Remote Sensing of Radiation Belt Energetic Electrons Using Lightning Triggered Upper Band Chorus

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Abstract Observations of magnetospheric chorus being triggered by lightning-induced whistlers are rare but provide a unique opportunity to remotely diagnose wave-particle interactions in the Earth's radiation belts. The observations presented herein are unique in that whistlers, originating from lightning, are seen to trigger upper band chorus repeatedly over the course of 2 hr. Each whistler exhibits a distinct upper frequency cutoff that is used to estimate the anisotropy of the hot plasma distribution. Resulting anisotropy estimates are in good agreement with previous in situ measurements. While the anisotropy determines wave growth in the linear regime, access to the nonlinear regime requires the in situ wave amplitude to exceed the threshold for phase trapping of energetic electrons. The results suggest that while upper band chorus is less favorable to be spontaneously generated, the conditions in this band are more conducive for triggering of the chorus instability by an external input wave.

Plain Language Summary The near-Earth space environment is in a plasma state and is also extremely variable due to the solar-driven phenomena and rich physical interactions between various layers of the upper atmosphere. This region hosts a large number of electromagnetic wave modes, which interact with high-energy particles that form the Earth's radiation belts. The state of the radiation belts affects communication and electrical power technologies in space and on Earth. Despite many years of investigation many fundamental properties of the near-Earth space environment remain poorly quantified. We report observation of the interaction of waves from atmospheric lightning with radiation belt particles. The observation provides a unique opportunity to remotely sense the dynamics of the energetic particle population in the Earth's radiation belts and how this population leads to amplification and generation of waves.

1. Introduction

Atmospheric lightning discharges generate electromagnetic wave energy over a broad range of frequencies and are termed sferics. A small fraction of the sferic energy couples into the magnetosphere and can propagate along geomagnetic field lines between hemispheres as a whistler-mode wave due to the presence of the background cold magnetized plasma and field-aligned density irregularities or ducts (Burgess & Inan, 1993; Smith, 1961; Strangeways & Rycroft, 1980). The very low frequency (VLF, ~ 3–30 kHz) band of the sferic is known to be a key source of whistler-mode wave energy injected into the Earth's inner magnetosphere from lower altitudes (Abel & Thorne, 1998; Inan et al., 1985; Meredith et al., 2006).

Lightning-induced VLF whistler-mode waves interact with energetic radiation belt electrons via Doppler-shifted cyclotron resonance. Under the assumption of small-amplitude waves, the linearized equations of motion predict that the wave-particle interaction will be unstable, that is, amplify whistler-mode waves, provided that the energetic electron distribution has sufficient temperature anisotropy (Kennel & Petschek, 1966). Once the amplified signals reach sufficient amplitudes, the resonant electrons can become phase trapped by the wave and the interaction becomes strongly nonlinear. This nonlinear cyclotron wave-particle interaction often triggers new daughter waves or triggered emissions that change dynamically in frequency (Gibby et al., 2008; Hosseini et al., 2017; Li et al., 2015; Nunn, 1974; Omura et al., 1991). Even in the absence of an external seed wave, the same underlying physics is believed to be responsible for the generation of naturally occurring waves known as magnetospheric chorus (Golkowski & Gibby, 2017; Omura et al., 2009). Chorus waves in turn play a significant role in both energization (acceleration) and/or precipitation (loss) of energetic electrons in the Earth's radiation belts (Bortnik & Thorne, 2007).
Despite dramatic improvements in particle measurements on spacecraft (Pollock et al., 2016; Wilder et al., 2016), accurately determining the distribution of energetic (hot) electrons in the Earth’s radiation belts is still a challenge of geophysical research. A common assumption is that the distribution is a bi-Maxwellian with some level of pitch angle anisotropy. Ground-based observations of waves (at a specific L-shell footprint on the Earth’s surface) that have interacted with radiation belt particles are another important tool for researchers to indirectly probe properties of the energetic electron distribution (Gołkowski et al., 2010; Hosseini et al., 2017).

Observations of chorus being triggered by lightning-induced whistlers are rare but have been reported since the 1970s at ground stations in Antarctica. Carpenter (1978) reported VLF noises or bursts in Antarctica (at Eights and Siple Station) that are frequently triggered or activated by whistlers that propagate outside of the plasmapause. Smith et al. (1985) investigated whistler-triggered VLF noise bursts observed on the DE-1 satellite and simultaneously at Antarctic ground stations. Nunn and Smith (1996) attempted a 1D Vlasov hybrid simulation to reproduce risers and fallers triggered off the upper arm of the whistler traces observed at Antarctica ground stations Halley and Faraday.

We present more recent ground-based evidence of whistler-triggered banded chorus emissions from Alaska. These are the first observations of such phenomena from a ground station outside of Antarctica. The unique repetitive nature of the observations in which 12 highly similar cases occur over 2 hr provides a rare opportunity to remotely evaluate the particle distribution and wave-particle interactions at $L = 4$–5.

2. Observations

Observations were made in Chistochina (62.56° N, 144.66° W, $L \approx 4.9$) on 25 September 2004 over a 2-hr period using VLF receivers with orthogonal crossed loop antennas oriented in north-south (N/S) and east-west (E/W) as described by Hosseini et al. (2018). The magnetosphere was in the recovery phase of geomagnetic storm conditions with Kp index of $\approx 1.5$ at the time of observations (05:45 to 07:45 UT) with a max Kp of $\approx 4.1$ in the preceding 48 hr.

Over the 2-hr period lightning-induced single hop whistlers repeatedly triggered long trains of chorus emissions yielding a total of 12 similar cases. The lightning-induced whistlers originate from lightning in the Southern Hemisphere and are observed in Alaska after one traversal of the magnetosphere along a field-aligned propagation path. The nature of ground observations of magnetospheric emissions is that near-parallel (to the geomagnetic field lines) propagation is required for the waves to be able to penetrate the sharp gradients of the lower ionosphere and be observed on the ground (Gołkowski & Inan, 2008; Smith, 1961). Therefore, the whistler and chorus waves discussed here have near-parallel wave normal angles.

Figures 1a and 1b show spectrograms of the earliest (Case # 1) observation of whistler-triggered chorus on both N/S and E/W channels. Chorus waves appear as groups of discrete and coherent but rising tone elements in the frequency range $\sim 2000$ to $\sim 6000$ Hz. There is a gap around $\sim 3500$ Hz dividing chorus into upper band chorus ($\sim 3800$ to $6000$ Hz) and the lower band chorus ($\sim 2000$ to $3400$ Hz). Such a gap in frequency is well documented and corresponds to $0.5\omega_{\text{c}}$ where $\omega_{\text{c}}$ is the equatorial electron cyclotron frequency (Meredith et al., 2001; Tsurutani & Smith, 1974). The value of $0.5\omega_{\text{c}}$ can be determined from whistler dispersion analysis as described below. Multiple closely spaced whistlers can be seen in the record, and these are whistlers propagating on different L shells but all induced by the same lightning discharge. The range of L shells for the whistler propagation paths has been identified using linear dispersion techniques described in the first paragraph of the next section. Figure 2 shows a close up of two cases where the features of the multipath whistlers and their relation to chorus can be observed.

In addition to the aforementioned repeatability, there are two remarkable features of the observations that can be seen in Figure 2. The first is that each whistler has an upper frequency cutoff above which no wave energy is observed. The upper-cutoff frequency is determined by identifying the frequency above which the power spectral density abruptly drops by 10 dB or more. The lead whistler demarked as #1 in Figure 2a and Figure 2b is seen to extend to above 5000 Hz, while the #5 whistler has a cutoff below 2 kHz. The values of cutoffs are tabulated in Table 1 and decrease with L shell of propagation.

The second remarkable feature is that upper band chorus only commences following the leading (#1) whistler, while the lower band chorus is uncorrelated with the observed whistlers. More specifically, lightning...
wave energy injected to the system is seen to facilitate the generation of upper band chorus. After it is triggered this chorus generation becomes self-sustaining for some time before it dies away and is subsequently brought to life again by another whistler on the same L shell. Although, the lightning whistler does not generate every single upper band chorus element directly, it can be seen that it is providing an initial condition that initiates the chorus generation instability. The whistler-triggered chorus phenomena occurred multiple times (12 cases) within the period of the 2-hr observation, and three additional examples (Cases # II–IV) are depicted in Figures 1c and 1d (N/S channel only). Upper band chorus only appears subsequent to a triggering whistler, but its duration, intensity, and frequency sweep

**Figure 1.** Spectrograms (color shows the power spectral density) correspond to north-south channel of (a) Case I, (c) Case II, (d) Case III, (e) Case IV, and (b) east-west channel of Case I.
rates vary from case to case. Since the ground-based receiver in the study contains two orthogonal air loop antennas oriented in north-south and east-west directions, the ratio of amplitudes observed on the two antennas can be used to infer the waves' direction of arrival. In Figures 1a and 1b, the fact that the lower band chorus is stronger in N/S channel, while the upper band chorus has same spectral intensity in both channels, indicates that these two bands are arriving at the receiver from different directions (on average ~ 60°). In the subsequent sections we analyze the cutoff frequency of each whistler and the triggering

![Figure 2](image)

**Figure 2.** Cold plasma dispersion analysis of two observation cases (# II–III) to determine the equatorial cold plasma density and propagation paths for each of the multiple whistler traces (#1 to #5).

<table>
<thead>
<tr>
<th>Whistler trace #</th>
<th>L Shell</th>
<th>(N_{eq}(\text{cm}^{-3}))</th>
<th>(0.5f_{cL}) (Hz)</th>
<th>(f_{\text{upper-cutoff}}) (Hz)</th>
<th>(A = \frac{\omega}{\omega_{ce}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.33</td>
<td>164.18</td>
<td>5379</td>
<td>5854</td>
<td>1.193</td>
</tr>
<tr>
<td>2</td>
<td>5.20</td>
<td>145.76</td>
<td>3105</td>
<td>2666</td>
<td>0.752</td>
</tr>
<tr>
<td>3</td>
<td>5.24</td>
<td>93.67</td>
<td>3035</td>
<td>2695</td>
<td>0.798</td>
</tr>
<tr>
<td>4</td>
<td>5.66</td>
<td>58.97</td>
<td>2408</td>
<td>2121</td>
<td>0.786</td>
</tr>
<tr>
<td>5</td>
<td>5.90</td>
<td>16.97</td>
<td>2126</td>
<td>1916</td>
<td>0.820</td>
</tr>
</tbody>
</table>
conditions for the upper band chorus using linear and nonlinear approaches to infer conditions of the magnetospheric hot plasma distribution.

3. Linear Analysis and Remote Sensing of Anisotropy

The frequency-time signature of each whistler is determined by the dispersion relation of the magnetospheric plasma and is dominated by the cold electron population (Park, 1972; Tarcsai, 1975). By fitting the frequency-time points of the observed whistler traces (Cases # II–III shown in Figure 2) to theoretical dispersion curves and assuming ducted field-aligned propagation (the standard assumption for ground observations), the cold plasma density and propagation path (L shell) can be estimated.

The determined magnetospheric paths corresponding to observation Case II of whistler-triggered chorus are depicted in Table 1. As expected from the propagation time delay between the whistlers and the causative spheric, the first whistler traversed through the magnetosphere at a lower L shell than the rest. As mentioned above, the salient feature of the observations illustrated in Figure 2a is that only the first whistler appears to trigger upper band chorus and each whistler appears to have a unique upper frequency cutoff. The subsequent whistlers that propagate at higher L shells have upper-cutoff frequencies that are at least 1 kHz below the frequencies of upper band chorus. This feature of the observations provides a unique tool for remote sensing properties of the radiation belt hot electron distribution.

Although the generation of chorus waves is believed to be due to complex nonlinear interactions between whistler-mode waves and resonant radiation belt electrons (Golkowski & Gibby, 2017; Harid, Golkowski, Bell, Inan, 2014; Omura et al., 2009), the initial amplification of the incoming whistlers can be determined using linear theory. Specifically, the self-consistent cyclotron interaction between the radiation belt electron population in the kiloelectron volt (keV) range and whistler-mode waves can be modeled by the Vlasov-Maxwell system of equations (Jaynes et al., 2015; Kennel & Petschek, 1966).

It can be shown that once the Vlasov-Maxwell system is linearized, the solutions predict exponential spatial wave growth (combination of both advection and temporal wave growth simultaneously) at a growth rate, \( \gamma_{\ell} \), given by the analytical expression (Kennel & Petschek, 1966),

\[
\gamma_{\ell} = \pi \frac{\omega_{\ell}}{N_c} \left( 1 - \frac{\omega}{\omega_{\ell}} \right)^2 \frac{v_{res}}{v_g} \left[ A - \frac{\omega}{(\omega_{\ell} - \omega)} \right] \eta
\]  

where \( v_g \) is the wave group velocity, and \( \omega \) is the wave frequency, while \( \eta \) and \( A \) correspond to the energetic particle (with general hot electron distribution of \( f_h \) flux (\( \eta = \int 2\pi f_h v_{\perp} \, dv_{\perp} \bigg|_{v_{\parallel}=v_{\text{res}}} \)) and anisotropy (\( A = \int \frac{f_h \tan \theta \, \, dv_{\perp}}{v_{\parallel}} \bigg|_{v_{\parallel}=v_{\text{res}}} \)), respectively (Kennel & Petschek, 1966). The terms \( \omega_{\ell} \) and \( v_{\text{res}} \) are the electron (with mass of \( m \), and charge of \( q \)) cyclotron frequency (\( \omega_c = \frac{qB}{m} \)) and cyclotron resonance velocity (\( v_{\text{res}} = \frac{\omega_c}{\omega} \)), respectively, \( N_c \) and \( k \) correspond to the cold plasma density and wave number. It is worth noting that we do not presume any specific energetic electron velocity distribution in our analysis. Therefore, our results are based on the general expression of \( A \) that comes from an integration over \( f_h \). For a bi-Maxwellian distribution \( A = \frac{T_{\perp}}{T_{\parallel}} - 1 \), where \( T_{\perp} \) and \( T_{\parallel} \) represent the average temperature (of the hot plasma) parallel and perpendicular to the geomagnetic field, respectively.

Spheric energy is known to peak near 10 kHz so the upper cutoff of each whistler trace is either due to a propagation effect or an amplification effect. It is assumed the upper cutoff is due to an amplification effect since whistler-mode waves are known to experience linear growth from pitch angle anisotropy. A key feature of the linear growth rate formula shown in equation (1) is that the anisotropy alone determines the sign of the growth rate at a specified frequency. Specifically, a change in sign of \( \gamma_{\ell} \) is equivalent to a change in the sign of the bracketed term (\( A - \frac{\omega}{(\omega_{\ell} - \omega)} \)). As shown in Figure 2 each whistler trace has an upper-cutoff frequency, \( \omega_{\text{uc}} \), that can be interpreted as the frequency at which the growth rate turns negative and results in damping (\( A = \frac{\omega}{(\omega_{\ell} - \omega_{\text{uc}})} \)). The high amplitude (~0.1 pT) of the observed whistlers on the ground is indicative of wave amplification along their propagation path, and amplification of lightning-induced whistlers in the linear regime has been documented before (Carpenter et al., 1986).
Using this fact and the corresponding propagation path \((L)\) for each whistler, the anisotropy of the energetic electron distribution function can be calculated. The cyclotron frequency, which is obtained from the \(L\) shell using a dipole model of the geomagnetic field (Walt, 2005), varies with latitude. However, the magnetic equator is known to be the source of chorus emissions and where anisotropy has a maximum. Consequently, the equatorial cyclotron frequency is considered for \(\alpha_{t}\). The estimated anisotropy for each whistler is listed in Table 1. It is interesting that the resulting values for \(A\) fall into a small range \(0.75 < A < 1.19\), despite a range of \(L\) shells. In our 12 observation cases, the \(A\) values change between 0.5 and 1.5, which are in reasonable agreement with previous Van Allen Probe Helium, Oxygen, Proton, and Electron (HOPE) measurements by Fu et al. (2014, \(A = 0.32\)) and Kubota et al. (2018, \(0.35 < A < 1.05\)).

### 4. Nonlinear Analysis

Although the upper-cutoff frequency can be used to determine the equatorial anisotropy for any lightning whistler (independent of the subsequent triggering process), it does not explain why only the first whistler triggers upper band chorus emissions. To answer the latter, we must consider the fact that the linear solution to the Vlasov-Maxwell system will in general grow to amplitudes that can exceed the threshold for phase trapping of electrons (Harid, Golkowski, Bell, Li, Inan, 2014). Chorus emissions are only triggered when the nonlinear cyclotron wave-particle interaction regime has been accessed. Although the exact reason for triggering is still an open subject of research (Helliwell, 1988; Helliwell et al., 1975; Inan et al., 2004; Li et al., 2015; Omura et al., 2008; Tao et al., 2017), theoretical and numerical analysis suggests that triggered emissions are produced due to phase trapping of resonant particles (Dysthe, 1971; Hikishima & Omura, 2012; Omura et al., 1991; Smith & Nunn, 1998; Vomvoridis et al., 1982). Thus, when the incident wave amplitude exceeds the threshold required for phase trapping for a long enough time (one triggering period), we would expect the triggering process to initiate. The energy of the triggered waves comes not from the original wave but from the unstable hot plasma distribution that has been modified to radiate semicoherent waves.

We hypothesize that the first whistler (which triggers chorus emissions) is much more likely (compared to the subsequent whistler traces) to reach amplitudes that exceed the triggering threshold for at least one trapping period \((T_{tr})\). The trapping period is \(T_{tr} = \frac{2\pi}{\omega_{tr}}\), where \(\omega_{tr} = \sqrt{\frac{q\mu_{B}B_{tr}}{\tau}}\) is referred to as trapping frequency (Omura et al., 1991). Assuming parallel propagation, the minimum amplitude required for phase trapping, \(B_{tr}\), can be solved for as (Dysthe, 1971; Matsumoto & Omura, 1981; Nunn, 1974; Trakhtengerts & Rycroft, 2008):

\[
B_{tr} = \frac{m}{qkv_{\perp}} \left[ \frac{k_{vl}}{2\omega_{c}} \right]^{\frac{3}{2}} \sqrt{\frac{\partial \omega_{c}}{\partial \omega_{c}}} \left( \frac{2\omega_{tr} - \omega_{c}}{2\omega_{tr}} \right) \left( 1 + \frac{v_{res}}{v_{g}} \right) \frac{\partial \omega}{\partial dr} \]

where \(v_{\perp}\) is the perpendicular component of electron velocity relative to the geomagnetic field, \(\overline{B_{tr}}\). The factor \(\frac{\partial \omega}{\partial dr}\) quantifies the influence of the inhomogeneous background geomagnetic field in controlling the interaction. The term \(\frac{\partial \omega}{\partial dr}\) can be comparable in magnitude to the spatial gradient of the cyclotron frequency. In the case of the triggering whistlers considered in this study, the \(\frac{\partial \omega}{\partial dr}\) term is approximately constant (fixed positive frequency time) and equal to \(-8\) \(kHz/s\) (slope at top portion of the triggering whistler). The effect of a nonzero positive \(\frac{\partial \omega}{\partial dr}\) is to shift the spatial \(B_{tr}\) profile minimum from the equator to the positive \(z\) direction (toward the wave). It is worth mentioning that there is another term in equation (2) corresponding to \(\frac{\partial \omega}{\partial dr}\) that is negligible near the equator in a diffusive equilibrium model of the cold plasma, where \(\omega_{p}\) is the plasma frequency (Inan, 1977; Omura et al., 1991).

As mentioned previously, the triggering process can only occur if the seed wave (whistler) reaches amplitudes that stay above the trapping threshold for more than one trapping period. The trapping threshold steadily increases as the wave propagates away from the equator. At specific locations away from the equator \(\left(\zeta_{2}^*\right)\) after the equator, and \(\zeta_{1}^*\) before the equator), the wave amplitude satisfies the condition \(B_{tr}^{\left(\zeta_{2}\right)} \geq B_{tr}^{\left(\zeta_{1}\right)}\), which is the nonlinear trapping distance condition, Dysthe, 1971; Matsumoto et al., 1980; Omura et al., 1991). Since the \(\frac{\partial \omega}{\partial dr}\) term (in \(B_{tr}\) equation (2)) eventually cancels out through the \(\zeta_{2}^* - \zeta_{1}^*\) subtraction for (approximately) constant frequency sweep rate, \(B_{tr}^{\left(\zeta_{2}\right)}\) can be derived using \(\frac{\partial \omega}{\partial dr} = 0\) in equation (2) for simplicity. In the latter case since the threshold amplitude is symmetric around the equator (see...
subplot at Figure 3b), we have $z^* = z^*$, which turns the above trapping distance condition into the following:

$$z^* \geq v_{res} \frac{\pi}{\sqrt{q v_{\perp} B_w(z^*)}}$$

(3)

where $B_w(z^*) \geq B_0(z^*)$ and the value of $T_{tr}$ has been substituted ($T_{tr} = \frac{2\pi}{\omega_{tr}} = \frac{2\pi}{\sqrt{q v_{\perp} B_w(z^*)}}$). The minimum wave amplitude ($B_w = B_0$) that satisfies the lower bound condition ($z^* = v_{res} \frac{z}{\sqrt{q v_{\perp} B_w(z^*)}}$) of equation (3) is termed the critical wave amplitude $B_{w_c}$. By substituting the $z^*$ value into the $B_{w_c}$ formula (equation (2)):

$$B_{w_c} = \frac{2\pi B_0}{q v_{\perp} \omega_{tr}} \left( \frac{v_{res}}{2\omega_c} + \frac{3}{2} v_{res} \right)^{\frac{3}{2}}$$

(4)

where $B_0$ and $\sigma$ are parameters under the parabolic geomagnetic field approximation, $B(z) = B_0(1 + \sigma(z - z_{eq})^2)$ (Walt, 2005), which are used to determine the $\frac{\partial w}{\partial z}$ term.

**Figure 3.** (a) Normalized linear growth rate versus frequency (in Hz, subplot) and versus normalized frequency (in terms of $f_{ce}$, main plot) for different whistler traces. (b) Relative spectral profile (in terms of $f_{ce}$) of critical wave amplitude for different whistler traces (main plot) and spatial ($z$ is the distance along the field line) profile of nonlinear trapping threshold amplitude with trapping distance ($Z_{tr}$) and critical wave amplitude ($B_{w_c}$) remarks (subplot).
Using the estimated values for anisotropy and $L$ shell from the previous section, the normalized linear growth for each whistler as a function of frequency is shown in Figure 3a. It can be seen that, in addition to extending to higher frequencies, the first whistler (lowest $L$ shell) has a lower peak linear growth rate than the subsequent whistlers. The peak linear growth rate (marked as solid circles) is the highest for the last whistler propagating at the highest $L$ shell as compared to the rest. The critical wave amplitude ($B_{c}^*$) for phase trapping is shown in Figure 3b. Here the critical amplitude is lowest for the first whistler (lowest $L$ shell) and highest for the last whistler (highest $L$ shell), and this relationship holds for all frequencies. There is thus a tradeoff between favorable linear growth conditions and lowest critical amplitude for nonlinear triggering between the whistlers. The first whistler has less favorable linear growth but is more likely to trigger chorus. Since the second- and higher-order whistler traces have peak growth rates (shown with solid circles) that are at frequencies where the nonlinear trapping threshold is the highest (so as $B_{c}^*$), the probability of triggering chorus decreases. On the other hand, since the first whistler trace has a higher linear growth rate at frequencies where the threshold is the lowest, it is much more likely to trigger chorus than the subsequent whistlers (see discussion below). This further implies that although the particle distribution is unstable, the trapping conditions for upper band chorus make it more likely to be triggered by an external input wave when compared to lower band chorus. This is consistent with upper band chorus being triggered only by the first whistler trace in all of the 12 observed cases.

5. Discussion

The two most important findings of this work are the estimate of anisotropy to be close to unity and the identification of favorable conditions for spontaneous generation of lower band chorus facilitated through linear growth and the proclivity of upper band to be generated through external triggering. Lower band chorus being more often observed than upper band chorus is well documented (Meredith et al., 2001; Tsurutani & Smith, 1974). Meredith et al. (2001) report that equatorial (|λ| < 15°) and high-latitude (|λ| > 15°) chorus emissions are strongest in the lower band during active conditions ($AE > 300$ nT), while an inner population of upper band substorm-independent emissions is seen on the nightside during quiet ($AE < 100$ nT) or moderate (100 nT < $AE < 300$ nT) conditions. They argue that the most likely candidates for the substorm-independent chorus emissions are lightning-generated whistler and VLF signals from ground-based transmitters. It is also worth noting that waves from science dedicated transmitters at Siple Station ($L = 4.3$, 1.5 kW) and HAARP experiment ($L = 4.9$, less than 0.5 W) both triggered free-running chorus-like emissions below the half cyclotron frequency, but those above observed to be triggered only by Siple transmitter (Carpenter & Bao, 1983; Golkowski et al., 2011; Sazhin & Hayakawa, 1992). In summary, upper band chorus is more favorable for triggering by a strong external wave (lightning or VLF transmitter signals) due to the lower threshold for nonlinear trapping. However, although linear growth is more favorable in the lower band, the nonlinear threshold is considerably higher and the growth rate is not sufficiently fast to bring the fields up to the point of triggering. The observational support is that the observed whistlers trigger only upper band chorus.

Anisotropy values close to 1 in Figure 3a imply that there is a band close to half the cyclotron frequency where linear growth conditions deteriorate and nonlinear thresholds are still high, which is consistent with the gap in wave power near half the cyclotron frequency. For higher values of anisotropy ($\gg 4$) linear growth conditions would be favorable for a broader range of frequencies, and this is also in agreement with both lower and upper band chorus being regularly observed under disturbed geomagnetic conditions (Sazhin & Hayakawa, 1992). Although the results of this work indicate the preferential triggering of upper band chorus, additional physical phenomena may be important to model the well-known half cyclotron frequency separation between the two chorus bands. Several theories have been put forth to explain the banded emissions by either the distinct generation or the preferential amplification of each bands. Bell et al. (2009) suggest that lower (upper) band chorus is guided within enhanced (depleted) cold plasma density irregularities during the generation process. Liu et al. (2011) argue that a distinct population of anisotropic warm (hot) electrons independently provides the upper (lower) band of whistler-mode emissions. Tsurutani and Smith (1974) postulate that the gap between chorus emissions is due to Landau damping (resonance) of the wave. Omura et al. (2009) put forth on the suppression of waves close to $0.5\omega_c$, by explaining that longitudinal component of an obliquely propagating whistler-mode wave leads to nonlinear damping at $0.5\omega_c$ (Hsieh & Omura, 2018). Ratcliffe and Watt (2017) further numerically investigate this behavior and
conclude that the nonlinear damping is inherently a two-dimensional effect. Therefore, future remote sensing of radiation belt energetic electrons should include electrostatic nonlinear phase trapping via Landau resonance, as well as transverse nonlinear phase trapping through cyclotron resonance.

The accuracy of the anisotropy estimates presented here derives from the determination of the upper-cutoff frequency and the equatorial gyrofrequency along the ducted path. The latter is derived from cold plasma dispersion analysis, which has been shown to be accurate for broadband whistlers. The fact that 12 consecutive observation cases give consistent values of both cutoff frequency and equatorial gyrofrequency is a source of confidence. In this context, the repetitive nature of the observations also points to the anisotropy and nonlinear growth condition determinations being applicable to an active distribution function at the equator. In other words, this distribution does not show evidence of achieving a relaxed state over the 2 hr of observations despite significant whistler-mode wave generation and amplification. Whether or not a substorm injection event or other phenomena are necessary for sustaining such a distribution is a valid question for future work.

6. Conclusion

Determining the distribution of energetic electrons in the Earth’s radiation belts is still an area of theoretical and experimental active research. Observation of magnetospheric nonlinear banded chorus being triggered by lightning-induced linear amplified whistlers enables remote sensing of the energetic electron anisotropy. Alternative options to study electron populations are in situ measurements which can be expensive and also provide only sparse coverage. There are VLF receivers and magnetometers on the ground that are constantly recording wave data for various research goals and can be leveraged for radiation belt remote sensing.

Since anisotropy alone determines the sign of the linear growth rate, the upper-cutoff frequency of each whistler trace has been used to calculate the anisotropy of the energetic electron distribution function. Resulted anisotropy estimates are in good agreement with previous in situ measurements and numerical simulations. While the anisotropy of the hot plasma distribution determines wave growth in the linear regime, access to the nonlinear regime requires the in situ wave amplitude to exceed the threshold for phase trapping of energetic electrons. Calculation of the threshold for each whistler shows that the upper band triggering of chorus corresponds to a lower nonlinear threshold. The results suggest that while upper band chorus is less likely to be spontaneously generated, the distribution in this band is ripe for triggering of the chorus instability with an external input wave.

References


