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A generation mechanism for discrete very low frequency emissions observed at Varanasi

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Abstract. A new type of discrete VLF emissions recorded at the low-latitude ground station Varanasi (geomag. lat. 14°55′ N, geomag. long. 154°E; $L = 1.07$) during the strong magnetic activity on 29–30 April 1990 have been reported. A generation mechanism for various temporal and spectral features of discrete VLF emissions recorded at Varanasi is presented on the basis of cyclotron resonance interaction between whistler mode wave and energetic electrons ejected by substorm electric fields. An attempt is also made to determine parallel energy and wave growth relevant to the generation process of discrete VLF emissions. Finally, our results are discussed with other published works.

Keywords. Physics of magnetosphere; trapped particles; waves: propagation and excitation.

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1. Introduction

Very low frequency (VLF) emission is a class of natural radio phenomenon which is often observed in close association with whistlers both at the Earth's surface and on satellites [1]. Two different groups of magnetospheric VLF emissions: (1) unstructured continuous emissions in both time and frequency which tend to maintain a steady state like hiss, resonance bands and noise bands near the ion gyrofrequencies, (2) structured discrete emissions with a repetitive and even periodic character which tends to be transient like chorus, periodic emissions and other transient discrete emissions such as hooks, risers, pseudowhistlers, have been reported [1–5]. A significant part of these emissions is generated in the magnetosphere in the course of interactions of elliptically polarized whistler waves with energetic electrons of Earth's radiation belts.

Early observations of discrete VLF emissions came from mid- and high latitudes [3–5]. Later on discrete VLF emissions were also reported from low latitudes [4,6–9]. A better understanding of the generation mechanism of these VLF emissions observed at low latitudes would be more useful for analyzing the properties of high-energy trapped electrons.

It is generally accepted that the generation mechanism of discrete VLF emissions is related to the cyclotron instability (CI) of radiation belt electrons. Helliwell [10] developed a model based on the cyclotron resonance of energetic electrons with whistler mode waves, which manifest themselves as backward wave oscillators. In this model the idea of second-order cyclotron resonance was first formulated and it explained numerous types of discrete emissions with different frequency vs. time characteristics. Tsurutani and Lakhina [11] have given basic concepts of wave–particle interactions in very simple manner.

In the present paper, first we present a detailed analysis of the discrete VLF emission events observed at Varanasi during the routine recording of whistlers. Further, a generation mechanism of these discrete VLF emissions is proposed. An attempt has been made to determine various discrete emission parameters of VLF emissions recorded at Varanasi. Finally, our results are discussed in light of recent reported works.

2. Experimental observation and analysis

An improved ground-based VLF station was set up at Varanasi in the year 1990 and the recording of VLF waves was started from January 1990 on a routine basis. The wideband VLF waves were received by a T-type antenna, suitably amplified by pre- and main-amplifiers and recorded using a tape recorder. The recorded VLF data were analyzed by Sonograms and advanced VLF data analysis system (AVDAS). At low latitude, the VLF emission occurrence rate is low and sporadic. But when it appears its occurrence rate is comparable to that of mid-latitude [12,13]. The present study is based on the VLF observations made at the low-latitude ground station Varanasi during the period from January 1990 to December 1992. In this paper, the discrete VLF emissions recorded in the night of 29 April 1990 were analyzed.

Typical spectrograms of the discrete VLF emissions recorded on 29 April 1990 at Varanasi are shown in figure 1. Figure 1a contains three discrete VLF emissions (falling tones) observed at 1800 UT. The mean upper boundary frequency ($f_{\rm UB}$) for these emissions is 5.5 kHz. In figure 1b we find four discrete emissions with mean upper boundary frequency 5 kHz observed at 2000 UT. The duration of each discrete element is about 0.5 s. The average frequency sweep rate of discrete elements $\mathrm{d}f/\mathrm{d}t$ is 2 kHz/s.

These emissions were recorded during the strong magnetic activity period on 29–30 April 1990 with minimum Dst-index of − 98 nT on 29 April 1990. The intense discrete emissions were registered in the night of 29 April at the recovery phase of substorm, when the magnetic activity was highest ($\Sigma K_p = 32$).

These discrete emissions started at 1810 UT in the frequency range of about 2.0–5.5 kHz. In course of time the upper band frequency increases to 6 kHz and then decreases to 5 kHz by 2000 UT. The observed discrete emissions have the following parameters: $f_{\rm min} = 2.4$ kHz, $f_{\rm max} = 6$ kHz, average $f_{\rm UB} = 5.5$ kHz, average frequency sweep rate, $\mathrm{d}f/\mathrm{d}t = 2$ kHz/s and average duration of each discrete element, $T = 0.5$ s.

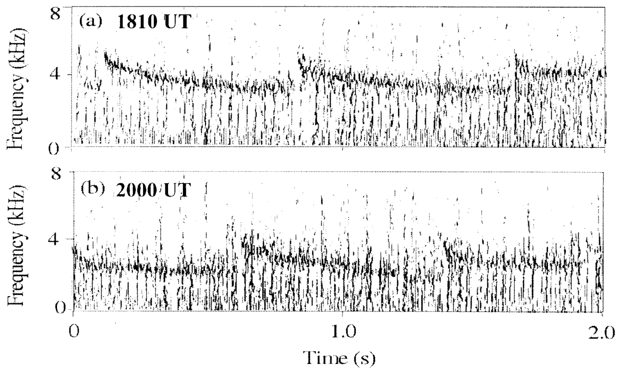

Figure 1. Typical frequency–time spectrograms of discrete VLF emissions observed at Varanasi on 29 April 1990.

3. Generation mechanism

In order to explain the observed features of discrete chorus emissions recorded at Varanasi, we propose cyclotron resonance interaction between whistler mode wave and energetic electrons ejected by substorm electric fields. For effective transfer of energy from the interacting particle to the wave resonance condition has to be satisfied. The relativistic cyclotron resonance condition is written as

$$1 - \beta_{\parallel} = \frac{\omega_H}{\gamma\omega}, \tag{1}$$

where $\beta_{\parallel} = v_{\parallel}/c, v_{\parallel}$ is the electron velocity along the magnetic field and $\gamma = (1 - \beta_{\parallel}^2)^{-1/2}n$. The refractive index for parallel propagating waves under the condition $\omega^2 \ll \omega_H^- \omega_H^+$ and $n \gg 1$ is written as [14]

$$n^2 = \frac{\omega_{pe}^2}{\omega_{He}(\omega + \omega_{Hi})}, \tag{2}$$

where ω_{pe}, ω_{He} are the electron plasma frequency and electron gyrofrequency respectively and ω_{Hi} is the proton gyrofrequency. The resonant energies for various frequencies of emissions can be written as [15]

$$E_{\parallel} = (\gamma_n - 1)m_0c^2, \tag{3}$$

where $E_{\parallel}$ is the resonant energy, m_0 is the rest mass of electron, c is the velocity in vacuum, and γ_n is the relativistic factor to be obtained from the relation

$$(\gamma_n^2 - 1) = \left(\frac{\omega_{He}}{\omega_{pe}}\right)^2 \left(\frac{\omega_{He}}{\omega}\right) \left(1 + \frac{\omega_{Hi}}{\omega}\right). \tag{4}$$

The interacting waves under favorable conditions are amplified. For wave amplification, the high-energy tail of the velocity distribution function should have some finite anisotropy $A = (T_\perp/T_\parallel) - 1$, where $T_\perp$ and $T_\parallel$ are respectively the temperatures of the electrons perpendicular to and parallel to the geomagnetic fields. In the regime of linear theory, the growth rate of the wave for $\omega \ll \omega_{He}$ is given by [16]

$$\Gamma = \pi\omega_{He}\left(1 - \frac{\omega}{\omega_{He}}\right)^2 \frac{J(>E_\mathrm{R})}{2V_\mathrm{R}N_\mathrm{T}}\left[A(V_\mathrm{R}) - \frac{1}{(\omega_{He}/\omega) - 1}\right], \quad (5)$$

where $J(>E_\mathrm{R})$ is the omnidirectional flux of electrons having energy greater than the resonance energy, V_R is the resonance velocity and N_T is the total number density of electrons.

4. Results and discussions

The observations of VLF emissions at the low-latitude station Varanasi show that the occurrence rate of discrete VLF emissions is low and sporadic. It is also noticed that the number of VLF emissions recorded during magnetic storm are large.

In order to link the observed fine structure of the discrete VLF emissions with the process of wave–particle interactions in the corresponding magnetospheric region, we have followed the upper boundary frequency (UBF) method developed by Smirnova [17], to find out the location of source for the discrete emission events. The L value of the discrete emission source is then computed as [17]

$$L = (440/f_\mathrm{UB})^{1/3}, \quad (6)$$

where f_UB is in kHz. Using the above method the L value of the source region for the reported event of discrete emission is found to be $L_\mathrm{source} = 4.3$. The higher L value of the source compared to that of Varanasi ($L = 1.07$) shows that the maximum of emission intensity moves towards lower latitudes with increase in the geomagnetic activity which may be due to the motion of the propagating channels and source region towards the Earth [17].

In order to test cyclotron resonance interaction as a possible generation mechanism for discrete VLF emissions we have computed the resonance energy of the high energy interacting electrons (using eqs (3) and (4)) and growth rate of whistler waves (using eq. (5)) in the equatorial plane. The variation of parallel energy of resonating electrons with wave frequency for different L are shown in figure 2. The plasma frequency ω_{pe} was calculated from the ionospheric model of Singh [18]. From figure 2, it is found that the energy of resonating electrons decreases as L increases for a given frequency band. The computed value of resonant energy for various frequencies of the discrete VLF emissions observed at Varanasi are in good agreement with the other reported results at low latitudes [19].

For the computation of wave growth, the density of energetic electrons at different L are derived from the measurement of Katz [20] who has reported the variation of electron flux as a function of energy for different L. The variation of wave growth rate with excited frequency for $L = 3$ and 4 is shown in figure 3. It is observed that the growth rate is larger and it increases with frequency. This large amplification causes significant enhancement in wave amplitude which in turn triggers discrete VLF emissions to be observed at the low-latitude ground station Varanasi.

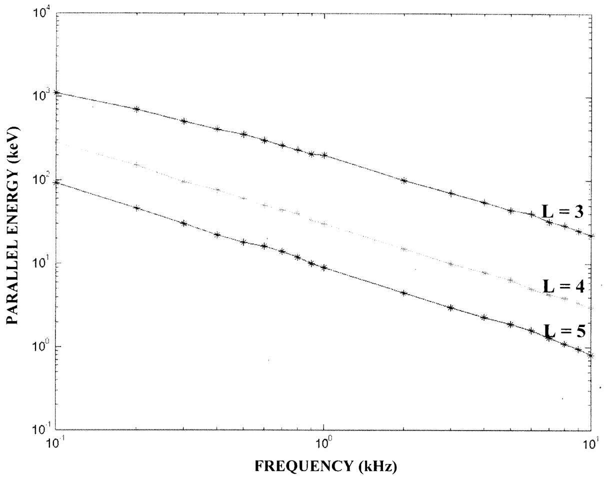

Figure 2. Variation of the parallel energy of resonating electrons with whistler wave frequency for different values of L.

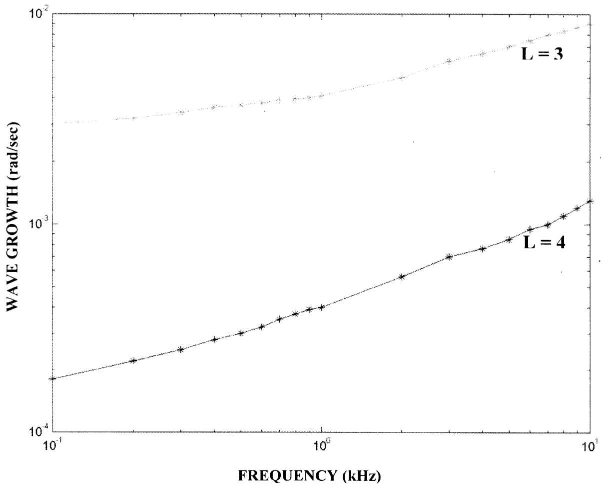

Figure 3. Variation of wave growth with frequency for different values of L.

5. Conclusion

A generation mechanism for various temporal and spectral features of discrete VLF emissions recorded at the low-latitude ground station Varanasi is presented on the basis of the cyclotron resonance interaction between the whistler mode waves and energetic particles injected by substorm electric fields. The parallel energy of resonating electrons for observed emissions comes out to be 5 to 30 keV. The limiting growth rate of the wave is also computed which explains the generation of discrete VLF emissions at Varanasi.

Further experimental and theoretical studies of discrete VLF emissions are required to contribute for a complete understanding of this phenomenon.

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