Exohiss wave enhancement following substorm electron injection in the dayside magnetosphere

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Abstract: Exohiss is a low-frequency structureless whistler-mode emission potentially contributing to the precipitation loss of radiation belt electrons outside the plasmasphere. Exohiss is usually considered the plasmaspheric hiss leaked out of the dayside plasmapause. However, the evolution of exohiss after the leakage has not been fully understood. Here we report the prompt enhancements of exohiss waves following substorm injections observed by Van Allen Probes. Within several minutes, the energetic electron fluxes around 100 keV were enhanced by up to 5 times, accompanied by an up to 10-time increase of the exohiss wave power. These substorm-injected electrons are shown to produce a new peak of linear growth rate in the exohiss band (< 0.1 $\Omega$). The corresponding path-integrated $\Omega$-value is in the range of 13.4, approximately explaining the observed enhancement of exohiss waves. These observations and simulations suggest that the substorm-injected energetic electrons could amplify the preexisting exohiss waves.

Keywords: exohiss; substorm injection; radiation belt; whistler-mode instability

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1. Introduction

Wave-particle interaction is one of the most important mechanisms controlling the radiation belt dynamics (see review by Thorne, 2010). In particular, two types of whistler-mode waves, chorus and plasmaspheric hiss, are frequently invoked to explain the acceleration and loss of radiation belt electrons (e.g., Abel and Thorne, 1998; Horne and Thorne, 1998; Summers et al., 1998, 2002; Horne et al., 2005; Shprits et al., 2006; Artemyev et al., 2012; Thorne et al., 2013; Ni BB et al., 2014; Su ZP et al., 2014a, 2016; Gao ZL et al., 2016; Yang C et al., 2016). The generation/evolution of the two types of whistler-mode waves has been studied extensively. The substorm-injected anisotropic energetic (from a few keV to tens of keV) electrons outside the plasmasphere are believed to provide the free energy of chorus (e.g., Kennel and Engelmann, 1966; Li W et al., 2009; Su ZP et al., 2014b); the discrete frequency-time structures (e.g., Santolik et al., 2014) of chorus are usually considered a result of the nonlinear cyclotron resonance (e.g., Nunn et al., 1997; Omura et al., 2008). For plasmaspheric hiss, the candidate generation mechanisms include: (1) origination from lightning whistlers in the plasmasphere (e.g., Sonwalkar and Inan, 1989; Green et al., 2005), (2) excitation by electron cyclotron instability in the outer plasmasphere (Thorne et al., 1979; Li W et al., 2013; Chen LJ et al., 2014; Summers et al., 2014), and (3) origination from chorus outside the plasmasphere (Bortnik et al., 2008, 2009; Su ZP et al., 2015; Liu NG et al., 2017).

In fact, there exists another type of whistler-mode wave, named exohiss, outside the plasmasphere (Russell et al., 1969; Thorne et al., 1973; Solomon et al., 1988; Kurth and Gurnett, 1991; Golden et al., 2009, 2011). Different from the normal (Santolik et al., 2002,
growth rate can be expressed as a function of the wave frequency (Chen LJ et al., 2010, equations (A3)) with angular frequency \( \omega \), wave normal angle \( \psi \), and wave number \( k = k \cos \psi \hat{e}_x + k \sin \psi \hat{e}_y \). The electron phase space density and its partial derivative with respect to the velocity vector are required to calculate \( D \) (Chen LJ et al., 2010, equations (A4)). Those fitting parameters for the electron phase space density are specified in the following sections.

3. Event on 21 February 2014

3.1 Observation

Figure 1 gives an overview of the exohiss enhancement event observed by the twin Van Allen Probes in the time range 06:00–12:00 UT on 21 February 2014. During this time range, the magnetosphere was experiencing a moderate storm (SYM-H ~ -50 nT) and some moderate substorms (AE > 600 nT). A steep density gradient in the plasmapause was detected by Van Allen Probe A around 06:50 UT and by Van Allen Probe B around 11:30 UT. There existed plasmaspheric hiss waves (0.1–2 kHz) inside the plasmasphere but chorus (0.1–0.5\( f_{ce} \)) and exohiss (0.1–0.4 kHz) outside the plasmasphere (Here \( f_{ce} \) represents the equatorial electron gyro-frequency). The three types of whistler-mode waves were right-hand polarized with ellipticity values >0.7, but had distinct characteristics of normal angle, planarity, and Poynting flux direction. Due to bounce propagation in the plasmasphere, plasmaspheric hiss waves had low values of planarity, broadly distributed wave normal angles (30°–70°), and nearly randomly distributed Poynting flux directions. Chorus waves possessed small wave normal angles (< 20°), large planarity values (> 0.7) and negative Poynting fluxes, indicating their equatorial generation and poleward propagation. Exohiss waves exhibited small wave normal angles (< 30°) and moderate planarity values (0.5–0.8). The Poynting flux direction of exohiss appeared to be dependent on magnetic latitude and wave frequency (Zhu H et al., 2015). Around the most negative latitudes (−17° < MLAT < −14°), exohiss waves were dominated by equatorward propagations. As the twin probes moved toward the equator, the expanding high-frequency part of exohiss showed poleward propagations. These observations imply the leakage of plasmaspheric hiss from both the Northern and Southern Hemispheres of the plasmasphere. Compared to plasmaspheric hiss, exohiss had an up to 2 orders of magnitude lower power spectral density. A substorm injection arrived at Probe A around 09:30 UT; about five minutes later, Probe B also encountered the substorm injection. During the time period of the substorm injection, both probes were in the dayside (MLT ~ 12:00–13:00) southern hemisphere (MLAT < −10°) at \( L \sim 6 \). The fluxes of injected electrons in the energy-time domain were wedge-shaped resulting from the energy-dependent azimuthal drift of electrons. The upper energy cut-offs of the substorm injection were \( \sim 200 \) keV, and the corresponding minimum cyclotron resonant frequencies were 0.1–0.3 kHz (depending on \( L\)-shell). The substorm injection promptly enhanced the exohiss wave power detected by both probes. For Probe A, there was a 10 times enhancement of exohiss power and the enhanced exohiss and chorus bands merged after the substorm injection. For Probe B, the exohiss wave power increased...
less than 5 times and a gap with a minimum of wave power between exohiss and chorus bands existed all the time.

Figures 2 and 3 show the wave fine structure observed by two probes before and after the substorm injection. In the frequency-time spectra, the pre-injection chorus and exohiss were basically split in frequency by 0.1f_{ce}. After the substorm injection, the wave power spectral densities over a wide frequency range were enhanced obviously but no significant changes in wave fine struc-

Figure 1. Exohiss amplification event recorded by Van Allen Probes A (left) and B (right) on 21 February 2014. (a) Geomagnetic activity indices AE and SYM-H with the yellow shadow marking the interval of interest; (b, i) Cold electron density; (c, j) Electron differential flux; (d, k) Wave magnetic power spectral density; (e, l) Wave normal angle; (f, m) Wave ellipticity; (g, n) Wave planarity and (h, o) sign of Poynting flux parallel to background magnetic field (positive value for northward direction and negative value for southward direction). Dotted lines in Figures 1c and 1j denote the upper energy cut-off of the substorm, and dotted lines in Figures 1d and 1k denote the corresponding minimum resonance frequency. Dashed lines in Figures 1d–1h and 1k–1o represent 0.1f_{ce} and 0.5f_{ce}. The vertical red and black lines mark the location of the plasmapause and the arrival time of the substorm injection, respectively. The normal angle, ellipticity, planarity and Poynting direction are shown only for the corresponding power spectral densities P_{B} > 5 \times 10^{-8} \text{nT}^{2} \text{Hz}^{-1}.
Before the substorm injection, the hot electron phase space density was modeled as a combination of three subtracted Max-wellian components (Ashour-Abdalla and Kennel, 1978):

$$ F = \sum_{i=1}^{3} F_i = \sum_{i=1}^{3} \frac{n_i}{\sqrt{\pi} \mu_{i,1}} \mu_{i,2} \exp \left(-\frac{v_{i,1}^2}{\mu_{i,2}}\right) \times \left[ \sigma_i \exp \left(-\frac{v_{i,2}^2}{\mu_{i,1}}\right) + \frac{1}{1-\sigma_i} \exp \left(-\frac{v_{i,2}^2}{\mu_{i,1}}\right) - \exp \left(-\frac{v_{i,2}^2}{\mu_{i,1}}\right) \right], $$

with density parameter $n_i$, thermal parameters $\mu_{i,1}$ and $\mu_{i,2}$, and loss cone parameters $\sigma_i$ and $\beta_i$ of each component. After the substorm injection, the two low energy components are assumed to be unchanged. To reproduce the phase space density peak near $E_i = 100$ keV, the third component is expressed as

$$ F_3 = \rho \left( \sin^2 \alpha + \epsilon \right) \exp \left[ -\frac{(v_i - \mu)^2}{\tau} \right], $$

with density-like parameter $\rho$, thermal parameters $\mu$ and $\tau$, and loss cone parameters $\zeta$ and $\epsilon$. All these fitting parameters before and after the substorm injection are listed in Table 1. Clearly, the modeled and observed electron phase space densities agree reasonably well with each other for both probes.

Figure 5 shows the wave growth rates and spectral densities before and after the substorm injection. According to the observa-

Figure 2. (a–f) Pre-substorm and (g–l) post-substorm wave fine structure recorded by Van Allen Probe A. (a, b, g, h) Power spectral density; (c, i) Wave normal angle; (d, j) Ellipticity; (e, k) Planarity, and (f, l) sign of Poynting flux parallel to background magnetic field. The dashed lines in each panel represents the frequency of 0.1 and 0.5$f_{ce}$. The normal angle, ellipticity, planarity and Poynting direction are only shown for the corresponding power spectral densities $P_b > 10^{-8}$ nT²Hz⁻¹.
Figure 3. Same as Figure 2 but for Probe B.

Figure 4. Observed (circles) and modeled (lines) electron phase space densities for Van Allen Probes A (a–c) and B (d–f): (a, d) energy-dependent profiles at the pitch angle $\alpha = 90^\circ$; (b, c, e, f) pitch-angle-dependent profiles at the selected energies.
tions in Figures 1e and 2c, the linear instabilities of parallel-propagating whistler waves are analyzed for Probe A. Before the substorm injection, the most pronounced peak of the growth rate occurs in the chorus band centering at $f/f_{ce} = 0.25$. After the substorm injection, the modeled electron phase space densities below $E_e < 60$ keV are unchanged (Figure 4) and the magnitudes of wave growth rates in the frequency range $f/f_{ce} = 0.15–0.37$ increase slightly, roughly explaining the insignificant variation of the power spectral densities in the chorus band. In contrast, the enhancement of electron phase space densities above $E_e > 60$ keV produces a new peak ($1.1 \times 10^{-7}$ m$^{-1}$) of wave growth rate in the frequency range $0.03–0.1f_{ce}$. According to the linear theory, the preexisting exohiss lying in the frequency range below $0.1f_{ce}$ should experience an amplification. Assuming that the exohiss amplification occurs within 10° latitude of the magnetic equatorial plane (with the magnetic field line length $s \sim 1.3 \times 10^7$ m) and that the wave growth rates are constant ($K_i \sim 10^{-7}$ m$^{-1}$), we can roughly obtain the path-integrated amplification ratio of exohiss power $\bar{P} = \frac{P_i}{P_f} = [\exp(K_i s)]^2 = 13.4$ (with final wave power $P_f$ and initial wave power $P_i$). The simulated amplification generally explains the observed intensification (up to 10 times) of exohiss power spectral densities. Considering the observed normal angle
variations for Probe B (Figures 1l and 3i), we have calculated the wave linear growth rates at normal angles of 0°, 15°, 25°, 30° and 35°, respectively. One can find that, for the whistler wave with a larger normal angle, the frequency range allowing wave growth becomes narrower, and the corresponding peak growth rates become lower. Because of the increase of exohiss wave normal angle after the substorm injection (Figures 1l and 3i), Probe B observed a weaker enhancement of wave power than Probe A. The wave growth rates at larger normal angles exhibit a more obvious gap between exohiss and chorus bands, explaining the merged quasi-parallel bands of RBSP-A and the split oblique bands of RBSP-B.

Considering the temporal evolution of injected electron fluxes, we analyze the dynamic instabilities of whistler waves over a time period to give a more comprehensive view of exohiss amplification. As shown in Figure 5, the exohiss is amplified mainly by energetic (> 60 keV) electrons. We use the smooth cubic spline approximation (Reinsch, 1967) to model the electron phase space density observed by MagEIS (> 30 keV) and adopt the B-spline interpolation (De Boor, 1977) to evaluate the required partial derivative of the electron phase space density with respect to the velocity vector (more details given by Liu NG et al., 2018a). In Figure 6, one can observe clear correlations between enhancements in the observed wave power and in the calculated growth rates of exohiss waves. The obtained growth rates appear to be quite small (10^{-8}–10^{-7} m^{-1}), suggesting that it is difficult for energetic electrons alone (without preexisting source waves) to produce observable whistler waves. However, when wave growth is allowed in the frequency range of < 400 Hz, the preexisting exohiss can be effectively amplified. After 09:50 UT, the peak frequency of the wave growth rate increases rapidly, accounting for the observed frequency variation of exohiss waves. The main cause is the rapid decrease of the upper energy cut-off of the substorm-injected electrons. Corresponding to the observed weakening of wave

![Figure 6](image_url). Variations of wave power $P_B$ (a, c) and convective growth rate $K_i$ (b, d, e) for whistler-mode waves around the substorm event on 21 February 2014. Dashed lines in each figure represent 0.1, 0.2, and 0.5 $f_{ce}$. The vertical black lines mark the arrival time of the substorm injection.
power for Probe A after 10:55 UT and for Probe B after 10:30 UT, the calculated growth rates decrease significantly because of the reduction of electron temperature anisotropy.

4. Event on 5 May 2014

To illustrate the generality of the previously obtained results, we additionally show an exohiss amplification event observed by the Van Allen Probes on 5 May 2014. An overview of this event is given in Figure 7; the wave fine structure of Probe B before and after the substorm injection is given in Figure 8. The propagation characteristics of plasmaspheric hiss, chorus, and exohiss were quite similar to those of the previous event on 21 February 2014. Outside the plasmapause, both the exohiss and the lower band chorus appeared to be structureless, while some rising tones constituted the upper band chorus. Around 07:30, the chorus exhibited a reversion in the direction of Poynting flux across the equator, indicating its equatorial generation (Santolik et al., 2003b). In contrast, the exohiss leaked out of the high-latitude plasmapause (Thorne et al., 1973) had bi-directional Poynting flux near the...
equator (Zhu H et al., 2015). The substorm injection was detected by the twin Van Allen Probes around 06:35 UT in the dayside (MLT ~ 08:00–09:00) equatorial region at L ~ 5–6. The upper energy cut-offs of the substorm injection were ~ < 200 keV, and the corresponding minimum cyclotron resonant frequencies were well below the lower frequency cut-offs of the exohiss waves. After the substorm injection, the exohiss waves were obviously intensified (up to 10 times, at the location of Probe B). Using the MagEIS data (>30 keV), we calculate the linear growth rates of parallel-propagating whistler waves (Figure 9). Just after the substorm injection, the modeled growth rates peak around 600 Hz for Probe A, producing relatively limited effect on exohiss in the frequency range of 100–500 Hz. About 20 min later, the decreased background magnetic field allows the growth of waves at lower frequencies, corresponding to the significant enhancement of exohiss waves observed by Probe A. In contrast, Probe B encountered the substorm injection at an outer L-shell with a weaker background magnetic field and then observed a prompt enhancement of exohiss after the substorm injection. These results support the conclusion that substorm injected energetic electrons amplify exohiss.

5. Summary
Generation and evolution of whistler-mode chorus and plasmaspheric hiss have attracted considerable attention in past decades. In this study, we focus on the evolution of a poorly-understood whistler-mode emission outside the plasmasphere named exohiss (Thorne et al., 1973). On 21 February 2014, the twin Van Allen Probes detected a substorm injection in the noonside (MLT ~ 12:00–13:00) southern hemisphere (MLAT < –10°) outside the plasmasphere (L = 6.0). In response to the sudden enhancement of 60–200 keV energetic electron fluxes by up to 5 times, the power spectral densities of exohiss waves exhibited intensification of up to 10 times. The linear instability of energetic electrons (Kennel, 1966; Chen LJ et al., 2010) is shown to be able to generally explain the timing and the magnitude of exohiss wave enhancement. Before the substorm injection, the growth rates are found to peak in the chorus band (0.1–0.5fce). The substorm-injected energetic electrons are able to produce a new peak of growth rate in the exohiss band (< 0.1fce). The corresponding peak growth rate is about 10⁻⁷ m⁻¹ and the path-integrated amplification rate of wave power within 10° latitude of the magnetic equatorial plane reaches $P = 13.4$. The analogous evolution characteristics of exohiss were also observed by Van Allen Probes on 5 May 2014. These data and modeling tend to support the amplification of exohiss, probably originating from the plasmaspheric hiss, by substorm-injected energetic electrons.

It should be mentioned that this study is limited to simple analyses of some local plasma instabilities. More rigorous future testing of the exohiss amplification scenario should be done with ray-
tracing simulations (e.g., Horne, 1989) and/or particle simulations. For the events reported here, the substorms caused the exohiss amplitude to increase from <10 pT to ~40 pT. Future studies should investigate the statistical characteristics of exohiss and adopt some global models (e.g., Varotsou et al., 2008; Albert et al., 2009; Shprits et al., 2009; Su ZP et al., 2010, 2011; Tu WC et al., 2014) to accurately evaluate the role of exohiss waves in radiation belt electron dynamics.

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Figure 9. Same as Figure 6 except for the 5 May 2014 event.
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