ELF/VLF radio signals observed at low-latitude station Srinagar, India (L = 1.28)

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This communication reports dynamic spectra of different ELF/VLF emissions such as hiss, chorus, hiss-triggered chorus and whistler-triggered emissions. We also discuss their various observed features. It is argued that most of the emissions are generated during Doppler-shifted cyclotron resonance interaction between the whistler mode wave and energetic electrons. Resonance energy of the participating electron and interaction length are evaluated to explain the generation mechanism of some of these emissions observed at the Indian station Srinagar.

Keywords: Chorus and hiss emission, ELF/VLF radio signals, whistler mode.

LIKE whistlers, very low frequency (VLF) and extremely low frequency (ELF) emissions are a class of natural electromagnetic wave phenomena[1]. These emissions have over the past decades become an important diagnostic tool for probing the plasmasphere and beyond. These emissions although less well understood than whistlers are believed to have their origin in the ionosphere–magnetosphere coupled system and may be due to plasma instabilities or *in situ* electromagnetic radiations from high-energy particles. Since the discovery of radiation belts, the interactions between ELF/VLF waves and energetic particles became a subject of interest. 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 a few hertz to 30 kHz, both continuous or unstructured and discrete or structured in nature, are a unstructured challenging and interesting natural phenomenon. Helliwell[1] has classified these emissions into hiss, discrete, periodic, quasiperiodic, chorus, hook, inverted hook and triggered emissions. Figure 1 shows the model spectral form of some of these emissions.

Low-latitude satellite observations have enabled us to determine the global distribution of ELF/VLF radio noises in the ionosphere[2–10]. It has been found that ELF/VLF emissions of magnetosphere origin occur predominately in the two characteristic latitude regions, high latitude (auroral zone) and medium latitude (just around the plasmopause). The high-latitude VLF radio emissions are found to occur in the auroral zone. They are generally considered to be generated by Cerenkov instability of precipitating electrons (<1 keV) from the neutral sheet[11]. On the other hand, the medium latitude VLF emissions are closely associated with geomagnetic storms and exerted just around the plasmapause in terms of cyclotron instability of intensified energetic electrons in the outer radiation belt[12]. Hence the investigations of global distribution of these types of VLF/ELF emissions are thought to be extremely useful in studying the wave–particle interaction process in the particle dynamics responsible for wave expectations.

Unlike mid- and high-latitude ELF/VLF emission have not been used much for exploring the inner magnetosphere, the main reason being that the propagation characteristics of these emissions in the low-latitude ionosphere are not properly known because of the scarce satellite and ground-based observational results. Hence, the mechanism of their generation source and propagation is not well-understood. Therefore, an understanding of the generation and propagation mechanisms of the ELF/VLF emissions observed at low latitudes could be useful to infer the properties of high-energy trapped electrons, with this aim, we have set up VLF/ELF receiving station at Srinagar (geomagn lat. 24°10′N, L = 1.28), India in 2009. During the course of our analysis of a huge amount of ELF/VLF data collected during January 2009–December 2012 at Srinagar, we have found excellent

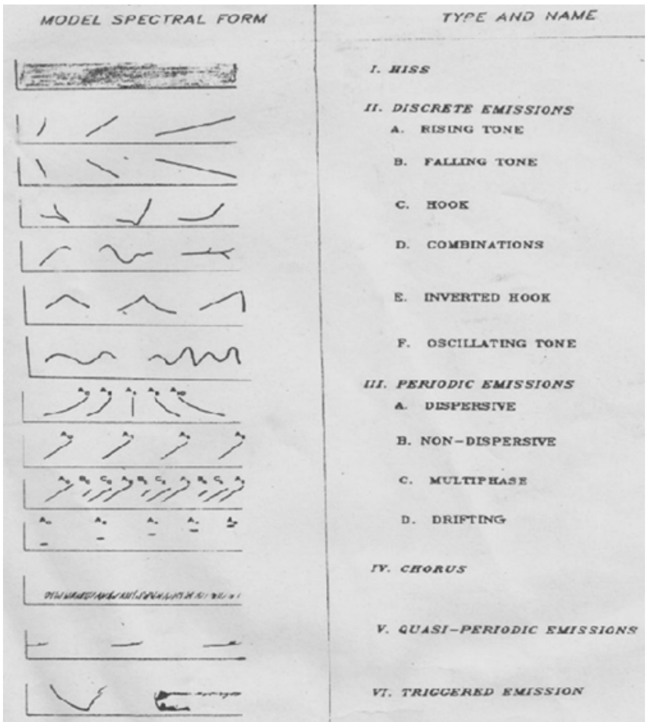

Figure 1. Model spectral forms of VLF emissions.

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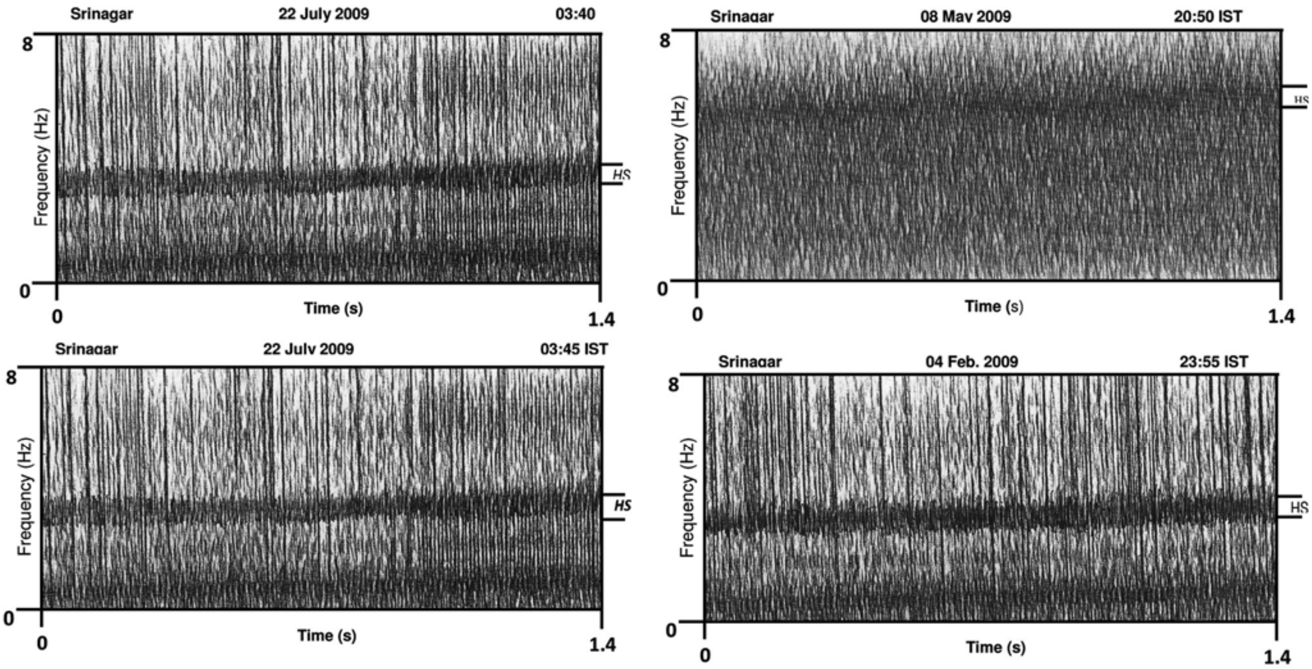

Figure 2. Dynamic spectrogram of VLF hiss (HS) emissions observed at Srinagar, India.

records of different types of emission with a discussion of their most probable generation mechanism.

This communication deals with different types of ELF/VLF emissions observed at our low-latitude ground station Srinagar during day and night-time. We also discuss their most probable generation and propagation mechanism, as well as experimental observations and analysis. Next, salient features of these emissions are discussed followed by their generation and propagation mechanisms.

The present study is based on ELF/VLF radio signal observations made at our Srinagar station (L = 1.28) from January 2009 to December 2012. The whistler mode signals are received by a T-type antenna, amplifiers and a tape recorder having band width 50 Hz–15 kHz. The T-type antenna is 25 m in vertical length and 6 m long horizontally and 3.2 mm in diameter. Its impedance is about 1 mΩ. The antenna is rendered a periodic with the help of suitable R–C network, to avoid any possible ringing effect. The antenna is placed 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 filtering unit is introduced to reduce the local noise to a minimum in the frequency range 100–500 Hz. The filter is constructed from a suitable R–C network along with the operational amplifier to be operated in positive feedback mode. The lower cut-off frequency of the filter is about 50 Hz and voltage gain is 1.2 up to 15 kHz. In this recording set-up we have not used anti-aliasing filter. The gain of the pre/main amplifier is varied from 0 to 40 dB to avoid overloading of the amplifier at the time of great VLF activity. The observations are taken continuously both during day and night-time. The VLF/ELF data are stored on magnetic tapes, which are analysed using a digital sonograph. Digitization of the analogue signal is carried out at 16 kHz sampling frequency. The in-built software in the spectrum analysis of the sonograph machine provides a dynamic spectrum, which updates in real time typically covering 8 kHz and 2.54 sec.

During the routine observations, different types of ELF/VLF emissions are observed. Figures 2 and 3 show the spectrogram of VLF and ELF hiss respectively, recorded at Srinagar.

During the course of analysis of the huge amount of ELF/VLF data collected in 2009–2012 at Srinagar, we have found some discrete type of chorus riser emissions. Figure 4 shows an example of discrete chorus riser emissions observed at Srinagar on 4 February 2009. Relative intensities of these emissions widely vary from event to event and their traces are sharp as well as diffused. Events with different slopes (df/dt) are observed. df/dt changes with frequency in the same event. Figure 5 shows an example of the daytime hiss-triggered chorus emissions recorded at Srinagar on 30 March 2009, which have been recorded for the first time at low-latitude stations during daytime. Most of the reported observations are mainly either from satellites[13] or during night-time. During the observation it was noted that the chorus was triggered when hiss intensity became high. The most intensive events were observed on 30 March 2009 during recovery phase of the substorm[14].

Figure 6 presents whistler-triggered chorus emission recorded at Srinagar on 14 February 2009. The K_p index during the observation period varied between 2 and 1^{+}. Detailed analysis showed that the whistler has a dispersion of 17 $s^{1/2}$ and had propagated along geomagnetic field line $L = 2$ either in ducted mode or in pro-longitudinal mode. After exiting from the ionosphere, the whistler wave along the triggered emissions excites the earth–ionosphere wave guide and propagates towards equator. The relative amplitude of triggered emissions is the same of that of triggering whistlers. In other cases some of the triggered emissions have their relative intensity greater than the triggering whistler.

Many theories have been proposed from time to time to explain the origin of these emissions. Some of the proposed mechanisms are the Cerenkov radiation, travelling

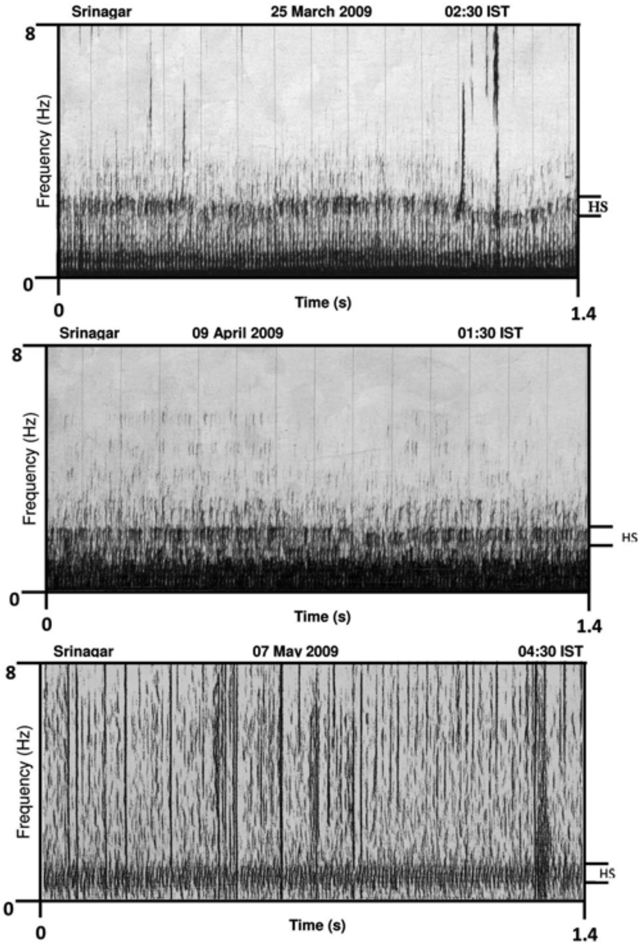

Figure 3. Dynamic spectrogram of ELF hiss (HS) emissions observed at Srinagar.

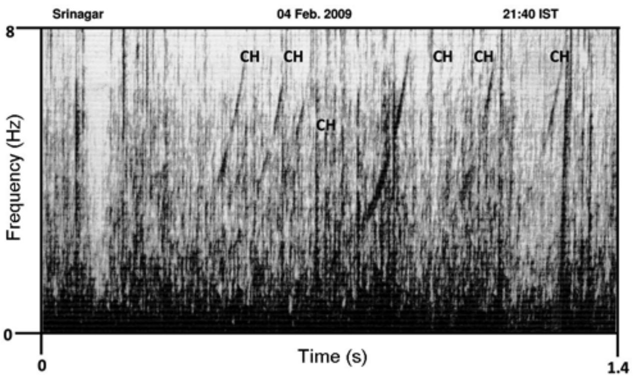

Figure 4. Dynamic spectrum of discrete chorus (CH) riser emission observed at Srinagar.

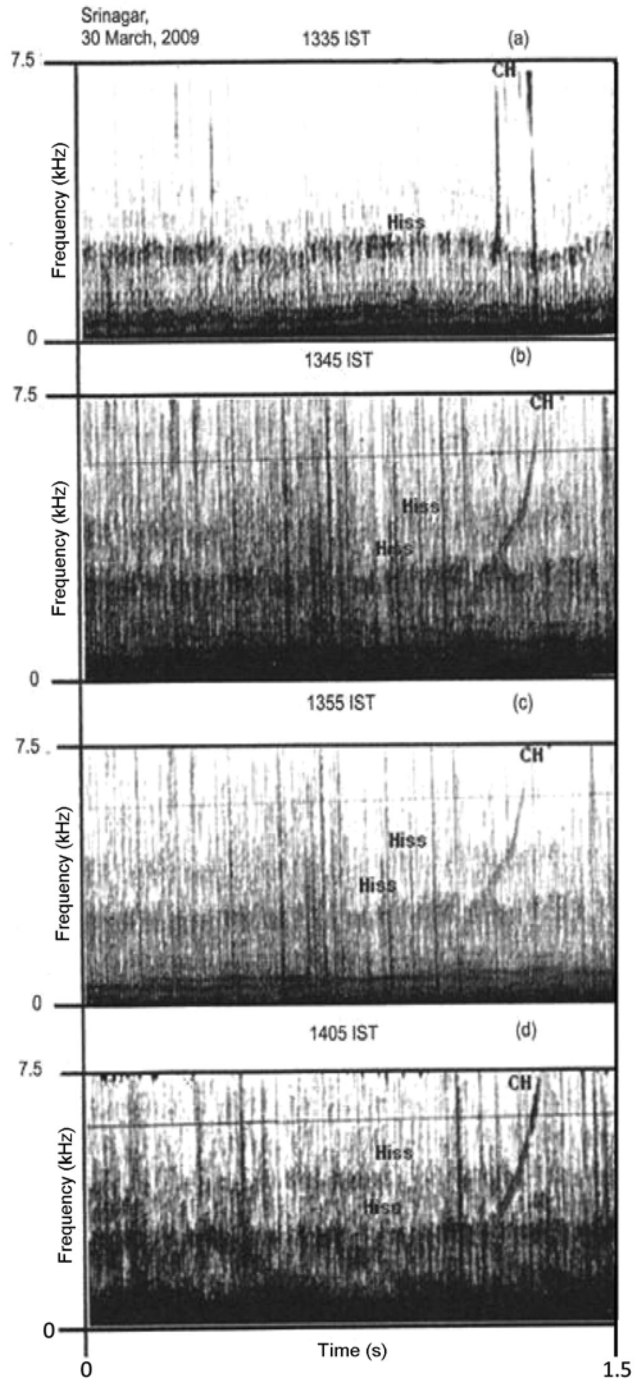

Figure 5. Dynamic spectrogram of daytime hiss-triggered chorus (CH) emissions observed at Srinagar.

wave tube in stability, cyclotron radiation and transverse resonance instability[15–43]. In the different mechanisms mentioned above, the energy of the emissions is derived from the ambient plasma particles populating the magnetosphere, although the physical process responsible for the transfer of energy from the particles to the wave is different in different mechanisms. Various types of VLF/ELF emissions have been explained with the different mechanisms advanced by various workers, which have been used successfully to explain different types of VLF/ELF emissions observed at Srinagar. These are discussed below.

Hiss is a widely studied VLF emission and the initial attempt was made to compute the incoherent Cerenkov radiated power to explain the observed intensity[44,45]. Assuming perfect guiding of the radiated wave and that all the electrons radiate incoherently in phase so that we can add all the produced power in the flux tube to obtain total received power on the surface of Earth. The total radiated power as a function of frequency for Srinagar and Varanasi station is shown in Figure 7. The radiated power peaks between 200 and 700 kHz. The frequency of observed VLF hiss is less than 10 kHz. The radiated power in the frequency range 10 kHz lies between 5×10^{-15} and 5×10^{-14} Wm^{-2} Hz^{-1}. If the wave attenuation is taken into account and the assumption of perfect guiding is not met, then the total power will decrease considerably. Thus, the computed power cannot explain the observed power spectral density. To make up this difference in the experimental and theoretical power, we suggest that the generated waves of small amplitude interact with the energetic electrons while bouncing back and forth along geomagnetic field lines and are thus amplified. The computed growth rate is too small to explain the required amplification[43]. Hence we suggest that the nonlinear theory of wave–particle interaction be studied to explain the observed power. The effect of inhomogeneous magnetic field and step-like deformation of the distribution function at the boundary between resonant and non-resonant electrons[46] should be included in the wave–particle interaction to make the model more realistic.

The chorus emissions reported here are for daytime and they are markedly different in frequency and df/dt with those events reported by other workers for night-time[47–49]. The night-time observations were explained in terms of these emissions being generated at high L-values in the vicinity of the plasma-pause. The emissions were supposed to have propagated to our ground stations at Jammu and Srinagar after successive magnetospheric reflections as proposed by Tsurutani *et al.*[50] to explain the chorus observed by satellites in the inner zone radiation belt. This mechanism may not be tenable due to the heavy attenuation during daytime. Further, at the base of the F-region ionosphere, the wave normal angles of non-ducted waves are such that the waves are unlikely to reach the ground. Therefore, it is believed that these emissions are generated in the equatorial plane of the inner zone radiation belt (L = 1.28) by cyclotron resonance interaction between whistler-mode waves and counter streaming energetic electrons[51]. The computed resonant energies for the various frequencies of emission lie in the range 1–5 MeV. The resonant energy for higher L-values (L > 3) is in the range 5–500 keV. Various features of the chorus emissions could not be explained by the linear theory of wave–particle interaction[52] and hence a nonlinear theory needs to be developed.

Detailed spectral analysis of hiss-triggered chorus emissions suggests that each chorus element has a tendency to originate from the hiss band. Koons[53] has analysed hiss-triggered chorus events observed onboard the SCATHA satellite and concluded that large-amplitude waves exist in the hiss band. Singh *et al.*[43] have proposed that the large-amplitude wavelets existing at the upper edge of the hiss band cause the phase bunching of resonant electrons which produces continuous radiation through the cyclotron instability mechanism at different

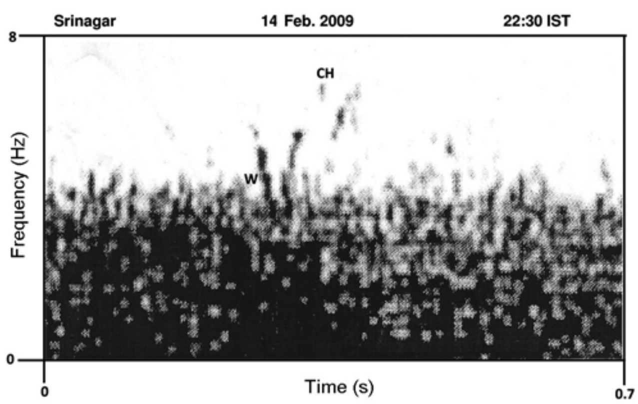

Figure 6. Dynamic spectrum of whistler (W)-triggered chorus (CH) emissions observed at Srinagar.

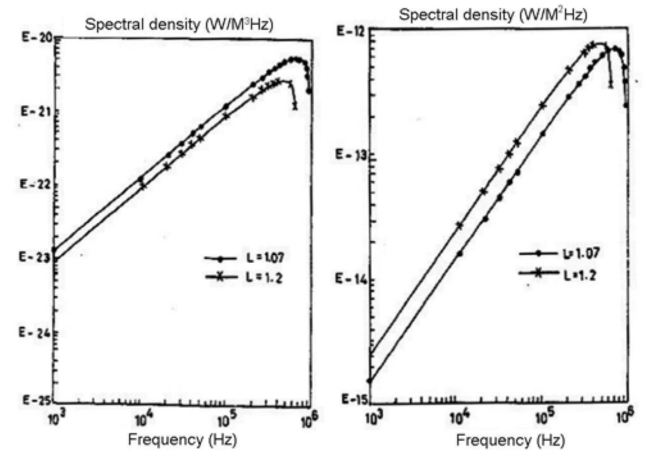

Figure 7. Variation of total radiated power per unit volume with frequency for Srinagar and Varanasi station.

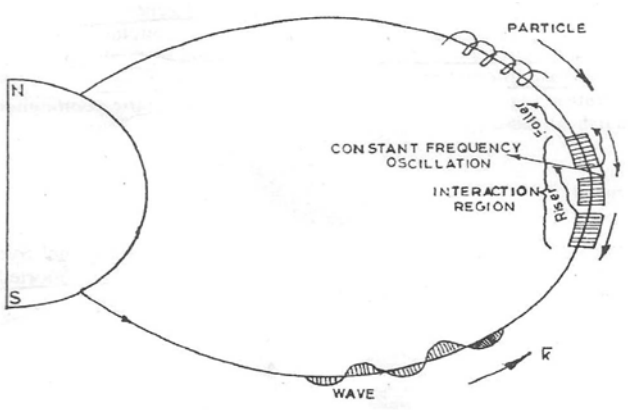

Figure 8. The frequency spectrum of the VLF emission can be understood by considering the movement of interaction region.

latitudes as they travel away from the equator. Following the theoretical formulation of Helliwell[54], we have computed the interaction length, which comes out to 950 km for 5 kHz wave frequency and plasma parameters correspond to $L = 1.2$ (Srinagar). As wave frequency increases, the interaction length decreases. The resonant current comes out to be $\sim 10^{-10}$ amp/m^2, which also decreases with frequency. The theory has been simplified and needs further development, including the inhomogeneity in plasma medium and other nonlinear effects.

The theory of triggered emissions based on the nonlinear self-consistent interaction of cyclotron resonant electrons with narrow-band VLF waves in the Earth's magnetosphere has been developed and many of the qualitative physical features underlying these emissions have been identified and understood[55,56]. Attempts have been made to solve nonlinear theory using different models such as sheet current model[57], nonlinear resonant current model[58], electromagnetic full particle model[59], fluid particle (hybrid) model[60] and Vlasov hybrid model[55]. These models have been developed to stimulate the wave–particle interaction and explain the various types of triggered emissions observed at ground stations.

Figure 6 shows the whistler-triggered chorus emissions recorded at our low-latitude station Srinagar. Dispersion analysis shows that the whistlers have propagated along paths with L-values lying between 1.9 and 2.4, suggesting that these are to be regarded as mid-latitude whistlers. These waves could have propagated along the geomagnetic field lines either in a ducted mode or in a prolongitudinal mode. The measured intensity of the triggered emission is either equal to or more than that of the source wave and also varies from one event to another. It is proposed that these emissions are generated through a process of resonant interaction of the whistler waves with energetic electrons. Parameters related to this interaction are computed for different values of L and wave amplitude. The proposed mechanism explains some aspects of the dynamic spectra shown in Figure 6.

Till date no single theory has been able to explain all the observed features of the VLF emissions. The frequency spectrum of VLF emissions can be understood by considering the movement of interaction region is as shown in Figure 8. According to this model constant frequency oscillations are generated from the interaction regions situated at the equator. Risers and fallers are generated if the interaction region is situated on the downstream and upstream sides of the magnetic equator[54].

We have presented dynamic spectra of VLF emissions such as hiss, discrete chorus, hiss-triggered chorus and whistler-triggered emissions recorded at Indian station, Srinagar and explained the generation mechanism of these emissions. From the discussions presented here it can be concluded that VLF emissions are generated in the equatorial region of the magnetosphere through the process of nonlinear cyclotron resonance interaction between the wave and particles. The VLF waves after leaving the generation region propagate in whistler mode along the geomagnetic field lines and reach the Earth's surface.

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