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Quite period- associated low latitude VLF/ELF emissions with frequency drift observed in the premidnight sector

M. ALTAF [1*], M.M. AHMAD, and SHEIKH NAZIR AHMAD[2]

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Abstract

Characteristics of nighttime VLF/ELF emissions are examined on the basis of the data obtained at a low latitude ground station Jammu (geomag. lat., 22o 26' N; L = 1.17), India during our VLF/ELF campaign. From the detailed analysis of the acquired VLF/ELF data at Jammu we have found two remarkable events which clearly exhibit a rise in their frequency with time in pre midnight sectors during magnetically quiet periods. Our analysis shows that the emissions observed are of hiss and hissler types and are recorded during magnetically quiet period followed by disturbances. The observed frequency drift in VLF/ELF emissions at Jammu seems to be a rare phenomenon at low latitudes during magnetically quiet period in pre midnight sectors. This property of temporal frequency drift in VLF/ELF emissions observed at our station Jammu are interpreted in terms of a electron-cyclotron wave-particle interaction for wave excitation. The initial frequency increase is believed to be due to combined effect of L-shell drift of energetic electrons.

1. Introduction

Like whistlers, very low frequency / extremely low frequency (VLF/ELF) emissions are whistler mode ionospheric noises a class of natural radio phenomenon[10]. These emissions have over the past decades become a very important diagnostic tool for probing the plasma sphere and beyond. These emissions although less well understood than whistlers are believed to have origin in the ionosphere magnetosphere coupled system and may be due to plasma instabilities or in-situ electromagnetic radiations from high energy particles. In fact, several types of emissions are often observed in close association with whistlers. VLF/ELF emissions depending upon their dynamic spectrum are classified as unstructured and structured emissions. Continuous emissions in both time and frequency which tend to maintain a steady state: hiss, resonance bands, and noise bands

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**Corresponding Author:* E-Mail: - altafnig@rediffmail.com

near the ion gyro-frequencies seem to fit in unstructured type[10]. The other type structured emissions includes: (1) discrete emissions often with a repetitive and even periodic character which tend to be transient,(2) chorus periodic emissions, and (3) various other transient discrete emissions such as hook, pseudo-whistlers and pseudo-noses[10]. Low latitude satellite observations have enabled us to determine the global distribution of VLF emissions within the ionosphere and it is found that VLF emissions of magnetospheric origin occur predominantly in the two characteristic latitude regions, high latitude (auroral zone) and medium latitude around plasma pause[9].

The whistler mode waves and their interactions with energetic particles have been a subject of interest, since the discovery of radiation belts. These interactions establish the high levels of VLF/ELF noise in the ionosphere and magnetosphere and play an important role in the acceleration, transport and loss of energetic particles in planetary magnetospheres[30]. In the Earth's magnetosphere, waves known to interact strongly with particles include chorus and hiss emissions, lightning generated emissions and man-made signals from VLF transmitters. VLF/ELF emissions in the subauroral and medium latitudes, being evidently associated with sub storms are shown to exhibit a characteristic rise in their frequency around the dawn sector[23,2,3,19,6], and it is considered that these frequency drifts of associated VLF emissions are of great importance in investigating not only the wave- particle interaction process, 3 but also the dynamics of energetic electrons from the plasma sheet and the convection electric field[19] Hayakawa *et al.*,[8]. Hayakawa *et al*. (1988) have examined a new type of frequency drift (different from those in the dawn) for pre-midnight VLF emissions on the basis of the data obtained at two stations, Brorfelde in Denmark (L ~3) and Chambon-la-Foret in France (L~2) as well as ISIS satellite measurements and they have interpreted it in terms of a combined effect of L-shell drift of energetic electrons and the change in convection electric field during the sub storm developments. Hayakawa[9] has made a further study of the frequency drift of mid-latitude VLF emissions associated with sub storm. He found that it does not seem to be a rare phenomenon that sub storm associated VLF emissions (structured and unstructured) exhibit a regular frequency increase in the dawn sector. The frequency drift reported so far are only from mid and high latitudes as well as from ISIS satellite measurements and are associated with sub storms[9].

The investigations cited above are based mainly on mid and high latitudes VLF/ELF data made either on temporarily for a few months or on event studies. Unlike mid and high latitudes, the frequency drift in VLF/ELF emissions observed at low latitudes have not been used so far for exploring the plasmasphere. So we felt it was necessary to make a study on the properties of the frequency drifts in VLF/ELF emissions observed at low latitudes on the basis of the acquired data, such as from the routine measurements made at a ground station Jammu, and then to elucidate the associated wave-particle interaction process, dynamics of particles and convection electric field during magnetically quiet periods[16-18].

In the following we have presented the data of the frequency drifts in VLF/ELF emissions observed for the first time during nighttime at a low latitude ground station Jammu and discuss in somewhat detail their spectral characteristics. Generation and propagation mechanisms are also briefly discussed.

2. Data selection and analysis :

The present study is based on the VLF observations made at a newly setup station Jammu (L=1.17) in India. Broad band VLF signals are received by a T-type of antenna, amplifiers and tape recorder having band width of 50Hz – 15 kHz. T-type antenna is 25 meter in 4 vertical length, 6 meter long horizontally and 3.2 mm in diameter. Its impedance is about 1MΩ. The antenna is rendered a-periodic with the help of a suitable RC network, to avoid any possible ringing effect. The antenna is erected at a suitable distance from the main building to reduce the power line hum and any other type of man made noises. Between the antenna and pre/main amplifiers, an active filter unit is introduced to reduce the local noise to a minimum in the frequency range 100Hz to 500Hz. The filter is constructed from a simple R-C network along with operational amplifier to be operated in positive feedback mode. The lower cut off frequency of the filter is about 600Hz and voltage gain is 1.2 up to 15 kHz. In this recording setup we have not used anti-aliasing filter. The gain of the pre/main amplifier is varied from 0 to 40dB to avoid overloading of the amplifier at the time of great VLF activity. The observations were taken continuously both during day and night times. The VLF data were stored on the magnetic tapes which were analyzed using a digital sonograph. Digitization of the analog signal was carried out at 16 kHz sampling frequency. The inbuilt software in the spectrum analysis of the sonograph machine provides dynamic spectrum, which updates in real time typically covering 8 kHz in frequency and 2.54 second in time. The frequency range may be varied from 100Hz to 40 kHz.

The period of data analysis is precisely chosen as one year from 1 January 1999 to the end of December 1999, due to the fact that we have detected two remarkable events reported in this paper which clearly exhibited frequency drifts in VLF/ELF emissions observed during the said period in nighttimes at a low latitude ground station Jammu. Various types of emissions are found to have occurred in VLF (≥ 3 kHz) and in ELF (≤ 3 kHz) in the year 1999 at Jammu. VLF/ELF steady hiss, pulsing hiss, hisslers, chorus, discrete rising and falling tones, and triggered emission events in large numbers have been found from this analysis during magnetically quiet periods in the nighttimes. Our study based on the long-term data at low latitudes[4,5,11,12,13,22-28] has indicated that once an emission event is commenced, it lasts, at least, for a few hours, so it is reasonable to consider that the emissions are continuous for one hour. In order to select the events with frequency drift we have imposed the following criteria to all of the VLF/ELF emission events observed at Jammu. The first condition is the exclusion of ELF (≤ 3 kHz) emission. The second criterion is that the emissions with frequency drift should last at least for one successive hour and this criterion is, in turn, indicative of our adopting only rather intense emissions. Mid and high latitudes VLF emissions are known to be strongly sensitive to 5 geomagnetic disturbances[31,32,2-9]. But at low latitudes it is not yet well established that whether these emissions with frequency drift are sensitive to geomagnetic quiet or disturbed periods. With the aim of studying the observed characteristics of frequency drifts in VLF/ELF emissions at low latitudes have been undertaken in the present analysis.

(a) The event of June 05, 1999: The temporal evolution of Kp index for this event is illustrated in Fig. 1. Figs. 2-4 present the temporal evolution of the frequency spectra of hisslers as recently reported by Singh *et al*.[27] in two frequency bands observed at Jammu in premidnight sector during deep quieting period following disturbances. Hisslers are quasiperiodic falling –tone noises and are feature of auroral broad band VLF hiss, in that they occur during time interval when such hiss is observed at ground stations and occur in portions of space where auroral hiss are observed on polar orbiting satellites. These rapid frequency-dispersed signatures resemble atmospheric whistlers and have been dubbed “hisslers”. Hisslers look like minute-long sequences with average spacing between individual bursts of the order of seconds and falling tone do not overlap in time and were observed during magnetically quiet period (K_p = 2_). On June 05 the activity started at around 2000 hrs IST and continued for more than a hour. Typical examples of hisslers are shown in Figs. 2-4. There are two bands. The higher frequency band looks like the second[7] harmonic of the lower band. We have checked the records of these two dates and no evidence of the generation of the second harmonics due to instrumental effect has been obtained. Further, we have checked all the other possibilities of local causes of the emissions and we could not associate any cause for the artifact of the emissions. This is also confirmed from Fig. 10b where hisslers only in the second band have been observed. Thus the hisslers in the second band belongs to natural sources[27].

Hissler emissions in two frequency bands are shown in Fig. 2 observed on June 05, 1999 at Jammu. In the lower band of Fig. 2a, the lower frequency of each band lies between 0.7 kHz and 1.2 kHz where as the upper band frequency of the element lies between 1.0 and 2.2 kHz. The lower and the upper frequency in the upper band lies in the frequency range 1.5 – 2.7 kHz and 3.0 – 3.2 kHz respectively. The emission in the upper band is not exact harmonics of the emissions present in the lower band, although they look like the second harmonics. In Fig. 2b the lower band emissions have their lower frequency in the range 1.0 – 1.2 kHz where as the upper frequency lies in the range 1.5 – 2.0 kHz. The upper band emissions are characterized by the lower frequency in the range 2.0 – 2.5 kHz and corresponding upper frequency in the range 2.7 – 3.5 kHz. This also shows that the emissions in the second band are not exact second harmonics of the first band. An interesting event is shown in Fig. 3 which contains the spectrograms of both hissler and hiss emissions. The lower and upper frequencies of hissler element in the lower band lie in the frequency range 3.3 – 4.1 kHz respectively and the corresponding lower and upper frequencies in the upper band lie in the frequency range 6.3 – 7.6 kHz respectively. Hiss and hisslers both in this Fig. 2 show very clear temporal rise in their frequencies. The hiss emission has a band width of ~ 0.5 kHz. In Fig. 4a the lower and the upper frequencies of the hissler element in the lower band lie in the range 2.0 – 2.2 kHz and 3.5 – 4.0 kHz respectively. The corresponding frequencies for the lower band lie in the range 4.5 – 5.0 kHz and 5.5 – 6.5 kHz respectively. In Fig 4b the lower and upper frequencies of the lower band hisslers lie in the range 2.2 – 2.5 kHz and 2.7 – 3.2 kHz respectively. The same of the upper band corresponds to 4.2 - 4.7 kHz and 5.0 – 5.7 kHz. Careful analysis shows that hiss emission is present in both bands of this figure and persisted throughout the hissler activity period. Hiss and hissler emissions both clearly exhibit a remarkable temporal rise in frequency during the period of their activity. If we take the centre frequency of the hissler emissions after one hour in both bands, the rate of frequency[8] increase is estimated to be about 1.7 kHz h^{-1}. Where as in the case of hiss emissions the estimated value of the rate of frequency increase is found to be ~ 3.5 kHz h^{-1}.

(b) The event of June 06, 1999: The temporal variation of Kp index for this event is shown in Fig. 5. The corresponding spectra of VLF emissions (hisslers) for this event are given in Figs. 6-7 as recently reported by Singh *et al.*[27]. The hissler activity continued from about 2100 hrs IST to about 2300 hrs IST recorded on 06 June 1999. These hisslers were observed during quiet period (K_p = 1_) followed by disturbances. In Fig.6a the lower and the upper frequencies of hissler elements in the lower band lie in the frequency range 0.7 – 1.2 kHz and 1.5 – 2.0 kHz respectively. In the upper band corresponding frequencies lie in the range 2.0–2.5 kHz and 3.2–4.0 kHz respectively. In Fig. 6b the ranges are respectively 0.7 – 2.2 kHz and 2.2 – 3.0 kHz (upper band). Fig. 7a contains hissler elements in two bands. The lower band and the upper band frequencies vary in the range 2.2 – 2.5 kHz and 3.7 – 4.7 kHz (lower band); 5.2 – 5.7 kHz and 6.2 – 7.5 kHz (upper band). Fig 7b contains only one band with frequency range 2.7 – 3.0 kHz and 3.2 – 3.7 kHz respectively, almost at the end of the hissler activity[27] on 6 June 1999. On June 6, 1999 both hiss and hissler emissions exhibit remarkable rise in their frequency in the pre-midnight sector. Hiss and hissler emissions shown in Fig.3 have yielded the drift rate of ~ 3.5 kHz h-1 and ~1.7 kHzh-1 respectively almost same value as that of the emissions observed on 5 June 1999.

3. Observational Results and Discussion

After having picked up every nighttime VLF/ELF emissions during our continuous recording of emissions at a low latitude ground station Jammu, we have made the data analysis after having imposed on them a few criteria. One of them is that the emission events should last for one hour at least, and this implies that the selected emissions are rather intense, we have found two remarkable events with frequency drift (increase) and those are hiss and hisslers whose properties have been discussed in detail in section 2 of this paper. The VLF/ELF emissions with frequency drift reported in this paper occurred both in pre- and post midnight sectors during magnetically deep quieting periods prior to the expansion phase of the substorms as well as during magnetically disturbed periods where as the VLF/ELF emissions with frequency drift reported from sub auroral and mid latitudes occurred only in the dawn sector 9 associated with sub storms. The two events reported in this paper have shown a definite regular frequency drift (increase). The drift rates are found to lie in a range from ~1.7 to ~3.5 kHz h^{-1}.

The reception of VLF/ELF waves on the Earth's surface clearly shows that the wave may have been propagated along the geomagnetic field lines either in ducted mode or in non-ducted pro-longitudinal mode. The source may lie in the equatorial region of low latitudes or in the auroral region. It is commonly believed so for from the study of VLF/ELF emissions observed at low latitudes that they originate in the equatorial magnetosphere of mid/high latitudes and may have propagated 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 at the entrance into the waveguide is such that they propagated towards the equator and are received at our low latitude ground station Jammu. The upper boundary frequency (UBF) method as developed by Smirnova[29] has been generally used to find out the location of VLF/ELF emissions observed at low latitude ground stations[1,14,15,28]. The upper boundary frequency (f_{UB}) of the ground observed VLF/ELF emissions are determined on the assumption of dipolar geomagnetic field configuration, by the half electron gyro frequency in the generation region irrespective of the observation station. The L-value of the VLF/ELF source is then computed with the help of the relation[29].

$$L = \left(\frac{440}{f_{UB}}\right)^{1/3} \tag{1}$$

Where f_{UB} is in kHz. Such an approach is called UBF method. Making use of Eq. (1) and the observed parameters, the values of source region of the emissions with frequency drift observed at Jammu are found to be ~ L=4. Thus our spectrum analysis clearly shows that the source of VLF/ELF emissions observed at Jammu is in the auroral region. Based on long-term VLF/ELF data observed at Moshiri, Japan (geomag. Lat., 34.5o N; L = 1.59) Hayakawa[9] has shown that emissions (either structured or hiss) at medium latitudes, being generated just around the plasma pause, tend to exhibit a regular frequency drift, when they are closely associated with sub storms, and this tendency seems to be very universal for medium latitude VLF emissions. Also, the generation of those sub auroral and mid latitude VLF emissions is, in turn, supposed to be due to the electron cyclotron instability as discussed[10] in detail in Hayakawa *et al.*[6,7]. This instability can be triggered by the penetration of plasma sheet into the inner magnetosphere and quenched by their subsequent pitch angle diffusion by the wave field and their final precipitation into the loss cone. Several quantitative models of mid-latitude VLF/ELF emissions were based on a self-consistent consideration of all these processes (Hayakawa et al., 1988). The most recent among these models is that of Sazhin[20], which was further developed by Sazhin[21]. This model has been successfully usedby Hayakawa *et al.*[7] when interpreting the events in the morning side magnetosphere and recently by Hayakawa *et al.*[9] for the interpretation of sub storm associated VLF emissions with frequency drift observed in the premidnight sector observed at two stations Brorfelde in Denmark (L ~ 3) and Chambon-La-Foret in France (L ~ 2) as well as ISIS satellite measurements. Here in this paper the model of Sazhin[21] and the method developed by Hayakawa *et al.*[9] will be applied to the interpretation of the nighttime VLF/ELF emissions with frequency drift observed during magnetically quiet periods recorded at Jammu. The generation of low latitude VLF emissions could be due to electron cyclotron instability as discussed in detail by Hayakawa *et al.* (1988). The frequency corresponding to maximum intensity of the waves can be estimated[9,19-21] as

$$\omega_{\max} = \frac{c^2 f_{Heq}^3}{q w_{//} f_p^2} \qquad (2)$$

Where f_{peq} and f_{Heq} are the electron plasma frequency and electron gyro frequency respectively in the equatorial magnetosphere in the excitation region, *c* the velocity of light, // *w* is the characteristic parallel thermal velocity of incoming electrons, *q* is the coefficient depending on the anisotropy of the incoming electrons as well as the distribution of electron density along magnetospheric field lines. After taking the reasonable value of q = 1.4 as used by Hayakawa *et al.*[9]. The Eq. (2) can be rewritten in a convenient form (see for details Hayakawa[9] *et al.*).

$$f_{\max}(kHz) = \frac{1.6\times10^9}{L^9 n_e w_{//}} \qquad (3)$$

Where n_e is the electron density in per cubic centimeters, $w_{//}$ is the parallel energy of incoming electron in keV, and $f_{max} = \omega_{max}/2\pi$ and is in kHz. $w_{//}$ is identified as a total electron energy *w*. Each of the parameters *L*, n_e and $w_{//}$ on the right hand side of equation (3) can change during the development of the events described in detail in Hayakawa[9] *et al.*, which results in corresponding change of f_{max}. The rate of this change can be estimated from the formula

$$\frac{df_{\max}}{dt} = f_{\max}\left[\frac{-9}{L}\frac{dL}{dt} - \frac{1}{n_e}\frac{dn_e}{dt} - \frac{1}{w_{//}}\frac{dw_{//}}{dt}\right] \qquad (4)$$

Before comparing the prediction of Eq. (4) with experimentally observed $df_{\max} / dt$ at Jammu, we will say few words about the choice of parameters *L, ne* and $w_{//}$. Single stationed statistical studies of low latitude emissions close to 5 kHz reveal that these emissions are mainly excited around *L* ~ 4 as determined by UBF method as given in Eq. (1). This is consistent with the model of Sazhin (1984), the value of *ne* is assumed to be equal to 0.5×103cm^{-3}, although the reliability of this value is not large; it can change within about an order of magnitude (see Chappel *et al.*, 1978; Hayakawa *et al.*, 1988). As pointed out by Hayakawa *et al.* (1988) n_e remains roughly constant within the individual events and reduction of ne does not influence significantly the value of *fmax* and in what follows we shell set *dne/dt* = 0 in complete accordance with Hayakawa *et al.* (1988).

The parameter on which the value of f_{max} depends is the characteristic parallel electron energy $w_{||}$. In order to estimate this parameter, Hayakawa *et al.* (1988) have discussed in details the parameters of electron trajectories in the equatorial plane in the pre midnight sector by a schematic illustration of the drift orbits of energetic electrons injected from the plasma sheet. If the electron trajectory is lying far away from the Earth in the evening-morning direction: $x > 1.76\xi$ (x_o is the initial position in the down–dusk direction at infinite distance from the Earth towards nightside direction) and

$\xi = (\mu_0/|eE|)^{1/4}$, μ is the electron magnetic moment $\mu = w_\perp/B$, B is the Earth's magnetic field induction, a is the magnetic moment of Earth, e is the electron charge, and E is the value of a large–scale electric field; (see Alfven and Falthammar, 1963), then the influence of the inhomogenectic of the Earth's magnetic field is small and the electron drift from the nightside to the dayside magnetosphere without encircling the Earth. When $xo < 1.76\ \xi$, then the electrons change the direction of their drift (Hayakawa et al., 1988). Assuming $r_o = L_0 R_e$ (R_e is the Earth's radius) and $w L_0^3 R_e^{\ 3} / a\ \ \xi$ and taking into account the definition of ξ and we have

$$L_0 = w_\perp / R_e\ |eE| \qquad (5)$$

Podovkin *et al.* (1977) has shown that the value of E changes from 10^{-4} V/m during quiet conditions to 10^{-3} V/m during disturbed conditions. Under this condition Hayakawa *et al.* (1988) has shown that L_o can change from disturbed to quiet periods. He has applied these properties of the trajectories of the electrons with fixed energies W for the rough estimates of the trajectories of the electrons distributed with respect to W, *i.e.*, the electrons have been W as their characteristic energy[16-18].

Hayakawa *et al.* (1988) have tried to identify the part of electron trajectory where the waves are predominantly generated for which a schematic illustration of the drift orbits in the equatorial plane of energetic electrons injected from the plasma sheet is shown in Fig. (12) of the Hayakawa *et al.* (1988). They show that the drift time (T_D) of these energetic electrons around the earth can be evaluated by

$$T_D(hours) = \frac{0.8 \times 10^3}{Lw(keV)} \qquad (6)$$

Where T_D is in hours and w is in keV. They have assumed that equatorial pitch angle of the drifting electron is equal to $\pi/4$. w is the characteristic energy of electrons under consideration. Eq. (6) enables us to estimate the value of $dw_{//}/dt$ due to the velocity of drifting electrons. In our estimation we have assumed that the waves are registered at one station in two subsequent local times, t_a and t_b. We have also assumed that the characteristic electron energy is w_a at t_a and w_b at t_b. Then the corresponding value of $dw_{//}/dt$ is given from the following equation (Hayakawa et al., 1988).

$$\frac{dw_{\square}}{dt} = \frac{(w_b - w_a)}{2(t_b - t_a)} \qquad (7)$$

After calculating the parameters $dw_{//}/dt$ by using Eq. (7) and substituting this value in Eq. (4) we obtained $df_{\max}/dt \approx 2$ kHzh^{-1} for all events (a, b and c). Such a theoretical values, which is obtained after many approximations is close to our experimental data shown in Figs. 2-4, 6-7. The discrepancy between the theoretical and observed values can presumably be explained by the fact that the equatorial plasmapause is located at larger L- shell than that 14 measured on-board ISIS satellite (Chappel *et al.*, 1970; Hayakawa *et al.*, 1988) and also depends upon the electron density model used for particular L-values. The origin and propagation mechanism of VLF/ELF emissions recorded at low latitude ground station is less clear and hence further experimental studies of this phenomenon are needed before we get a clear phenomenological

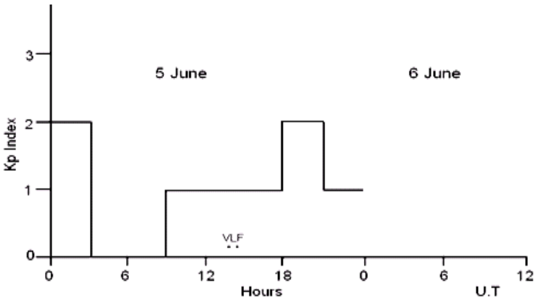

Fig. 1. Temporal evolution of the geomagnetic activity K_p index for the event 5 June 1999 The times when VLF emissions are observed, are indicated by rectangles just above the abscissa of the panel.

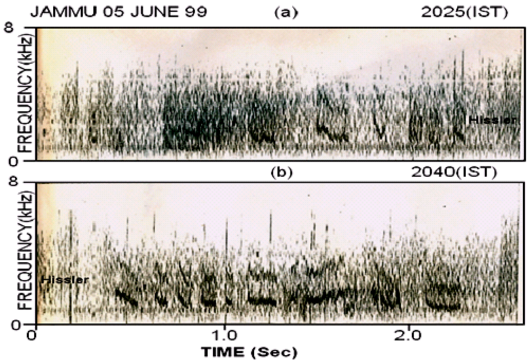

Fig. 2. Temporal variation of frequency spectra of hissler emissions observed at Jammu (L = 1.17).

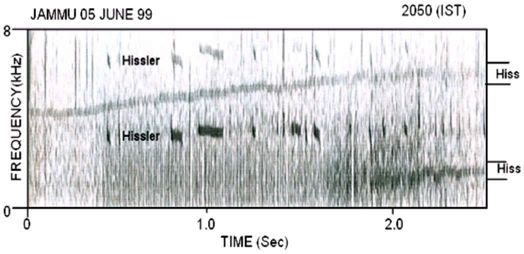

Fig. 3. Temporal variation of frequency spectra of VLF hiss and hissler emissions observed at Jammu (L = 1.17).

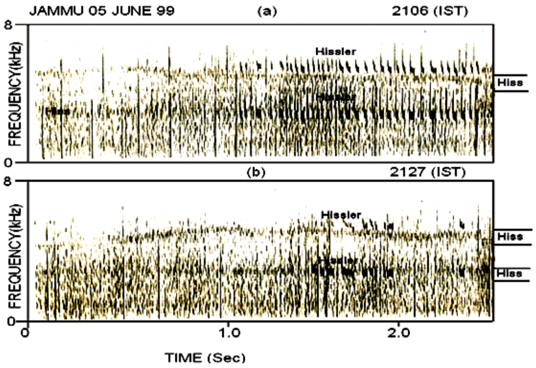

Fig. 4. Temporal variation of frequency spectra of VLF hiss and hissler emissions observed at Jammu (L = 1.17).

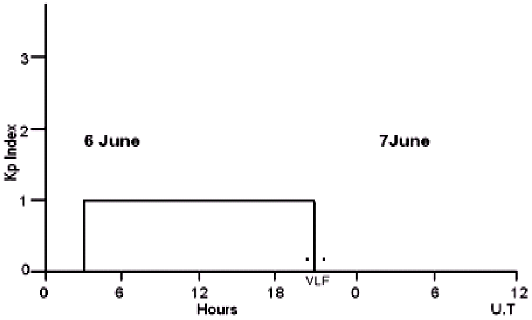

Fig. 5. Temporal evolution of the geomagnetic activity K_p index for the event 6 June 1999 The times when VLF emissions are observed, are indicated by rectangles just above the abscissa of the panel.

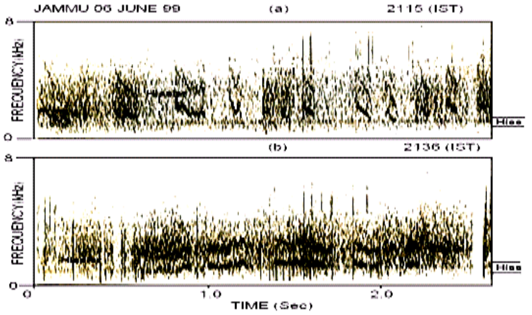

Fig. 6. Temporal variation of frequency spectra of VLF emissions (hiss and hissler) emissions observed at Jammu (L = 1.17).

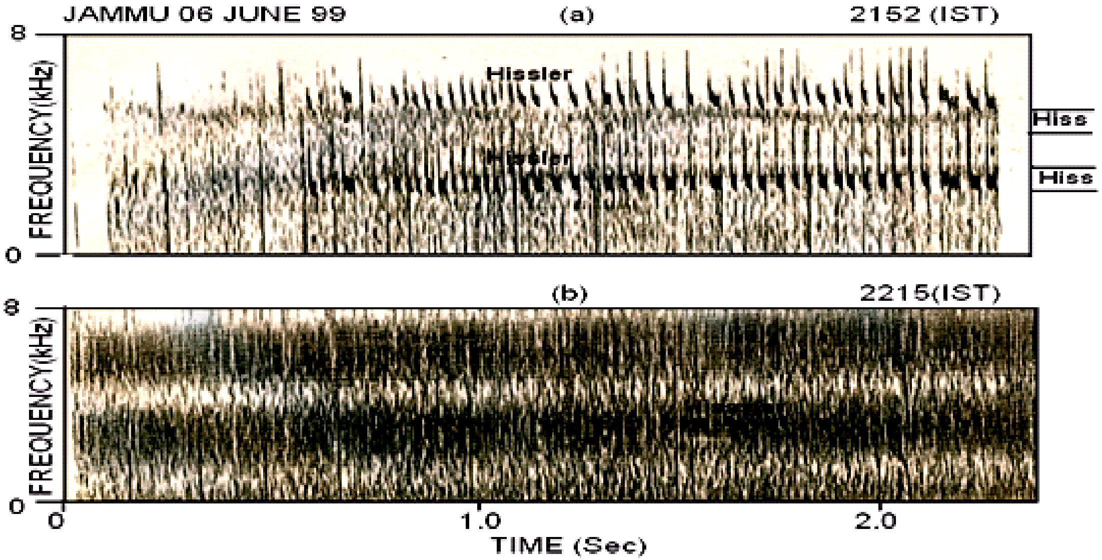

Fig. 7. Temporal variation of frequency spectra of VLF emissions (hiss and hissler) emissions observed at Jammu (L = 1.17).

model, which will be a first step towards a physical model. Therefore, multi-station ground measurements, including direction finding at low latitudes would be desirable to give a better descriptive model of the emissions[1-18].

4. Conclusions

This paper presents the interesting ‘first observation’ based on the long data of VLF/ELF emissions with frequency drift at a low latitude ground station showing that they are not limited to mid and high latitudes. These are observed during magnetically quiet periods in pre mid-night sectors. Our computations show that these emissions with frequency drift are generated at ~ L = 4 around plasma pause. The generation of these low latitude VLF emissions is, in turn, supposed to be electron cyclotron instability as discussed in detail in Hayakawa et al. (1986, 1988).

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