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Simultaneous Observations of Daytime Whistlers and VLF/ELF Emissions at a Low Latitude Indian Ground Station

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Abstract

This paper reports an unexpected simultaneous observation of whistlers and different types of ELF/VLF emissions during daytime at a low latitude Indian ground station Jammu (geomag. lat., 22° 26′ N; L=1.17), which are (a) pulses of atmospheric bursts, (b) discrete chorus riser ELF emissions triggered from the bottom of the atmospherics, (c) whistlers, (d) whistler-triggered discrete chorus riser VLF emissions triggered from the lower end of the whistler, (e) long enduring ELF/VLF hiss emissions, (f) band limited quasi-periodic pulsing ELF/VLF hiss emissions, (g) hook and inverted hook ELF emissions, (h) oscillating tone discrete chorus riser ELF emissions. The data shown in this paper indicate that there is a strong possibility that lightning is an important source of different types of VLF/ELF emissions, at least in the embryonic sense, recorded at Jammu. The present observation is in fact the first simultaneous occurrence of different types of VLF/ELF emissions alongwith whistlers recorded on a single day during daytime at a low latitude ground station.

Keywords: *Whistlers; ELF/VLF emissions; Hiss; Chorus; Pulsing hiss; hook and inverted hook.*

1. INTRODUCTION

Whistler mode waves and their interactions with energetic particles has been a subject of interest since the discovery of the radiation belts. The wave particle interactions occurring in the magnetosphere generate a variety of emissions in the ELF/VLF range. ELF/VLF emissions from the Earth's magnetosphere in the range of few hertz to 30 kHz, both continuous or unstructured and discrete or structured in nature are very fascinating, challenging and interesting natural phenomena (Helliwell *et al*. 1965). Although the ELF/VLF emissions of different types are often observed at different times at low latitude ground stations in Japan and India (Hayakawa *et al.* 1975; Khosa *et al.* 1981; Singh *et al.* 1999), but almost there is no evidence of their simultaneous occurrence during daytime.

We here report the first simultaneous observation of whistlers and different types of ELF/VLF waves during daytime at a low latitude Indian ground station Jammu which includes (a) pulses of atmospheric bursts, (b) discrete chorus riser ELF emissions triggered from the bottom of the atmospherics, (c) whistlers, (d) whistler-triggered discrete chorus riser VLF emissions triggered from the lower end of the whistler, (e) long enduring ELF/VLF hiss emissions, (f) band limited quasi-periodic pulsing ELF/VLF hiss emissions, (g) hook and inverted hook ELF emissions, (h) oscillating tone discrete chorus riser ELF emissions. Our spectrum analysis results show that ELF discrete chorus riser emissions are triggered almost from the foot of the lightning generated atmospherics observed in the beginning of ELF/VLF activity provide an experimental evidence of the origin of discrete chorus emissions generated by lightning discharge at low latitudes.

2. GENERATION MECHANISM

Several mechanisms have been proposed from time to time to explain the generation mechanism of ELF/VLF waves (Kimura *et al.* 1967; Helliwell *et al*. 1967; Roux *et al*. 1978; Helliwell *et al.* 1982; Molvig *et al*. 1988; Trakhlengerts *et al*. 2000; Singh *et al*. 2005). Experimental observations show strong evidence that these emissions are generated near the magnetic equator by trapped energetic

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electrons. Out of various mechanisms proposed from time to time, the non-linear cyclotron resonant interaction between whistler mode waves and energetic electrons could explain most of the characteristics of different types of ELF emissions recorded simultaneously on our ground station Jammu during daytime. In resonance interaction the kinetic energy of electrons increases as frequency decreases. In our proposed mechanism for the generation of these emissions, a simple model has been advanced by Singh et al. According to this model constant frequency oscillations are generated from the interaction region if situated on the equator, whereas interaction region situated on the downstream (upstream) sides of the magnetic equator generates oscillations with rising (falling) frequency (Helliwell *et al*. 1967). The cyclotron resonance condition which is basis for this mechanism is expressed as

$\omega - \omega_H \beta = k v_\parallel$ (1)

where ω and k are the angular wave frequency and wave vector of the whistler waves, k = |k|, ω_H is the electron gyrofrequency, $v_\parallel$ is the field aligned component of the electron velocity, $\beta = (1 - v^2 / c^2)^{-1/2}$ is the relativistic correction factor, v, is the velocity of interacting particle and c is the velocity of light in free space, for ducted whistler propagation $k_\parallel$, B_o. B_o being the vector geomagnetic field. In an inhomogeneous magnetic field, ω_H, k and $v_\parallel$ are functions of the coordinate z along the magnetic field B_o. The electrons with different $v_\parallel$ interact with the same wave (ω, k) at different points along the geomagnetic field lines.

In order to explain the frequency spectrum of the ELF/VLF emissions observed at Jammu we have applied the non-linear cyclotron resonance mechanism as discussed in detail by Singh et al. Under the second order cyclotron resonance condition df/dt values of the dynamic spectrum of ELF/VLF emissions can be written as (Trakhlengerts *et al*. 2000).

$$\frac{df}{dt} = \frac{1}{2\pi}\left(\frac{\omega}{2\omega + \omega_H}\right)\left[\left(3v_R - \frac{kv_\perp^2}{\omega_H}\right)\frac{\partial \omega_H}{\partial z} - 2\Omega_{tr}^2 s\right] \quad (2)$$

Where f is the wave frequency, v_R is the resonance energy of the electrons, $v_\perp$ the perpendicular velocity of the electron, z is the coordinate along the geomagnetic filed line. $\Omega_{tr} = (kv_\perp eB_\omega / m)^{1/2}$ (the oscillation frequency of the trapped electrons) where e the charge of electron m the mass of electron, B_ω the wave-magnetic field and S is the inhomogeniety in the magnetic field. Equation (2) depend upon the resonant velocity of the electron, inhomogeneity in the magnetic field, wave amplitude, etc. In the parabolic approximation for dipolar magnetic field $\partial \omega_H / \partial z = 2\omega_{Heq} z a^{-2}$ where a = (√2/3) R_E L, ω_{Heq} is the equatorial electron gyrofrequency, R_E is the radius of the Earth and L is the McIlwain parameter (Omura *et al*. 1991).

We have computed df/dt as a function of wave frequency, pitch angle and L-value. The results are given in Fig. 8. For the chosen magnetospheric parameters we found that

$$\left(3v_R - \frac{kv_\perp^2}{\omega_H}\right)\frac{\partial \omega_H}{\partial z} \square \; 2\Omega_{tr}^2 S \quad \text{for } S \le 1.$$

Thus, the sign of df/dt depends upon the sign of $\partial \omega_H / \partial z$ indicating that the riser (faller) will be generated when the interaction region lies in the increasing (decreasing) magnetic field region. Fig. 8. Shows the variation of df/dt as a function of frequency for different values of L, α = 15°, φ = 0° and S = 0.2, 0.5 and 0.8. The variation in df/dt with change in L arises due to a strong dependence on $\partial \omega_H / \partial z$. In fact $\partial \omega_H / \partial z$ plays a crucial role and forces the interaction region to generate either a riser or a faller or a triggered emission. Some times even a combination of riser and faller may be generated.

The most important among the events recorded simultaneously on 06 January 1999 at Jammu is QP pulsing hiss. In order to interpret dynamic spectrum of pulsing hiss recorded simultaneously for the first time during daytime at our low latitude ground station Jammu one should know the generation mechanism of this emission and its propagation from the source region to the observation point. This indicates that either the source is periodic or periodicity is introduced during propagation. Close association with aurora and micropulsation suggests that the processes causing these phenomena may also be influencing pulsing hiss. The source of energy could be charged particles populating the ionosphere and the magnetosphere. Knott and Bahnsen (Knott *et al*. 1981) suggested that the pulsed hiss type of emission is a plasmasheet associated phenomenon and depends critically on the level of anisotropy of energetic electrons (> 20 keV). The importance of anisotropy in the distribution function in the generation of VLF hiss including pulsed hiss during the Doppler-shifted cyclotron resonance interaction was also recognized by the other workers (Etcheto *et al*. 1973; Gendrin *et al*. 1975; Ward *et al*. 1983).

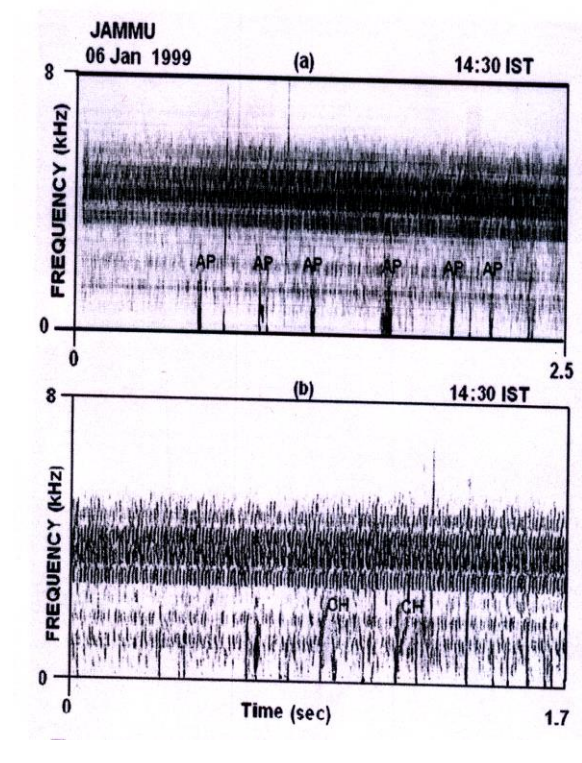

Fig. 1: Temporal evolution of the geomagnetic activity K_p index for the event 06 January 1999. The times when whistlers and ELF/VLF emissions observed are indicated by rectangles just above the abscissa of the panel

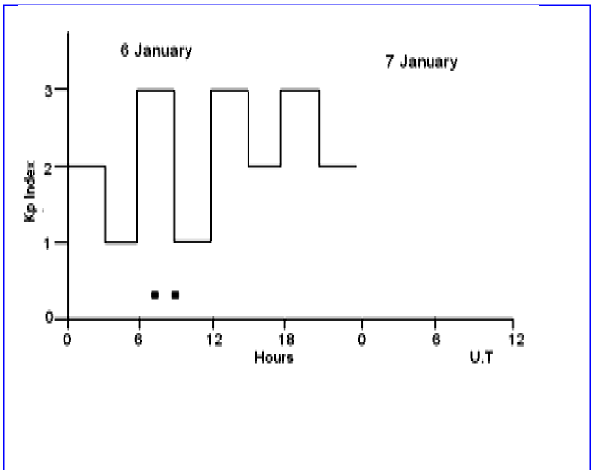

Fig. 2: Temporal variation of frequency spectra of pulses of atmospheric bursts and discrete chorus riser ELF emissions observed simultaneously during daytime at Jammu

Whistler mode waves propagating along geomagnetic field lines and interacting with counter streaming energetic electrons would scatter electrons in to the loss cone. This may drive highly localized field-aligned currents leading to generation of Alfven waves that may set up ULF waves along the field lines. Thus, the equilibrium conditions break down when considering such fast variations and interaction between the waves and the electrons becomes the function of time. However, the condition of resonance interaction remains the same, only the involved physical parameters become the function of time.

Considering the parameters appearing in the wave growth as time dependent functions, separating the variables and differentiating the basic equation for the wave growth coefficient γ can be written as.

$$d\ln\gamma/dt = d\ln\omega_H/dt + d\ln\eta/dt + d\ln A/dt \quad (3)$$

Where ω_H is the local electron gyrofrequency, η is fraction of electrons near resonance, $A = (T_\perp - T_{||})/T_{||}$ is an anisotropy factor. $T_\perp$ and $T_{||}$ are the characteristic temperatures of the electron's motion perpendicular and parallel to the local geomagnetic field respectively. In the presence of micropulsation of frequency ω_o, the local magnetic field is modified and can be expressed as

$$B = B_o(1 + b\cos\omega_o t);\ b \ll 1 \quad (4)$$

Where B_o is the background magnetic field having dipolar variation, b is the normalized amplitude of propagating micropulsation / ULF wave. The perturbation of local magnetic field affects all the three terms on the right side of Equation (3) because a change in B implies a change in ω_H, which governs the proposed mechanism of hiss generation through the Doppler– shifted cyclotron resonance condition $\omega - kv = \omega_H$. Thus, a change in $\omega_H$is directly linked withchange in γ.

For a Maxwellian distribution in $T_{||}$ and first adiabatic invariant $T_\perp \propto B$, Equation (3) can be written as (see for detail Ward *et al*. 1982; Singh *et al*. 2005)

$$d\ln\gamma/dt = \{-b\omega_0[\{(1+2A)/A\} - m\Omega_0^2/KT_\perp K_\omega^2]\sin\omega_0 t/1+b\cos\omega_0 t\} - [m\Omega_0^2 b^2\omega_0/KT_\perp K_\omega^2]\sin^2\omega_0 t/1+b\cos\omega_0 t \quad (5)$$

Where m is the mass of electron, K is the Boltzmann constant, K_ω is the wave vector of the interacting wave. The above equation reveals that pulsations in hiss could have two components of frequency $\omega_o$and $2\omega_o$, the former being due to the modification of $T_\perp$ by a changing magnetic field, whereas the latter is due to the independence of $T_{||}$ to such changes.

Integrating Equation (5) the growth rate is written as

$$\gamma = (1 + b\cos\omega_0 t / 1 + b)^{(1+2A/A)-(3m\Omega_0^2/KT_{\parallel}K_\omega^2)} \exp[\{2m\Omega_0^2 b / KT_{\parallel}K_\omega^2\}(\cos\omega_0 t - 1)] \quad (6)$$

This shows that hiss amplitude has fundamental frequency component of micropulsations. The second harmonics does not appear. We have evaluated Equation (6) for the parameters relevant to L = 1.17, 3, and 4.0 which is shown in Fig. 9. In the computation b = 0.05, $\omega = 2\pi f_o$, f_o =1.9987 Hz, A = 1.5, $T_{||}$ = 4.6615 × 10^{7o}K has been used, ω_H andω_P are chosen corresponding to the equatorial value for L = 1.17, 3.0, and 4.0and wave frequency is taken as 8 kHz. Growth rate in oscillating and amplitude of oscillation decreases as L-value increases for L = 4.0 the oscillation lies between 0.78 and 1.26.

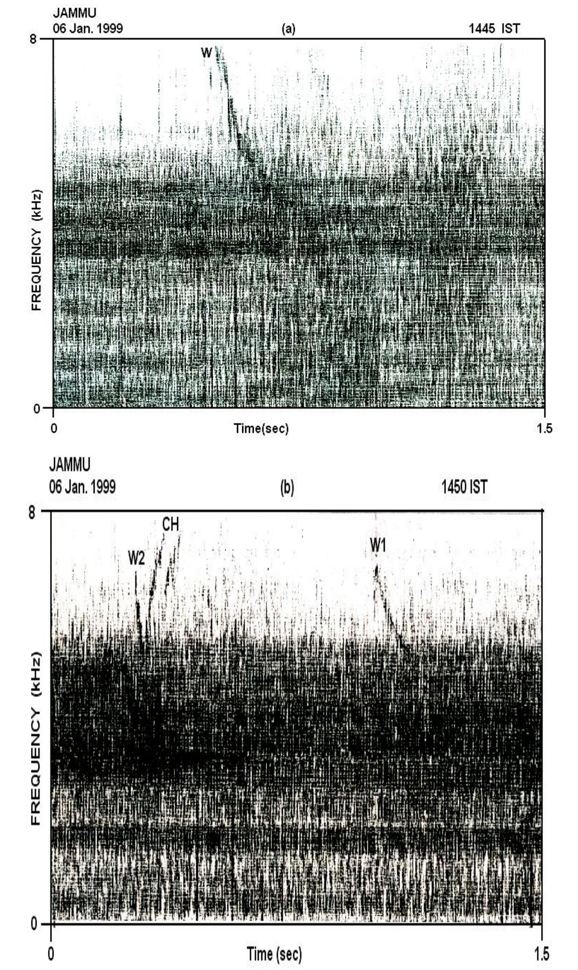

Fig. 3: Temporal variation of frequency spectra of whistler and whistler-triggered discrete chorus riser emissions observed simultaneously during daytime at Jammu (W:Whistler; WT: Whistler-triggered)

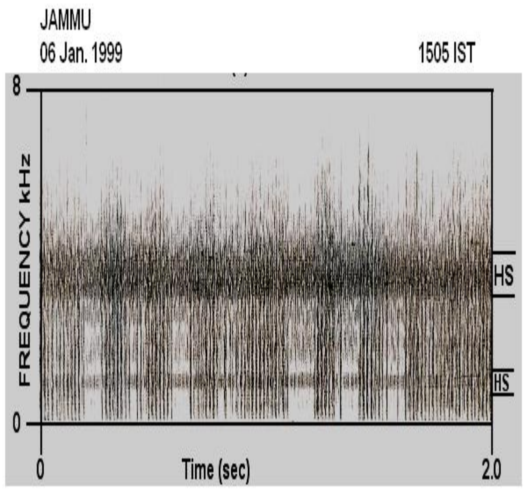

Fig. 4: Temporal variation of frequency spectra of ELF/VLF hiss emissions observed simultaneously during daytime at Jammu (HS: Hiss)

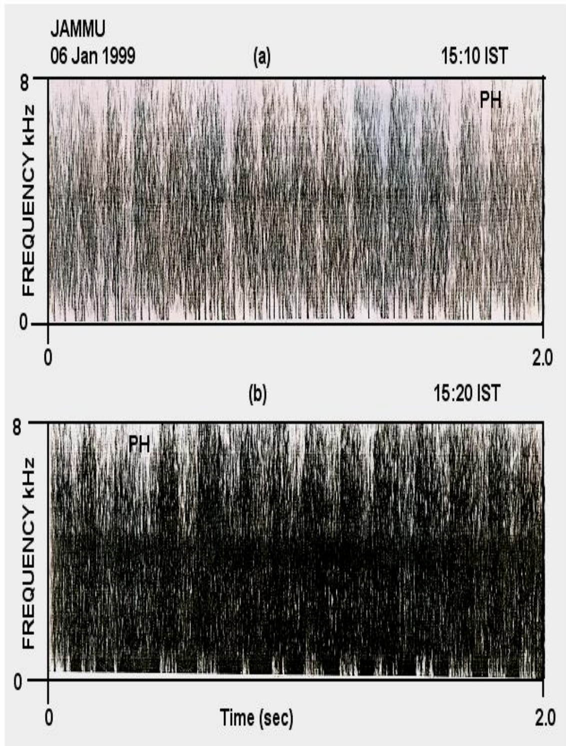

Fig. 5: Temporal variation of frequency spectra of quasi-periodic VLF/ELF emissions observed simultaneously during daytime at Jammu (PH: Pulsing hiss)

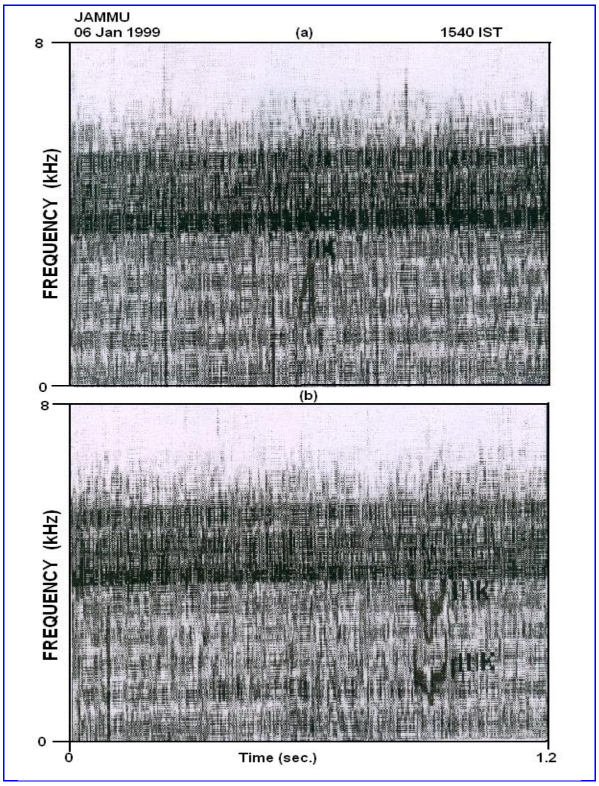

Fig. 6: Temporal variation of frequency spectra of hook and inverted ELF hook emissionobserved simultaneously during daytime at Jammu (HK: Hook; IHK: Inverted Hook)

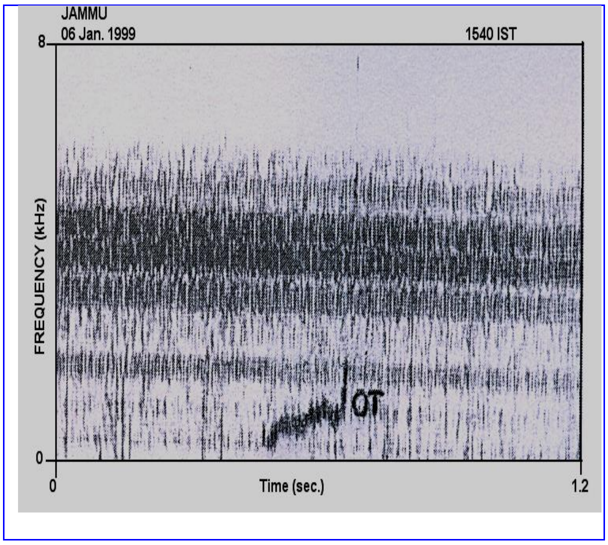

Fig. 7: Temporal variation of frequency spectra of oscillating tone discrete chorus riser emissions observed simultaneously during daytime at Jammu (OT: Oscillating Tone)

3. RESULTS AND DISCUSSIONS

We now discuss the implications of our simultaneous observations from several different perspectives. Detailed spectrum analysis of whistlers and different types of VLF/ELF emission events observed simultaneously on 06 January 1999 at Jammu were made in order to find out the possibility of their occurrence. The possibility that the occurrence of these events was just a coincidence does not seem to be likely because we have observed many similar events subsequently which occurred one after the other.

Under AllIndia Coordinated Program of Ionosphere Thermosphere Studies (AICPITS) program we have conducted initial observation of whistlers and VLF/ELF emissions at our ground based station Jammu and obtained an unique and very interesting result of the simultaneous occurrence of whistlers and different types of VLF/ELF emissions during daytime. Such type of daytime observations has never been reported from any of the low latitude ground stations so far and is the first result to be reported here. A preliminary description of whistlers and different types of VLF/ELF emissions recorded simultaneously during daytime at Jammu in the magnetically disturbed periods on 06 January 1999 alongwith their possible interpretations are given. It is very interesting to examine the simultaneous occurrence of whistlers and different types ELF/VLF emissions at a low latitude ground station in view of the origin of these reported emissions. Some typical and interesting examples of these simultaneously recorded ELF/VLF data at Jammu are shown in Figures 2- 7.The date and time of the observation of each whistler and VLF/ELF emissions are mentioned on the top of each figure. These were observed simultaneously only on a single day in winter local day times on 06 January 1999 during magnetically disturbed period with the sum of K_p indices as 18 ($\sum K_p$ = 18+). This activity started around 1400 hrs IST (Indian Standard Time) and continued for about two hours.

The temporal variation of geomagnetic activity during this event in Figure 1; 3-hour K_p indices are used. The times of having observed simultaneously whistlers and VLF/ELF emissions are indicated in the upper panel by rectangles just above the abscissa of the panel. It seems that the occurrence of these whistlers and VLF/ELF emissions appears to be well correlated with a geomagnetic substorms designated by a peak in K_p index at ~ 8h UT on 06 January 1999. Taking into account the relationship of local time IST = U.T. + 5.5h, every whistlers and emissions described below have taken place in the local after noon hours.

The dynamic spectrograms of figure 2 shows pulses of atmospheric bursts and triggered rising tone discrete chorus emissions in the ELF range (≤ 3 kHz) recorded at 1430 hrs IST on 06 January 1999. The spectrum analysis of the events shown in Figure 2a clearly shows that the VLF/ELF activity on this day was started with the pulses of atmospheric bursts in the ELF range with a regular time intervals of ~ 0.30 sec immediately after the commencement of the events, where as Figure 2b shows a dynamic spectrum of two sets of sharp discrete chorus riser emissions in the ELF range in the frequency range ~ 0.60 to 3.0 kHz with a time separation of ~ 0.30 sec between them. It is interesting to see that these emissions are triggered from the lower end of the lightning generated atmospherics above ~ 500 Hz. A band of noise (continuous hiss type structure) in the frequency range ~ 2.8 to 6.3 kHz is seen in this figure, it may have occurred due to some local noise present at the time of observation.One of the typical example of a Figure 3a depicts temporal variation of frequency spectra of a diffused whistler observed simultaneously at 1445 hrs IST. In this event the whistler marked W has a dispersion of ~ 55 $sec^{1/2}$ and the path of propagation has L = 4.35 where as Figure 3b shows anotherinteresting typical examples of a temporal variation of frequency spectra of VLF waves observed simultaneously at 1450 hrs IST. Firstly it contains a whistler-triggered chorus riser emission event. In this event the whistler marked W1 has a dispersion of ~ 28 $sec^{1/2}$ and a chorus emission (marked CH) is triggered from the lower end of the whistler W1. The corresponding path of propagation of whistler W1 is L = 3.4. Immediately after 0.8 second another whistler W2 appears with a dispersion of ~ 52 $sec^{1/2}$and the path of propagation has L = 4.25. Just below the spectra of whistler-triggered VLF chorus riser emissionand whistler, the same noise band structure is continued to be persisted in this figure also.

Figure 4 contains clear bands of both VLF and ELF hiss emissions with the presence of large number of atmospherics. The band of VLF hiss occurs in the frequency range ~ 3.8 to 6.0 kHz where as ELF hiss in frequency range ~ 1.1 – 1.8 kHz observed simultaneously at 1505 hrs IST respectively. Containing bands of large number of sferics is seen to occur at regular time of intervals. The time separation between the bands of sferics is ~ 0.1 sec. The frequency in figure 5 illustrates spectra of quasi-periodic pulsing hiss emissions recorded simultaneously at 1510 hrs IST. This figure contains pulsing hiss in both frequency range of VLF and ELF starting from ~ 300 Hz upto ~ 8 kHz frequencies. It is very interesting to see that the noise band structure are not at all visible and disappeared in this figure at the time of occurrence of these VLF/ELF hiss emissions. From the figure it is noted that the frequency spectrum of pulses is irregular in structure and intensity. The upper cut-off frequency varies from pulse to pulse. Time period is difficult to determine, although during 2 seconds, we have about 14 pulses of hiss emissions in the frequency range 50 Hz – 8 kHz. Before and after the pulsing hiss event a large number of sferics were seen with almost no noise at low frequencies. Pulsing hiss emissions during the entire period has approximately the same frequency range and periodicity. However, intensity of the emissions near the end of event decreases with time. The VLF activity at low latitudes is more prevalent during magnetically disturbed periods as it is clearly evident from the simultaneous observations of different type of VLF/ELF emissions reported in this paper. The band width of the pulsing hiss also decreases with increase in frequency. The entire dynamic spectrum has irregular structure and varied from pulse to pulse.

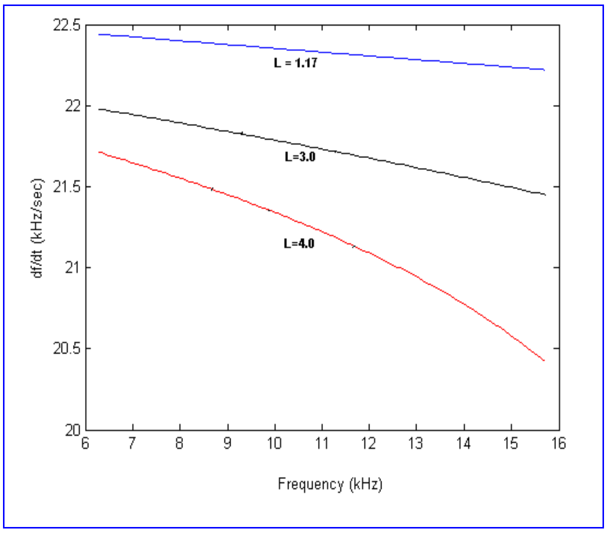

Fig. 8: Variation of df/dt as a function of frequency for α=15,φ=0 and S= 0.2,0.5and 0.8 for L =1.17, L=3.0 and L=4.0 respectively

The very interesting typical examples of a temporal variation of frequency spectra of hook (Fig. 6a) and inverted hook (Fig. 6b) emissions in ELF/VLF range recorded simultaneously alongwith other types of emissions on 06 January 1999 at 1530 hrs IST. In this figure a normal sharp hook emission first appear in the frequency range between ~ 1.5 and 2.6 kHz and immediately after ~1.5 seconds two traces of diffused inverted hook emissions appear one over the other in the frequency range ~ 1.1 to 2.3 kHz and ~ 2.4 to 3.4

kHz respectively. In this figure also dominant noise band structure persists on the spectrogram in the same frequency range as in Figs. 2, 3 and 4. In Figure7. we show a typical example of frequency spectrum of a diffused oscillating tone discrete chorus riser emission recorded simultaneously at 1540 hrs IST on 06 January 1999.This event is recorded after ten minutes of the occurrence of hook emissions shown in Figure 7 and appear in the ELF range between ~ 0.5 and 1.3 kHz. Noise band structure is also seen to be present in this spectrum.

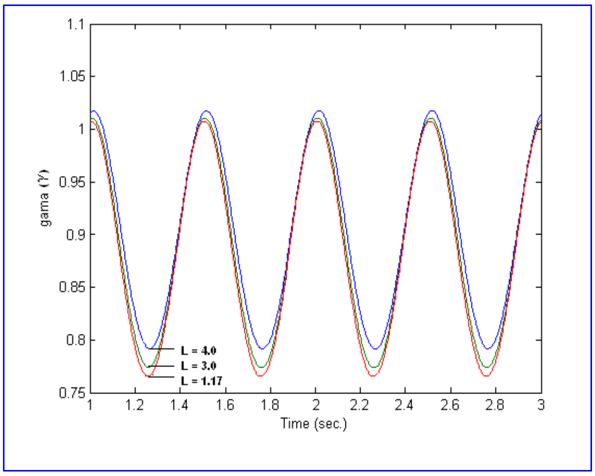

Fig. 9. Variation of growth rate with time for different L-values (L = 1.17, 3.0, and 4.0)

Careful spectrum analysis shows that bands of noise like structure appears almost from the very beginning of the start of the observation and persisted almost throughout the observation on 06 January 1999 but it disappeared in between especially at the time of occurrence of the hiss and quasi-periodic hiss emissions as shown in Figures 5 and 6. We could not find any possibility of its being an artifact. Hence, we strongly feel that it could be most probably due to some local noise.

From the dispersion analysis of the simultaneously observed whistlers, it is found that they have dispersions in the range ~ 28 to 55 $sec^{1/2}$ and correspondingly L- values were found in the range of ~ 3.4 to 4.35 derived from the Dowden-Allcock method (Dowden *et al*. 1971). Subsequently the L-value of VLF/ELF source computed with the help of the upper boundary frequency (UBF) method as developed by Smirnova (Smirnova *et al*. 1984) was found to be L ~ 4.0 for f_{UB}= 8.0 kHz. Our spectrum analysis of whistlers and VLF/ELF emissions simultaneously observed clearly shows that whistlers and VLF/ELF emissions have propagated in ducted mode along higher L-values and after existing from the duct they penetrated the ionosphere and are trapped in the Earth-ionosphere wave-guide. The wave normal (lying in the range of ~ 0.2-2.3°) at the entrance into the wave-guide is such that they propagated towards the equator and are recorded at Jammu [21]. It is now well established that whistlers at low latitudes are observed during daytime through ducted mode of propagation in the presence of the equatorial anomaly. We have made computations of df/dt for L = 1.17, 3.0 and 4.0. The observed df/dt values agrees well with the computed results for L = 1.17, 3.0 and 4.0. However, there are some calculated/observed values of df/dt which are difficult to understand. In the computation of df/dt, we have considered wave vector **k** of the wave to be parallel to the geomagnetic field lines, which is valid for the ground measurements. However, the spatio-temporal evolution of energetic electron beams under the influence of whistler wave packet and the subsequent adiabatic motion of electrons in an inhomogeneous magnetic field is not properly understood. This is important for understanding of the mechanism of triggered emissions, and needs further exploration.

According to the simplified model given by Singh et al. oscillating tones are triggered when interaction region oscillates near the equatorial zone along the field line. This explains the whistler-triggered emissions shown in Fig. 3b. The riser event (Fig. 2b) is generated when interaction region lies in the southern hemisphere.

In the present case of quasi-periodic pulsing hiss observed simultaneously at Jammu during daytime on 06 January 1999, the pulsing hiss time period is about 0.5 sec which corresponds to continuous pulsation PC 1. PC 1 forms a standing wave pattern along the geomagnetic field line and thus produces oscillation in the trapped electrons bouncing back and forth along the field lines. Thus the wave-particle interaction is also modified. Considering hiss emission intensity to be result of amplification of waves, we except corresponding pulsation in the hiss-emission intensity.

An alternate source of VLF/ELF hiss (Fig.5) could be lightning discharge. Parrot (Parrot *et al*. 1990) has shown that the regions of high thunderstorm activity are correlated with the maximum intensity of hiss, which is an indicative of the embryonic effect of lightning in generating hiss (Sonwalkar *et al*. 1989; Draganov *et al*. 1992). VLF hiss generating by embryonic process could also be modulated through wave-particle interaction in the presence of micropulsations. Ward et al. (Ward *et al*. 1982) and Ward (Ward *et al*. 1984) based on comparative study of pulsing hiss and pulsating aurora showed that hiss pulses and auroral pulses have similar periods whereas the micropulsations had periods which were considerably longer for the cases analyzed. These discussions show that while working out the generation mechanism of pulsing hiss, one should take into the account the generation mechanism of pulsing aurora and micropulsation, which find their origin in the ionosphere. Davidson and Chiu [28] have discussed a non-linear mechanism for auroral pulsation, which may provide some indication on the possible origin of pulsing hiss.

5. CONCLUSION

The present experimental study is the first simultaneous observation of whistlers and different types ELF/VLF emissions during daytime at low latitudes. Much detailed experimental and modeling study remains to be done in this area, but our results naturally account for the essential features of VLF/ELF emissions observed during daytimes. We note from the present study, the role of lightning in the magnetospheric wave-particle interactions at low latitudes. "The VLF/ELF data" shown in this paper (Figures 1-4) indicate that there is a strong possibility that discrete chorus emissions generated by lightning discharge is an important source of the origin of VLF/ELF hiss emissions, at least in the embryonic sense. This experimental study unlikely to be final word on the origin of different types of VLF/ELF emissions and further experimental confirmation will, of course, be required at latitudes. The most important among these simultaneous observations is pulsing hiss and its generation mechanism is reported for the first time during daytime. Dynamic spectra of pulsing hiss contain irregular structure. Intensity and frequency distribution varies from one pulse to the other pulse. Pulsing hiss emissions are supposed to be generated during Doppler-shifted cyclotron resonance interaction. ULF waves propagating along the geomagnetic field lines may have modulated the intensity of the emission resulting in to the pulsing hiss.Nonetheless, the idea has the potential to be a 'circuit breaker' in our understanding of the generation mechanism of the VLF/ELF emissions observed at low latitudes. However, further detailed mechanism (or process) of the data presented here is a challenging problem and this task will be left for further investigations.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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