018; Gao ZL et al., 2018; Shi R et al., 2019). In the study, the exohiss waves are divided among two types: the exohiss waves with unidirectional Poynting flux vector, and exohiss waves with bidirectional Poynting flux vector. In order to estimate whether the exohiss waves are unidirectional or bidirectional types, we calculate the Poynting flux vector with a time resolution of 6 s by singular value decomposition (SVD) method (Santolík et al., 2003). The determination is conducted as follows: (1) Distinguishing the direction of exohiss wave Poynting flux vector for every exohiss wave sample (every moment and frequency); (2) During a time interval of 5 minutes, if more than 70% samples of exohiss propagate in the same direc-

tion, we consider the exohiss waves as unidirectional. If the above conditions are not met, the exohiss waves are regarded as bidirectional ones.

Figure 1 presents an example of exohiss waves observed by Van Allen Probe A on 3 January 2014. The black vertical line marks the position of central plasmopause (L_{pp}), and the blue vertical line marks the outer position of plasmopause (L_{op}). In the time interval from 07:20 UT to 09:00 UT, Van Allen Probe A is located outside the plasmopause on the afternoon side. As indicated by the box with dashed red lines in Figure 1b, the ellipticity (>0.5), WNA ($<40^\circ$) and planarity (>0.3) indicate that the observed plasma waves below 400 Hz from 07:25 UT to 09:00 UT are exohiss waves. In addition, the chorus waves with a frequency >900 Hz are observed from 07:45 UT to 09:00 UT, and the hiss waves are observed inside the plasmopause. As shown in Figure 1f, the exohiss waves are classified into the unidirectional exohiss section indicated with a green panel, and the bidirectional exohiss section

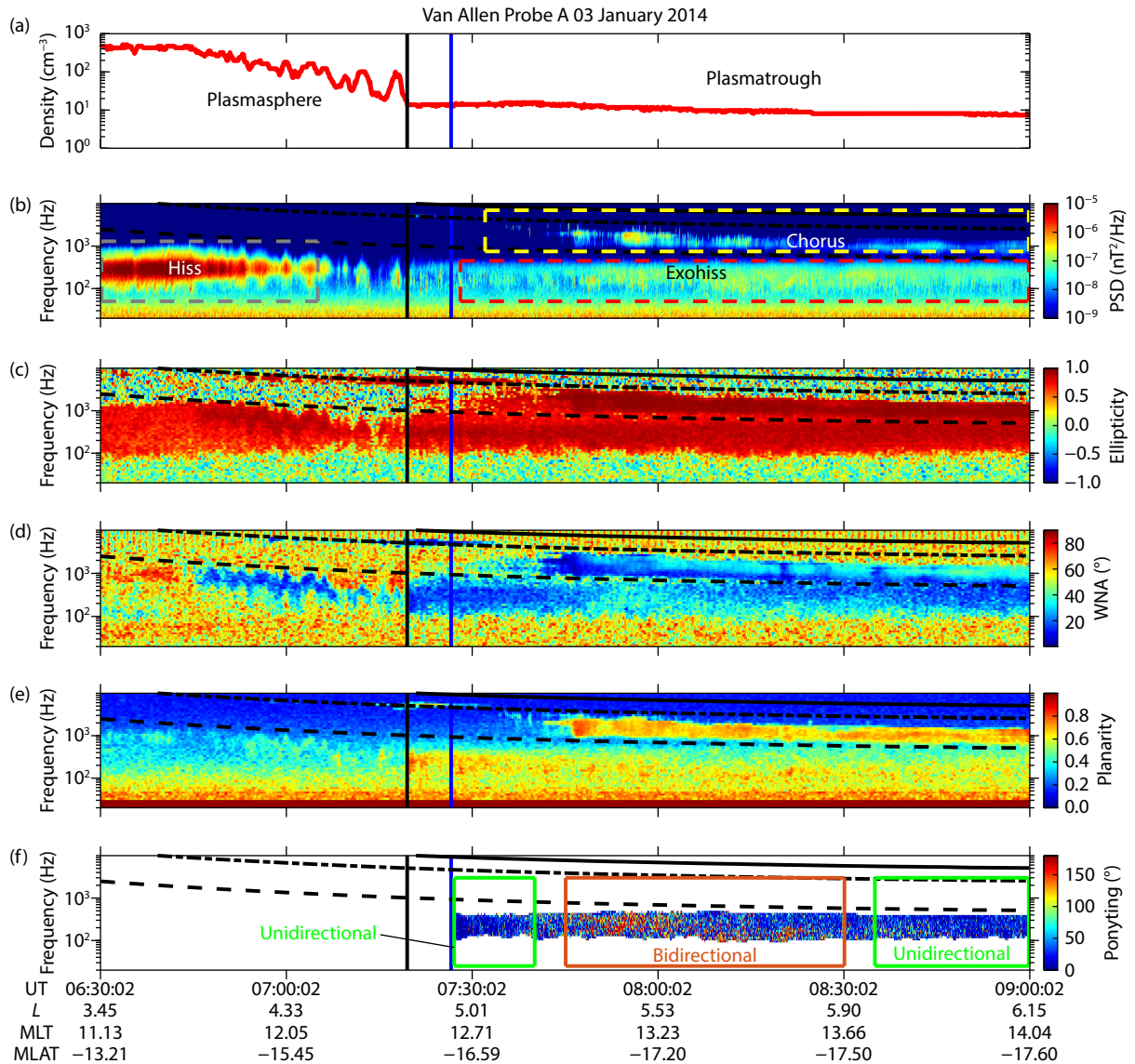


Figure 1. Examples of bidirectional and unidirectional exohiss waves on 3 January 2014. The black solid line shows the f_{ce} . The dash-and-dot line shows $0.5 f_{ce}$. The dashed line shows $0.1 f_{ce}$.

indicated with an orange panel, according Poynting flux vector. In the present study, both the poleward and equatorward exohiss waves are classified as unidirectional type.

3. Statistical Distribution of Exohiss Waves

Based on the observations of Van Allen Probe A from 1st January 2013 to 31st June 2017, Figure 2 shows the global distributions of mean exohiss wave amplitude (B_w) at different levels of geomagnetic activity (AE^*). The blank indicates that the number of exohiss waves sample (identified through the criterion described in Section 2.2) is <5 in this region. The AE^* indicates the maximum value of AE index in the preceding 3 hours. It seems that there is obvious day–night asymmetry throughout the exohiss waves distribution. The exohiss with high B_w is mainly observed from MLT ~ 04 to MLT ~ 20 . In addition, the exohiss waves can expand to lower L shells during stronger geomagnetic activity, which can be found within $L < 4$ while $AE^* > 100$ nT. This may be due to erosion of the plasmasphere during intense geomagnetic activity. Interestingly, in the prenoon sector, the intensity of exohiss decreases slightly with the enhancement of substorms, especially in the region with a large L shell. This differs from the statistical distributions of hiss and chorus waves, which suggest that the intensities of hiss and chorus waves increase with the enhancement of geomagnetic activity (Li W et al., 2009, 2011; Li W et al., 2015; Su

JP et al., 2018). On the other hand, the intensity of exohiss waves from MLT ~ 12 – 18 increase with the enhancement of geomagnetic activity.

Here, we classify the exohiss into unidirectional (including poleward and equatorward exohiss waves) and bidirectional types according to the Poynting flux vector. Because the intensity of poleward exohiss waves is much smaller than the intensity of equatorward exohiss, we combine these two exohiss wave types as one. As shown in Figures 3a–c, it seems that the amplitude of bidirectional exohiss waves is significantly stronger than that of unidirectional exohiss waves. This may indicate that the main source of exohiss waves are the residual energy of plasmaspheric hiss waves that simultaneously leak out of the plasmasphere from both the north and south directions. Similarly to Figure 2, there is no obvious positive correlation between the bidirectional exohiss wave intensities and geomagnetic activity on the prenoon side. On the other hand, the intensity of bidirectional exohiss waves on the afternoon side shows some increase with the enhancement of geomagnetic activity.

The variations of unidirectional exohiss waves are shown in Figures 3d–e. It suggests that the intensity of unidirectional exohiss waves is much weaker than that of bidirectional ones. The unidirectional exohiss waves are mainly distributed on the after-

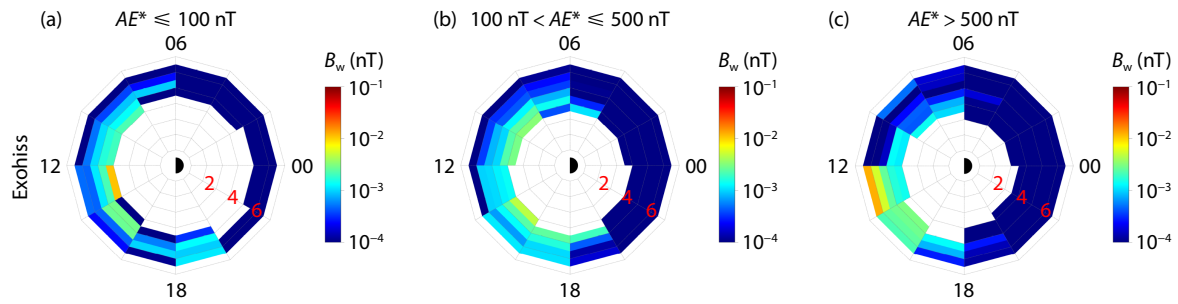


Figure 2. Global distributions of exohiss waves categorized by different AE^* .

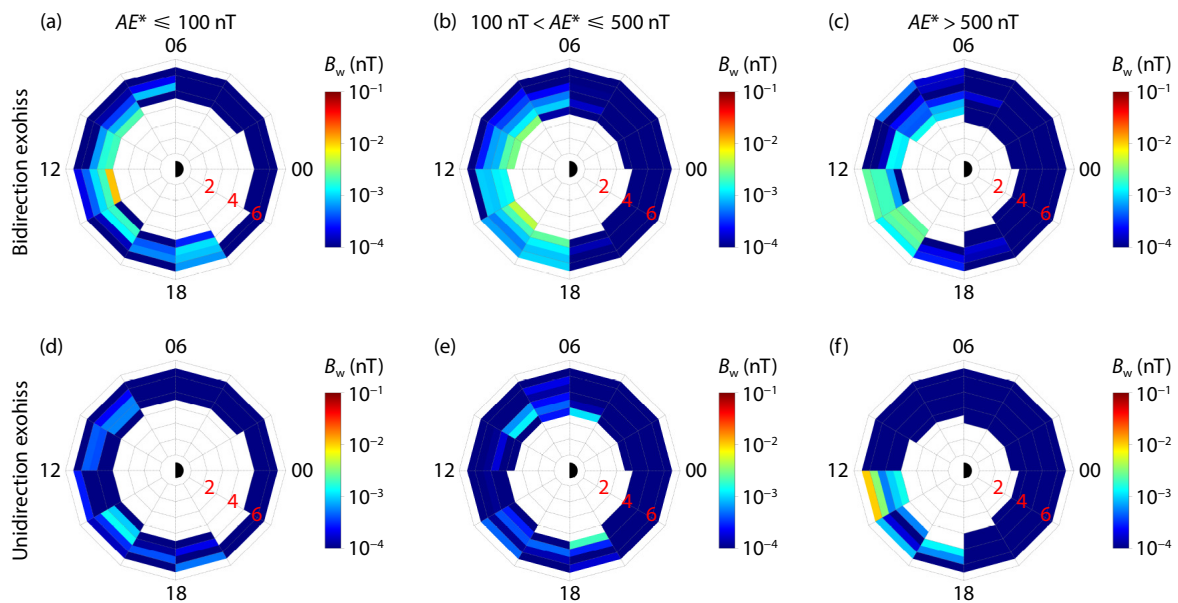


Figure 3. Global distributions of bidirectional and unidirectional exohiss waves categorized by different AE^* , respectively.

noon side. In addition, the intensity of unidirectional exohiss waves on the afternoon side obviously increase with the enhancement of geomagnetic activity.

4. Discussion

The main source of exohiss waves, especially for the bidirectional exohiss waves, is from inside the plasmasphere. Furthermore, the hiss-like waves suffer from obvious Landau damping during propagation. In order to better investigate the variation in distribution of exohiss waves under different levels of geomagnetic activity, the corresponding distributions of plasmaspheric hiss waves detected by Van Allen Probe A from 1st January 2013 to 31st June 2017 are shown in Figure 4. Here, the criterion to identify the plasmaspheric hiss waves is similar to that of exohiss waves, but they are distinguished inside the inner edge (L_{ie}) of plasmopause ($L_{pp} - 0.15L$). This implies a strong positive correlation between the intensity of plasmaspheric hiss and AE^* . Additionally, a noteworthy day–night asymmetry of plasmaspheric hiss waves is exhibited. The intensity of plasmaspheric hiss waves on the dayside is much higher than that on the nightside. As geomagnetic activity strengthens, the amplitude of plasmaspheric hiss waves clearly increases, especially for the region at MLT ~ 04 – 20 , which is generally associated with substorm injection. However, as described in Section 3, there is no obvious enhancement of bidirectional Exohiss waves during strong geomagnetic activity. Some other factors may also control the variation of exohiss waves besides the waves source (e.g. plasmaspheric waves).

The whistler-mode waves undergo Landau damping of the suprathermal electrons in the process of propagation, especially while outside of plasmopause (Bortnik et al., 2011; Chen LJ et al., 2012). In order to explain the amplitude variation of exohiss waves associated with AE^* , we attempt to estimate the Landau damping rate near the geomagnetic equator as functions of L and MLT

during different level of geomagnetic activity, based on the observations of Van Allen Probe A from 1st January 2013 to 31st June 2017. Here, the averages of background geomagnetic field, total electron number density, hot electron density and temperature at different L ($L \sim 2$ – 6) and MLT grids are calculated and averaged. In addition, we compute the hot electron temperature and density using the electron differential flux at the electron energy range of 0.1–10 keV, which are the energy levels of electrons most significantly involved in the Landau interaction (Bortnik et al., 2003). Landau damping rate is calculated by γ/Ω_{ce} , where γ indicates growth rate, and Ω_{ce} indicates electron cyclotron frequency. The calculation of γ refers to the study performed by Kennel (1966). In the present study, only the hot electron density and temperature in the magnetic equatorial plane are considered.

Figure 5 shows the global distribution of Landau damping rates during different levels of geomagnetic activity. It seems that the Landau damping rate with higher L shell is larger than with lower L shell. In the region with $L > 4.5$, the Landau damping rate on the nightside and prenoon side increases sharply with the enhancement of geomagnetic activity, which is generally associated with hot electron injection from the plasma sheet during substorm. However, there is no increase of Landau damping on the afternoon side with the enhancement of geomagnetic activity. This may be due to intense convection during high levels of geomagnetic activity, which brings about sunward motions of hot electrons and the decrease of hot electron flux on the afternoon side. During periods of strong geomagnetic activity, the exohiss waves (especially for bidirectional exohiss waves) on the prenoon side experience significant attenuation due to intense Landau damping with large L shells, this may offset the intensification of hiss source inside plasmopause.

For this study, we conduct ray-tracing in the pre-noon sector and the afternoon sector during different levels of geomagnetic activ-

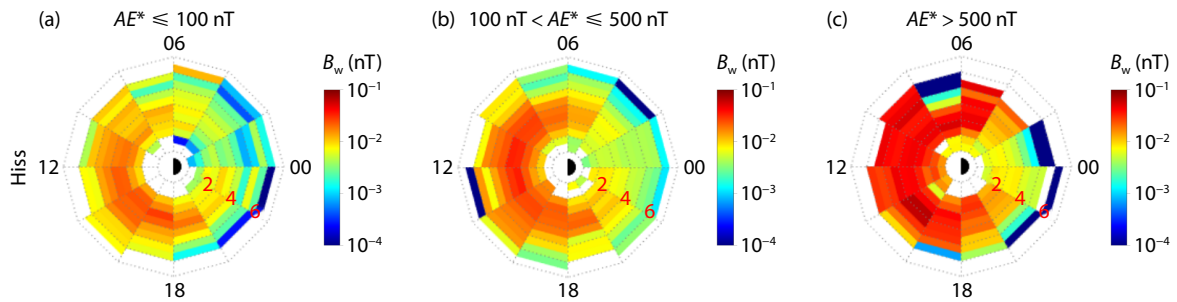


Figure 4. Global distributions of hiss waves categorized by different levels of AE^* .

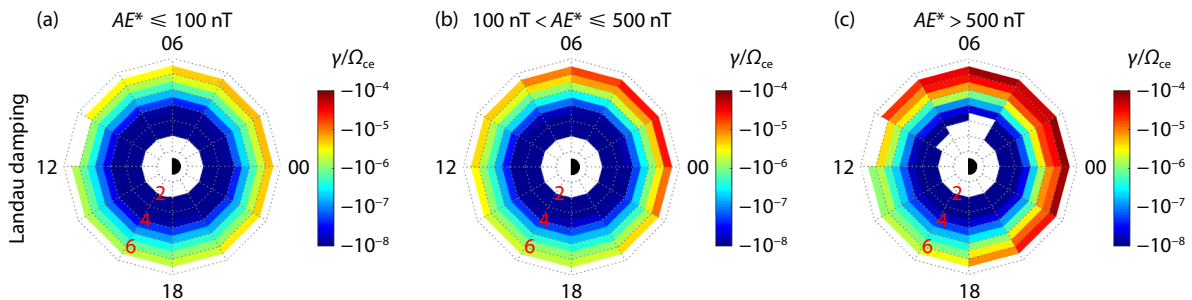


Figure 5. Global distributions of Landau damping rate during different level of AE^* .

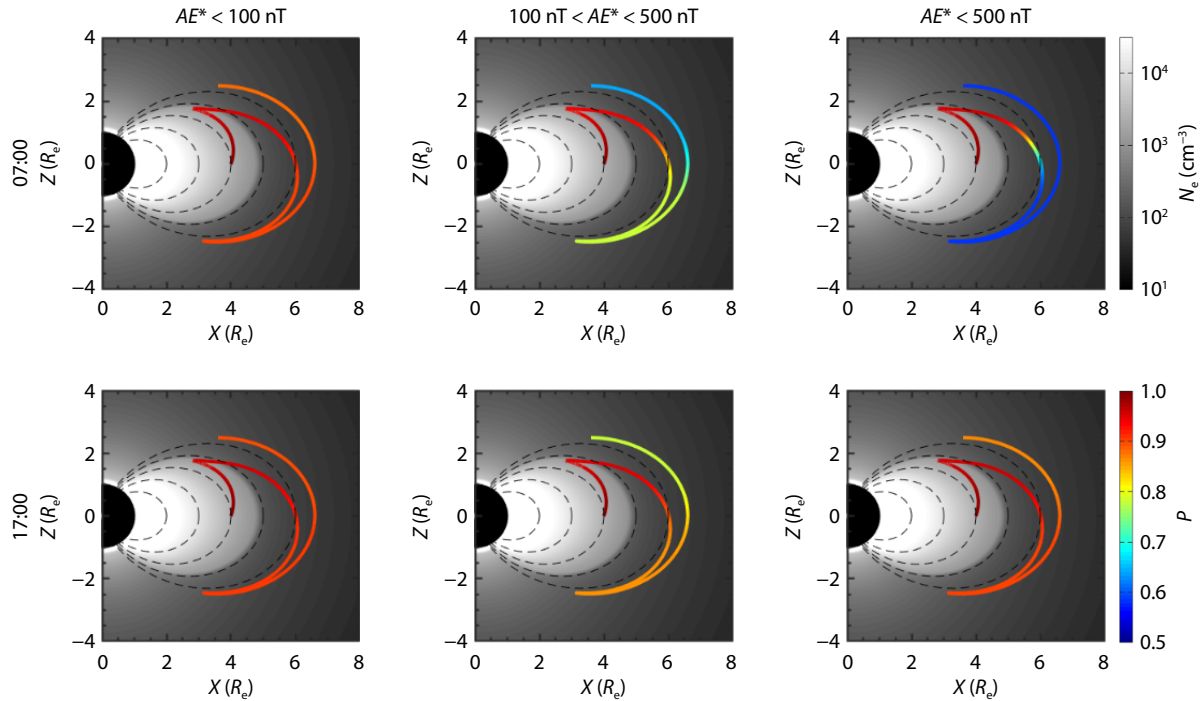


Figure 6. Raypaths of hiss rays with initial WNA = 50°, $L = 4$ at MLT = 7 and 17 during different levels of geomagnetic activity. It is represented in SM coordinate, R_e is the radius of the Earth, and p indicates represents the ratio of the PSD at this time to the initial PSD.

ity. Figure 6 shows the raypaths of hiss rays injected at $L = 4$ with initial WNA = 50° at MLT~7 and MLT~17 during different level of geomagnetic activity. The black and white background represents the plasma number density. The color represents the ratio of the PSD at this time to the initial PSD. It can be observed that the attenuation of the exohiss during the propagation process at MLT~7 gradually increases with the enhancement of geomagnetic activity, due to the increase of Landau damping. However, that at MLT~17 does not change significantly due to Landau damping does not increase obviously.

5. Conclusion

In the present study, we have calculated the root-mean-square amplitude of exohiss and the average suprathermal electron flux based on the date detected by Van Allen Probe-A from 1st January 2013 to 31st June 2017. The findings are summarized as follows:

- (1) The amplitudes of exohiss waves (including bidirectional and unidirectional types) during different levels of geomagnetic activity are statistically investigated. The exohiss waves are mainly distributed on the dayside, which is similar to the hiss waves.
- (2) The amplitude of exohiss waves is much lower than that of hiss waves.
- (3) The unidirectional exohiss waves mainly distribute on the afternoon side, and the waves become stronger during high levels of substorm activity.
- (4) The amplitudes of bidirectional exohiss waves on the prenoon side increase very little during periods of intense geomagnetic activity, which may be due to serious Landau damping during intense geomagnetic activity.
- (5) The bidirectional exohiss waves on the afternoon side are obvi-

ously amplified with the intensification of geomagnetic activity, as the Landau damping rate doesn't exhibit obvious enhancement on the afternoon side.

Acknowledgments

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Data Availability Statement

The Van Allen Probes data used for this study are publicly available at the websites: <https://spdf.gsfc.nasa.gov/pub/data/rbsp/>, and the AE data are publicly available at the websites <https://spdf.gsfc.nasa.gov/pub/data/omni/>.

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