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

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***Abstract*—Observations of magnetospheric VLF (~ 3-30 kHz) 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 here are unique in that whistlers originating from lightning in the southern hemisphere are seen to trigger upper band chorus repeatedly over the course of two hours, yielding 12 observation cases with very similar characteristics. Each whistler exhibits a distinct upper frequency cutoff and only the lowest L-shell whistler is observed to trigger upper band chorus. The observed cutoff frequencies along with L-shell and cold plasma density derived from dispersion analysis are used to estimate the anisotropy of the hot plasma distribution in the magnetosphere. Resulting anisotropy estimates are in good agreement with previous in-situ measurements and past work. 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 favorable to be spontaneously generated, the conditions in this band are more conducive for triggering of the chorus instability by an external input wave.***

## I. 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 between hemispheres as a whistler mode wave due to the presence of the background cold magnetized plasma and field aligned density irregularities. 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. 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, i.e. amplify whistler mode waves, provided that the energetic electron distribution has sufficient temperature anisotropy [1]. 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 wave-particle interaction often triggers new waves or 'triggered emissions' that change dynamically in frequency [2]. Even in the absence of an external seed signal, the same underlying physics is believed to be responsible for the generation of naturally occurring waves known as magnetospheric chorus. These 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 [3]. Despite dramatic improvements in particle measurements on spacecraft, determining the distribution of energetic (hot) electrons in the Earth's radiation belts is still a challenge of geophysical research. Ground based observations of the waves that have interacted with radiation belt particles are another important tool for researchers to indirectly probe properties of the energetic electron distribution. Observation of chorus being triggered by lightning induced whistlers are rare but have been reported since the 1970s on ground stations at Antarctica [4]. Here, we present more recent ground-based evidence of whistler triggered banded chorus emissions at Alaska. It is the first observation of such a phenomena from a ground station outside of Antarctica.

## II. OBSERVATION

Observations were made in Chistochina (62.56 N, 144.66 W, L ~ 4.9), Alaska on September 25, 2004 over a 2 hour 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* [5]. Over the two hour period lightning induced whistlers repeatedly triggered long trains of chorus emissions yielding a total of 12 similar cases. Fig. 1 a-b shows spectrograms of the earliest observation of whistler triggered chorus at both N/S and E/W channels. Chorus waves appear in dynamic spectra as groups of discrete and coherent but rising tone elements. The typical frequency range is from ~2000 to ~6000 Hz, and a gap at $0.5\omega_{c_0}$ (where $\omega_{c_0}$ is the equatorial electron cyclotron frequency) divides chorus into the upper band (~3800 to 6000 Hz) and the lower band (~2000 to 3400 Hz). The intense vertical broadband lines in the spectra correspond to sferics that arrive at the receiver after propagating through the Earth-ionosphere waveguide. A portion of the sferic energy escapes into the magnetosphere and returns to the ground (~2.5 seconds later) as a dispersed wave after field-aligned propagation through the magnetospheric plasma. The propagation through the magnetosphere is multi-path with whistler traces having propagated on a range of L-shells visible in the record.

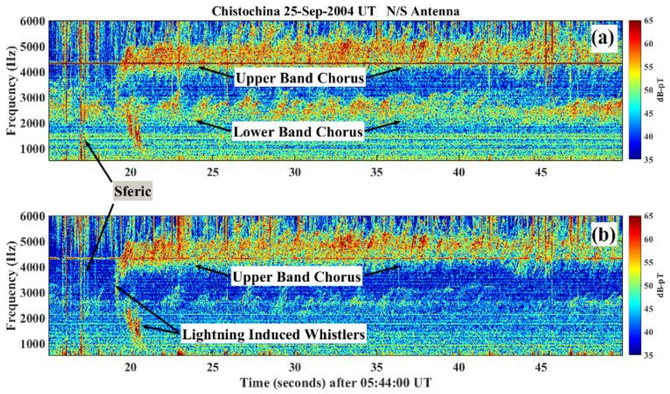

Fig. 1. Earliset Observation of lightning induced whistler triggered chorus on both N/S and E/W channels.

## III. ANALYSIS

Sferic energy that escapes into the magnetosphere can potentially induce multiple whistler traces via different magnetospheric paths (L-shells). The frequency-time signature of each whistler trace is determined by the dispersion relation of magnetospheric plasma and is dominated by the cold electron population. By fitting the observed whistler traces to theoretical dispersion curves and assuming ducted propagation, the cold plasma density and propagation path (L-shell) can be estimated. Although the generation of chorus waves is believed to be due to complex nonlinear interactions between whistler mode waves and resonant radiation belt electrons, the initial amplification of the incoming whistlers can be determined using linear theory. It can be shown that once the Vlasov-Maxwell system is linearized, the solutions predict exponential spatial wave growth at a growth rate, $\gamma_L$, given by the analytical expression,

$$\gamma_L = \pi \frac{\omega_c}{N_c}\left(1-\frac{\omega}{\omega_c}\right)^2 \frac{v_{res}}{v_g}\left[A-\frac{\omega}{\omega_c-\omega}\right]\eta \qquad , \qquad (1)$$

where $v_g$ is the wave group velocity, $\omega$ is the wave frequency, while $A$ and $\eta$ correspond to the particle anisotropy and flux respectively. The quantity $\omega_c$ and $v_{res}$ are the electron (with mass of $m$, and charge of $q$) cyclotron frequency ($\omega_c = \frac{qB_0}{m}$) and cyclotron resonance velocity ($v_{res} = \frac{\omega_c-\omega}{k}$), respectively. $N_c$ and $k$ corresponds to the cold plasma density and wave number. A key feature of the linear growth rate formula shown in Eq. 1 is that the anisotropy alone determines the sign of the growth rate at a specified frequency. Specifically, a change in sign of $\gamma_L$ is equivalent to a change in the sign of the bracketed term. Using this fact and the corresponding propagation path (L-shell) for each whistler, the anisotropy of the energetic electrons distribution function can be calculated

Although the upper-cutoff frequency can be used to determine the equatorial anisotropy, 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 cross the threshold for the phase-trapping of electrons [6]. The chorus emissions are only triggered when the nonlinear regime has been accessed. We hypothesize that the first trace is much more likely to reach amplitudes that can exceed the trapping threshold for more than one trapping period.

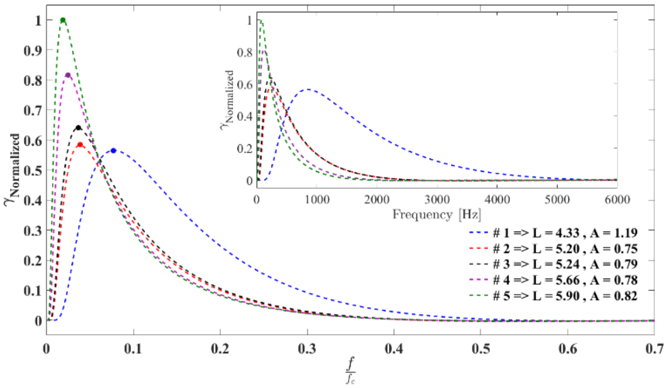

Fig. 2. Normalized linear growth rate versus frequency for different whistler traces.

Using the estimated values for anisotropy and L-shell from the previous section, the linear growth spectrum of each whistler as a function of frequency is shown at Fig. 2. It illustrates that the frequency which corresponds to the peak growth rate (marked as solid circles), is highest for the first whistler compared to the rest. At the same time, the trapping threshold for phase-trapping is lower at higher frequencies (not shown here). Therefore, 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. 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.

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