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Binbin Ni
University of California - Los Angeles

Wen Li
University of California - Los Angeles

R. M. Thorne
University of California - Los Angeles

J. Bortnik
University of California - Los Angeles

Qianli Ma
University of California - Los Angeles

See next page for additional authors

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Resonant scattering of energetic electrons by unusual low-frequency hiss

Binbin Ni¹, Wen Li¹, Richard M. Thorne¹, Jacob Bortnik¹, Qianli Ma², Lunjin Chen², Craig A. Kletzing³, William S. Kurth³, George B. Hospodarsky⁴, Geoffrey D. Reeves⁴, Harlan E. Spence⁵, J. Bernard Blake⁶, Joseph F. Fennell⁶, and Seth G. Claudepierre⁶

¹Department of Atmospheric and Oceanic Sciences, UCLA, Los Angeles, California, USA, ²Physics Department, University of Texas at Dallas, Richardson, Texas, USA, ³Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA, ⁴Space Science and Applications Group, Los Alamos National Laboratory, Los Alamos, New Mexico, USA, ⁵Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, New Hampshire, USA, ⁶The Aerospace Corporation, Los Angeles, California, USA

Abstract We quantify the resonant scattering effects of the unusual low-frequency dawnside plasmaspheric hiss observed on 30 September 2012 by the Van Allen Probes. In contrast to normal (~100–2000 Hz) hiss emissions, this unusual hiss event contained most of its wave power at ~20–200 Hz. Compared to the scattering by normal hiss, the unusual hiss scattering speeds up the loss of ~50–200 keV electrons and produces more pronounced pancake distributions of ~50–100 keV electrons. It is demonstrated that such unusual low-frequency hiss, even with a duration of a couple of hours, plays a particularly important role in the decay and loss process of energetic electrons, resulting in shorter electron lifetimes for ~50–400 keV electrons than normal hiss, and should be carefully incorporated into global modeling of radiation belt electron dynamics during periods of intense injections.

1. Introduction

Plasmaspheric hiss is an important magnetospheric emission responsible for inner magnetospheric electron precipitation over a broad energy range. Hiss-induced relativistic electron precipitation loss accounts for the formation of the slot region between the inner and outer radiation belts [Lyons and Thorne, 1973]. Hiss scattering also plays an important role in driving the slow decay of outer zone relativistic electrons (1–10 MeV) on time scales of tens to hundreds of days and more rapid loss of <1 MeV electrons with time scales of days or less [e.g., Meredith et al., 2006, 2007; Summers et al., 2007, 2008; Thorne et al., 2013; Ni et al., 2013]. The hiss wave normal distribution is primarily quasi-parallel near the geomagnetic equator and becomes more oblique when propagating to higher latitudes [e.g., Santolik et al., 2001; Agapitov et al., 2012], and the dominant wave power typically occurs over a band between 100 Hz and 2 kHz with a spectral intensity peak at several hundred hertz [e.g., Meredith et al., 2006, 2007, 2009; Summers et al., 2008], which is commonly adopted in models to quantify the resonant scattering of radiation belt electrons [e.g., Meredith et al., 2006, 2007, 2009; Summers et al., 2007; Thorne et al., 2013; Ni et al., 2013].

Recently, Li et al. [2013] reported an unusual enhancement of plasmaspheric hiss observed by the Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) instrument [Kletzing et al., 2013] on board the Van Allen Probes [Mauk et al., 2013] on 30 September 2012, which exhibited a frequency spectrum extending as low as ~20 Hz, with ~90% of the wave power below ~100 Hz. The observations also indicated that these unusually low-frequency hiss emissions were excited for a few hours by localized cyclotron resonance instability in the dawnside outer plasmasphere following convective injection of plasma sheet electrons into the plasmasphere. Here we adopt a realistic model for the unusual hiss and investigate its role in resonant scattering of radiation belt energetic electrons and the resultant dynamical evolution of the electron pitch angle distribution.

2. Unusual Hiss Observations and Model Development

The EMFISIS observations on board the Van Allen Probe A of the unusual intense hiss emissions on 30 September 2012 are shown in Figure 1 for the period of 15–19 UT. Enhanced broadband electromagnetic hiss
waves [Li et al., 2013] occurred at frequencies $\approx 40$ Hz to $\approx 2$ kHz for the first 2 h starting at 15 UT. Corresponding to the dramatic flux increase of $\approx 50$–200 keV electrons measured by the Magnetic Electron Ion Spectrometer (MagEIS) instrument [Blake et al., 2013] at $\approx 16:50$ UT, the plasmospheric hiss extended to lower frequencies, down to $\approx 20$ Hz with further intensification, and was observed continuously for more than 1 h until the satellite moved to lower altitudes of $L < \approx 3$. The upper hybrid frequency ($f_{uhr}$) line was identified by the EMFISIS high-frequency receiver channel and is shown as white curve in Figure 1b. Of particular interest to our study is the time interval of 16:50–18:15 UT when Probe A crossed the region of $L = 3.7$–5.3 at 8.5–10 magnetic local time (MLT) and observed the most intense hiss emissions with wave amplitudes ($B_0$) integrated over 20–2000 Hz well above 100 pT. The
ambient plasma density ($N_e$) inferred from the spacecraft potential and the upper hybrid line increased from $\sim 300 \text{ cm}^{-3}$ to $\sim 900 \text{ cm}^{-3}$.

The EMFISIS spectral intensity data for the 75 min time interval are shown in Figure 1f. While there were large variations in wave spectral intensity above 1 kHz, the hiss wave intensity peaked at frequencies $\sim 50$ Hz and the majority of the wave power was confined below 200 Hz. The quartiles of the spectral intensity data are shown as the thick dashed black curves, and the mean value, shown as the thick solid red curve, yields an average integrated hiss amplitude of 195 pT. For comparison, the thick solid blue curve shows the spectral intensity of normal hiss with the same amplitude but characterized by a nominal Gaussian frequency spectrum in terms of $\exp\left[-\left(\frac{f-f_m}{\Delta f}\right)^2\right]$ with the peak wave frequency $f_m = 550$ Hz, the frequency width $\Delta f = 300$ Hz, the lower cutoff frequency $f_c = 100$ Hz, and the upper cutoff frequency $f_u = 2$ kHz [e.g., Meredith et al., 2006; Summers et al., 2007; Thorne et al., 2013]. The normal hiss has larger spectral intensities at frequencies of 300–1200 Hz, but the unusual hiss is much stronger at frequencies $< 200$ Hz. At frequencies $> 1200$ Hz, the wave intensity of the unusual hiss is also stronger than normal hiss.

The distribution of wave normal angle as a function of latitude is another critical parameter required for reliable quantification of hiss-induced scattering rates, which cannot be directly obtained from observations for this event. To acquire this information, ray tracing simulations were performed [e.g., Chen et al., 2012] with a postdawn plasmapause between $L = 5.5$ and $L = 5.8$. A diffusive equilibrium density model [Bortnik et al., 2011] is used, with the equatorial density profile fitted by the plasma density derived from the EMFISIS observed upper hybrid line (Figure 1). Waves with frequencies between 20 Hz and 2 kHz (in steps of 10 Hz) were launched along the field line at the magnetic equator at $L = 5$, and the resulting raypaths are shown in Figure 2a, illustrating the propagation characteristics of hiss emissions at various frequencies inside the plasmasphere. The corresponding latitudinal variations of hiss wave normal angles are shown in Figure 2b. A secondary field-aligned component at high magnetic latitudes ($\sim 30^\circ$–$40^\circ$) occurs near the inner edge of the plasmapause as a consequence of the refraction associated with the density gradient. Because the secondary component only occurred over a narrow $L$ range near the inner edge of plasmapause and we are interested in a general trend of wave normal angle variation inside the plasmasphere of much larger $L$ shell range, the field-aligned component is ignored for our wave normal angle model. It is evident that the maximum magnetic latitude of the hiss power is strongly frequency dependent, increasing from $\sim 30^\circ$ for 20 Hz to $\sim 33^\circ$ for 100 Hz to $\sim 45^\circ$ for 2 kHz. At the same time, the waves become increasingly oblique when propagating toward higher latitudes, i.e., field-aligned at the equator and approaching high wave normal angles $> 80^\circ$ at the frequency-dependent maximum latitude. These ray tracing simulations are used to develop a model for
Line plots of the unusual hiss are reduced by a factor of over 3 compared to the normal hiss results. In contrast, for 20 keV electrons, the variations of hiss scattering rate as a function of equatorial pitch angle and kinetic energy corresponding to their respective latitudinal coverage, which is a good approximation based on the ray tracing simulations [Chen et al., 2012].

3. Electron Scattering Rates and Resultant Pitch Angle Evolution

The University of California, Los Angeles (UCLA) Full Diffusion Code [Ni et al., 2008; Shprits and Ni, 2009] is used to evaluate quasi-linear bounce-averaged diffusion coefficients of energetic electrons due to resonant interactions with broadband plasmaspheric hiss. We concentrate on the specific location at L = 4.5 and adopt a dipole geomagnetic field model. Based on the Van Allen Probes measurements, the average ambient electron density is 477 cm\(^{-3}\) for the period of 16:50–18:15 UT, producing a high ratio of equatorial electron plasma frequency to gyrofrequency of 21. Note that while during this time interval the severe erosion of the plasmapause was observed on the nightside with a compressed location down to well below 4 \(R_E\) [Baker et al., 2013], the dayside plasmasphere was not eroded yet with a plasmapause location at > 5.5 \(R_E\) [Li et al., 2013]. The diffusion rate computations for both the unusual hiss event and normal hiss include contributions from the 10 – 100 Hz waves to be confined to magnetic latitudes of \(|\lambda| \leq 30^\circ\) and 100–2000 Hz waves are confined to \(|\lambda| \leq 40^\circ\).

Furthermore, the wave spectral intensities for both frequency groups are assumed unchanged within the hiss latitudinal coverage and its wave normal angle. Specifically, we set the 20–100 Hz waves to be confined to magnetic latitudes of \(|\lambda| \leq 30^\circ\) and the 100–2000 Hz components to be confined to \(|\lambda| \leq 40^\circ\).

In addition, a realistic model of the hiss wave normal angle distribution as a function of magnetic latitude is constructed based on Figure 2b, which is tabulated in Table 1. The wave normal angle distribution follows a Gaussian function of \(\exp\left(-\frac{\tan \theta - \tan \theta_0}{\tan \theta_w/\tan \theta_0}\right)^2\), where \(\theta\) is the wave normal angle, \(\theta_m\) is the peak wave normal angle, and \(\theta_w\) is the angular width.

\[\text{Table 1. Adopted Wave Normal Angle Distribution at Each of the Indicated Eight Magnetic Latitude Intervals for the Unusual Hiss Event, According to the Ray Tracing Results Shown in Figure 2b.}\]

<table>
<thead>
<tr>
<th>(\lambda(\text{°}))</th>
<th>(\theta_m(\text{°}))</th>
<th>(\theta_w(\text{°}))</th>
<th>(\theta) Range (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–5</td>
<td>0</td>
<td>15</td>
<td>0–20</td>
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<tr>
<td>5–10</td>
<td>15</td>
<td>20</td>
<td>0–30</td>
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<td>30</td>
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<tr>
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<td>60</td>
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</tr>
<tr>
<td>35–40</td>
<td>80</td>
<td>70</td>
<td>55–85</td>
</tr>
</tbody>
</table>

*Note that 20–100 Hz waves are confined to the magnetic latitudes of \(|\lambda| \leq 30^\circ\) and 100–2000 Hz waves are confined to \(|\lambda| \leq 40^\circ\).*
larger by a factor of 3–6. The bottleneck becomes narrower for 20 keV electrons but broader for 200 keV – 2 MeV electrons for the unusual hiss event. Besides the common feature that the bottleneck shifts to pitch angles closer to 90° as electron energy increases, the minimum \( h_{\alpha\alpha} \) also moves to higher \( \alpha_{eq} \) for the unusual hiss event. Since \( h_{\alpha\alpha} \) at low pitch angles are very small for relativistic electrons \( \geq 1 \text{ MeV} \) and the observed unusual hiss only lasted for about 2 h, the net effect of the unusual hiss to scatter \( \geq 1 \text{ MeV} \) electrons is very likely to be negligible.

The pronounced differences in scattering rates between the unusual hiss event and normal hiss suggest that unusual hiss makes particular contributions to the dynamics of tens to hundreds keV energetic electrons, which we analyze subsequently using one-dimensional pure pitch angle diffusion simulations at a fixed L shell \[\text{e.g.,} \quad \text{Meredith et al., 2009; Thorne et al., 2013; Ni et al., 2013}\]. We solve the equation

\[
\frac{\partial f}{\partial t} = \frac{1}{T(\alpha_{eq}) \sin(2\alpha_{eq})} \frac{\partial}{\partial \alpha_{eq}} \left[ T(\alpha_{eq}) \sin(2\alpha_{eq}) h_{\alpha\alpha} \frac{\partial f}{\partial \alpha_{eq}} \right].
\]  

(1)

where \( f \) is the phase space density (PSD), \( t \) is time, and the electron bounce period is approximated as

\[ T(\alpha_{eq}) = 1.3802 - 0.3198 \left( \sin(\alpha_{eq}) + \sqrt{\sin(\alpha_{eq})} \right) \quad [\text{Lenchek et al., 1961}] \].

The boundary conditions for PSD in \( \alpha_{eq} \) space are \( f(\alpha_{eq} \leq \alpha_{LC}) = 0 \) and \( \frac{\partial f}{\partial \alpha_{eq}} (\alpha_{eq} = 90°) = 0 \), where \( \alpha_{LC} \) is equatorial bounce loss cone angle. By further assuming that the initial PSD follows a sinusoidal function of equatorial pitch angle, we model the temporal evolution of energetic electron pitch angle distribution due to the unusual hiss event and compare the results with those for the normal hiss case. Figure 4 shows the temporal changes of electron phase space density at five specified electron energies between 20 keV and 400 keV for a period of 2 h (the observed duration of the unusual hiss) corresponding to the cases of normal hiss and unusual hiss. The results are shown from the initial condition \((t = 0)\) with an increment of 10 min to the state at \(t = 2 \text{ h}\), and the modeled PSDs are normalized to the initial PSD at \( \alpha_{eq} = 90° \) so that all the values are \( \leq 1 \).

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Figure 3. Two-dimensional plots of drift- and bounce-averaged pitch angle scattering rates \( \langle D_{\alpha\alpha} \rangle \) as a function of electron kinetic energy \( E_k \) and equatorial pitch angle \( \alpha_{eq} \) due to (a) normal hiss and (b) the unusual low-frequency hiss at \( L = 4.5 \). (c) Lines plots of \( \langle D_{\alpha\alpha} \rangle \) as a function of \( \alpha_{eq} \) for the indicated five electron energies due to normal hiss (dashed) and the unusual low-frequency hiss (solid).
In accordance with the large differences in scattering rates for the two hiss cases, the modeled pitch angle evolution exhibits distinctly different features for radiation belt energetic electrons. Quantitative comparisons also indicated that normal hiss causes faster decay and loss of 20 keV electrons, but the unusual hiss event drives more rapid decay and loss of 50–200 keV electrons with the strongest removal occurring for 100 keV electrons within 2 h. The pancake pitch angle distribution \cite{Meredith1999} develops within tens of minutes for 20–100 keV electrons, which is more pronounced for the normal hiss scattering of 20–50 keV electrons and for the unusual hiss scattering of 50–100 keV electrons. We note that the top hat-shaped distribution due to the unusual hiss scattering is confined to larger pitch angles for 50–100 keV electrons. Overall, even though the wave duration was short (~ 2 h), the unusual hiss can significantly contribute to the pitch angle redistribution of energetic electrons.

Figure 4. One-dimensional pitch angle diffusion simulation results of the pitch angle distribution for (a) 20 keV, (b) 50 keV, (c) 100 keV, (d) 200 keV, and (e) 400 keV electron phase space density (PSD) due to resonant scattering by (left) normal hiss and by (right) the unusual low-frequency hiss at $L = 4.5$. A time step of 1 s in real time is used during the entire 2 h simulation run for each energy, and the results are shown every 10 min. The modeled PSD is normalized to the initial PSD at $\alpha_{eq} = 90^\circ$.
tens to hundreds keV electrons, leading to an electron temporal evolution substantially different from that driven by the 100–2000 Hz normal hiss. Scattering by the unusual hiss slows down the loss of 20 keV electrons but expedites the decay of 50–200 keV electrons. The resultant temporal evolution of the electron pitch angle distribution also represents a common two-step process that includes a relaxation from the initial condition toward the equilibrium state and a subsequent exponential decay as a whole (the lowest normal mode). Figure 4 indicates that the electron lifetimes due to scattering by the unusual low-frequency hiss can be of the order of 1 h for 50–200 keV electrons.

4. Conclusions and Discussion

Here we have performed a detailed investigation of the electron scattering effect of the unusual low-frequency hiss down to ~20 Hz observed by the Van Allen Probes on 30 September 2012. The drift- and bounce-averaged quasi-linear diffusion coefficients are evaluated for the unusual hiss event and are then adopted as inputs for one-dimensional diffusion simulations to model the evolution of the electron pitch angle distribution and the resultant time scales of relaxation toward equilibrium and subsequent overall decay under the lowest normal mode. Through quantitative comparisons with the results for normal hiss with a common Gaussian spectrum over 100–2000 Hz, the particular role of the unusual hiss in the loss and decay of radiation belt electrons is identified. Our main conclusions are summarized as follows:

1. Compared to the results for the normal hiss, the unusual hiss causes more efficient pitch angle scattering of >~50 keV electrons for a broad range of $\alpha_{eq}$ mainly due to its dominance of wave power at frequencies < 200 Hz. It also results in considerably decreased pitch angle scattering of < 50 keV electrons at most pitch angles and of ~50 keV–2 MeV electrons at high $\alpha_{eq}$. In addition, the scattering rate bottleneck becomes narrower for 20 keV electrons but broader for hundreds keV electrons with a decreased gradient in $\langle D_{\alpha\alpha} \rangle$ and a transition of minimum $\langle D_{\alpha\alpha} \rangle$ to higher $\alpha_{eq}$.

2. Pitch angle evolution of tens to hundreds keV electrons due to the unusual hiss scattering behaves distinctly from that due to normal hiss. Scattering by the unusual hiss can slow down the decay of 20 keV electrons but speeds up the loss of ~50–200 keV electrons, showing a maximum decrease by about 1 order of magnitude for ~100 keV electron flux within 2 h. The unusual hiss also causes enhanced pancake distributions of ~50–100 keV electrons but with a narrower top hat feature.

3. Hiss-induced temporal evolution of the electron pitch angle distribution represents a common two-step process that includes a relaxation from the initial condition toward the equilibrium state and a subsequent exponential decay as a whole. Electron lifetimes due to scattering by the unusual low-frequency hiss that only lasted for a couple of hours can be of the order of 1 h for ~50–200 keV electrons.

Our results clearly demonstrate that such unusual (low-frequency) hiss emissions, once present, play an important role in affecting the decay and loss process of energetic electrons, which behaves distinctly from that due to the normal (high-frequency) plasmaspheric hiss and should be carefully incorporated into global modeling of radiation belt electron dynamics, in particular during periods of intense injections. Although the events of enhanced unusual hiss with frequencies well down to tens of hertz are observed quite infrequently in contrast to normal hiss that is commonly confined to a spectrum of 100–2000 Hz, its occurrences are not rare based on the measurements from the Van Allen Probes. The statistical properties of such unusual hiss emissions, their correlations to source electron injection and plasmaspheric configuration, and the relative contribution that they make to the radiation belt electron dynamics is left as future work.

It is also noted that while our study demonstrates that the unusual low-frequency hiss event is important for scattering ~50–200 keV energetic electrons during the short emission duration of a few hours in the dawnside plasmasphere, some other physical processes, including sustained electron injections and electron interactions with chorus waves during the nightside drift trajectory, were also in operation. The effects of these various processes need to be incorporated, besides the pure pitch angle diffusion simulations adopted in this study, into a more sophisticated model to reasonably reproduce observed temporal variations of radiation belt electron distribution. In addition, despite the efficient electron scattering loss of tens to hundreds keV energetic electrons, the short-lived unusual hiss made negligible contribution to the electron flux dropout on 30 September 2012 observed by Van Allen Probes [Baker et al., 2013], which is more likely
attributed to combined effects of magnetopause shadowing, outward radial diffusion, and scattering by whistler mode chorus and electromagnetic ion cyclotron waves.

References


