J. Environ. Nanotechnol.
Volume 2, No.3 pp. 29-35
ISSN (Print) : 2279-0748
ISSN (Online) : 2319-5541
doi : 10.13074/jent 2013.09.132029

Whistler-Mode Chorus Emissions Observed at Nanital (L= 1.16)

M. Altaf[1*], J. M. Banday[2], M. M. Ahmad[3]

[1*,3]Department of Physics, National Institute of Technology, Srinagar, Kashmir, India.
[2]Department of Civil engineering, National Institute of Technology, Srinagar, Kashmir, India.

Received: 20.08.2013 Revised: 02.09.2013 Accecpted: 22.09.2013

Abstract

Observations of whistler-mode chorus emissions recorded at Nanital (19^0 $02^/$ N, 14.9^o $45^/$ E, L = 1.16) between 2200 and 0315 hours IST on 13 May and 8 June 1970 has been reported. The detailed spectral analysis of recorded chorus emissions shows that the chorus element originates from upper edge of the hiss band. To explain the observed dynamic spectra of these chorus emissions, a possible generation mechanism is presented on the non linear theory. It is observed that the seeds of chorus emissions with rising frequency are generated near the magnetic equator as a result of a nonlinear growth mechanism that depends on the wave amplitude. On the basis of this theory, the frequency sweep rate of chorus emission is computed and compared with that of our experimentally observed values, which in general shows good agreement.

Keywords : *Chorus; Ionosphere; Non linear; Magnetosphere; Whistler.*

1. INTRODUCTION

The most common form of very low frequency (VLF) emissions is whistler-mode chorus emission in the earth's magnetosphere. These emissions usually consist, of a succession of discrete elements with rising frequency and occur at frequencies below local electron gyrofrequency with the typical duration of chorus events being 0.5-1 h (Helliwell, 1965). The generation mechanism is generally accepted of these emissions is connected with the cyclotron instability of whistle-mode waves and radiation belt electrons (Burtis and Helliwell, 1976; Helliwell, 1967; Sazhin and Hayakawa, 1992), the formation of a spectrum of separate elements and the generation mechanism are still a subject of active experimental and theoretical research (Lauben *et al*.1997; Trakhtengerts, 1999; Singh *et al*. 2000; Meredith *et al*. 2001; Lauben *et al*. 2002; Santolik. *et al*. 2003, 2004, 2005; Singh *et al*. 2004; Singh and Ronnmark, 2004; Chum *et al*. 2007; Santolik, 2008; Bortnik, 2008; Omura *et al*. 2008; Singh *et al*. 2009). In the physics of earth's radiation belts, a gyroresonant interaction of electrons with chorus emissions plays an important role. Gyroresonant pitch angle scattering of electrons by chorus emissions can lead to significant precipitation into the atmosphere and net loss of energetic electrons from the outer radiation belt (Summers *et al*. 2005; Thorne *et al*. 2005).

The generation mechanism of chorus emissions has been extensively studied (Helliwell, 1967; Sazhin and Hayakawa, 1992; Singh and Ronnmark, 2004; Chum *et al*. 2007; Omura *et al*. 2008; Trakhtengers, 1995; Katoh and Omura, 2006, 2007). It is generally accepted that by cyclotron resonance with anisotropic electrons chorus emissions can be excited. (Trakhtengers 1999,1995) suggested a generation mechanism of chorus emissions based on the backward wave oscillator region of a magnetospheric cyclotron maser. In the previous

***M. Altaf Tel. : +91 9443354503**
E-mail : altafnig@rediffmail.com

studies, a coherent wave is assumed as a seed of a chorus element while the whistler-mode instability driven by temperature anisotropy gives a spectrum of waves that has positive growth rate (Omura and Summers, 2004). Still it is a subject of study as to what determines the frequency sweep rate of a chorus element (Omura *et al*. 2008, 2009). In this paper we present the observations of chorus emissions at the Indian ground station Nanital on 13 May and 8 June 1970. A periodic generation mechanism is presented based on the recent nonlinear theory of (Omura *et al*. 2008, 2009).

2. DATA SELECTION

On 13 May and 8 June 1970, discrete rising chorus emissions between 2200 and 0315 hours IST local time have been observed are shown in Fig. 1 and 2 respectively. The emissions recorded on 13 May 1970 occurred in the frequency range 2.5 – 4.5 kHz and 4.5 – 7.0 kHz, while emissions on 8 June, 1970 occurred in the frequency range of 3.5 – 5.5 kHz.

Fig. 1a of 13 May 1970 contains only one chorus riser with an upper cut-off frequency of about 4 kHz and a frequency sweep rate df/dt of 6.6 kHz S^{-1}. Fig. 1b contains 6 chorus riser with an upper cutoff 4 kHz, 4.2 kHz, 5.8kHz, 6 KHz and6.4 kHz and the frequency sweep rate df/dt of 6.6 -7 kHz S^{-1}. Fig. 1c contains one chorus riser with an upper cutoff frequency 4.6 kHz and a frequency sweep rate df/dt of 0.56 kHz S^{-1}. Fig. 1d contains two chorus risers with an upper cut-off frequency 4.2 kHz and 6.2 kHz and the frequency sweep rate df/dt of 2 kHz S^{-1} and 7.2 kHz S^{-1}. Fig. 2a contains 4 chours riser with an upper cut-off frequency 8 kHz and 5.4 kHz and the frequency sweep rate df/dt of 9.5 kHz S^{-1} and 3.6 kHz S^{-1}. Fig 2b contains one chorus riser with an upper cutoff frequency 4.4 kHz and a frequency sweep rate df/dt of 2.8 kHz S^{-1}. Fig. 2c contains 2 chorus riser with an upper cutoff frequency about 5.4 kHz and the frequency sweep rate df/dt of 3.2 kHz S^{-1}.

Fig. 2d contains one chorus riser with an upper cutoff frequency 5.2 kHz and a frequency sweep rate df/dt of 4.4 kHz S^{-1}. The observed mean chorus element parameters are as follows f_{min} = 2.5 kHz, f_{UB} = 6 kHz, frequency sweep rate df/dt = 4.25 kHz S^{-1}.

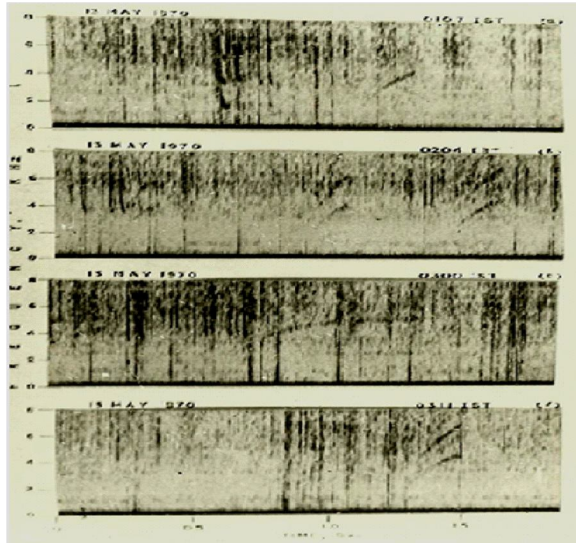

Fig.1. Dynamic Spectrum of discrete rising chorus emissions

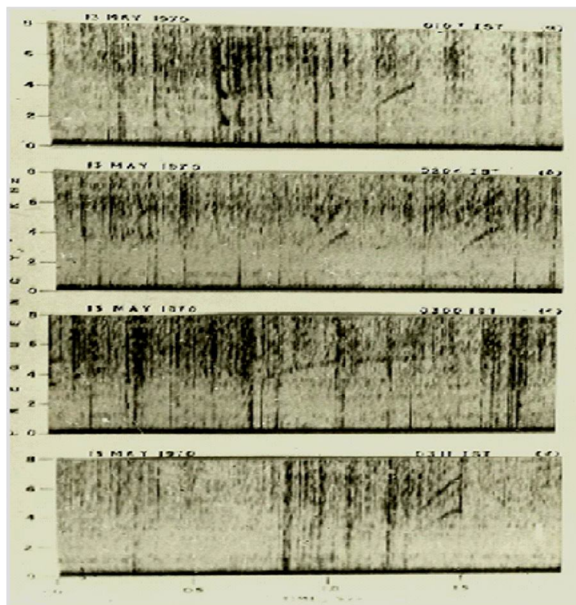

Fig.2. Dynamic Spectrum of discrete rising chorus emissions.

3. GENERATION MECHANISM

The generation mechanism of Chorus emissions has been analyzed in a number of studies (Helliwell, 1967; Trakhtengers, 1999; Singh and Ronnmark, 2004; Chum *et al*. 2007; Omura *et al*. 2008, 2009; Trakhtengers, 1995; Katoh and Omura, 2006, 2007; Nunn, 1974; Omura and Matsumoto, 1982; Singh *et al*. 2010). It is generally accepted that chorus waves can be excited by cyclotron resonance with anisotropic 10 – 100 KeV electrons. Inhomogeneity in the background magnetic field has been established as a controlling factor in the chorus generation mechanism.

It is assumed that a coherent whistler-mode with amplitude B_w and phase angle ø propagating parallel to the static magnetic field, and B_w is a slowly varying function of position h and time t and phase ø varies smoothly in space and time. We assume that an electron moves with parallel velocity $V_{ÐÐ}$ and perpendicularvelocity $V_{\perp}$. We define the resonance velocity V_R that satisfies the Doppler cyclotron resonance condition (Omura *et al*. 2008) as

$$V_R = \frac{1}{k}\left(\omega - \frac{\Omega_e}{\gamma}\right) \tag{1}$$

Where

$$\gamma = \left[1 - \frac{V^2_{\square} + V_{\perp}^{\ 2}}{c^2}\right]^{-1/2}$$ and Ω_e is

electron cyclotron frequency. If $V_{ÐÐ} = V_R$, the electron resonates with the wave and “sees” a constant phase of the wave field. The wave equation describing evolution of the wave emissions are likely to have originated from the underlying hissband (Hattori *et al.* 1991). Hattori Tsurutani, B.T. and Smith, E.J., Postmidnight chorus: a substorm phenomena, *J. Geophys. Res*., 79, 118 (1974).Maxwell’s equation after retaining the displacement current as (Omura *et al*. 2008).

$$\frac{\partial B_w}{\partial t} + V_g \frac{\partial B_w}{\partial h} = -\mu_o \frac{V_g}{2} J_E \tag{2}$$

And the dispersion relation with nonlinear correction terms,

$$c^2k^2 - \omega^2 - \frac{\omega\omega_{pe}^2}{\Omega_e - \omega} = \mu_o c^2 k \frac{J_B}{B_w} \tag{3}$$

Where μ_o is the magnetic permittivity in vacuum and J_E and J_B are components of the resonant current, parallel to the wave electric field **E** and wave magnetic field **B**, respectively. The resonant current is formed by the interaction of resonant electrons with wave. A negative value of J_E contributes to wave growth while J_B only modifies the dispersion relation. Wave growth is due to the nonlinear dynamics of resonant electrons under the action of a large-amplitude wave. According to linear theory, at the equator there is a finite spectrum of whistler-mode waves being generated by the temperature anisotropy of the resonant electrons. From these waves with different rates of phase variation $\frac{\partial \omega}{\partial t}$ that maximizes the value of $-J_E$. Higher wave amplitudes are thereby achieved. By setting $\frac{\partial \Omega_e}{\partial h} = 0$. The in homogeneity ratio parameter S at the equator is given by (Omura *et al*. 2008).

$$S_{Eq} = -\frac{\gamma}{\omega_r^2 \delta^2}\left(1 - \frac{V_R}{V_g}\right)^2 \frac{\partial \omega}{\partial t} \tag{4}$$

Where δ and ξ are dimensionalless parameters defined as (Omura *et al*. 2007).

$$\delta^2 = 1 - \frac{\omega^2}{c^2k^2} \tag{5}$$

amplitude of a chorus element can be derived from

$$\xi^2 = \omega \frac{(\Omega_e - \omega)}{\omega_{pe}^2} \tag{6}$$

Setting S_{Eq}= 0.4 in equation (4), we obtain a condition for the maximum nonlinear growth of the wave as

$$\frac{\partial\omega}{\partial t} = 0.4\frac{\omega_r^2\delta^2}{\gamma}\left(1-\frac{V_R}{V_g}\right)^{-2} \quad (7)$$

Using $\omega_r^2 = kv_\perp\Omega_\omega, where \Omega_\omega = \frac{eB_\omega}{m_o}$ we rewrite equation (7) at (Omura *et al.* 20 08)

$$\frac{\partial\omega}{\partial t} = \frac{0.4\delta v_\perp\omega}{\gamma\xi c\Omega_e}\left[1-\frac{V_R}{V_g}\right]^{-2}\frac{B_w}{B_o}\Omega_e^2 \quad (8)$$

where

$$V_R = c\delta\xi\left(1-\frac{\Omega_e}{\gamma\omega}\right) \quad (9)$$

and

$$1-\frac{V_R}{V_g} = 1+\delta^2\left(\xi^2+\frac{\Omega_e}{2(\Omega_e-\omega)}\right)\left(\frac{\Omega_e}{\gamma\omega}-1\right) \quad (10)$$

Thus, nonlinear wave growth continues over some distance from the equator to generate chorus elements. To test this theory of the generation mechanism, we have computed the frequencysweep rate of chorus elements using equation (7) – (10) and compared this with our observed values.

4. RESULTS & DISCUSSION

The observations of VLF chorus emissions at an Indian ground station Nanital, shows that chorus emissions are rare under quiet conditions on 13 May and 8 June 1970. The detailed spectral analysis of chorus events suggests that these and Hayakawa (Hattori and Hayakawa, 1994) suggests based on the direction finding measurements that a chorus event is triggered from a wavelet existing at the upper edge of the hiss band through a coherent wave-particle interaction. The observations of chorus events by satellite near the geomagnetic equator supports the idea that the source of chorus emissions is mostly near the equatorial region (Burtis and Halliwell, 1976; Tsurutani and Smith, 1974). The upper boundary frequency (UBF) method (Smirnova, 1984) has generally been used to find the location of the ground observed VLF emissions (Singh et al, 2004; Singh et al, 2009). The upper boundary frequency of the ground observed VLF emissions are determined on the assumption of a dipolar geomagnetic field configuration by the half electron gyro-frequency region, irrespective of the observation station. The L-value of the source is the computed with the help of the relation (Smirnova, 1984).

$$L = (440/f_{UB})^{1/2} \quad (11)$$

Where f_{UB} is the upper boundary frequency of the emission in KHz. Using equation (11) and the observed parameters, the value of the source region of the chorus emission observed at Nanital is found to be L_{source} = 7.4. This supports the possibility that these emissions may have been generated near the equatorial region (L=1.16) and have propagated in whistler mode to be received at the Indian ground station Nanital.

To examine the generation mechanism explained in the above section, we have computed the frequency sweep rate of chorus emissions using equation (7) – (10). The L- value of the source region is L_{source} = 7.4 and the equatorial electron gyrofrequency is f_G = 8.75 kHz for the discrete chorus emissions observed at Nanital. According to the empirical equatorial electron density profile model of (Carpenter and Anderson 1992), the electron density taken as ~ 16 electron cm^{-3} and the corresponding plasma frequency f_p ~ 36 kHz. Considering a frequency f = f_G /3, we find from thedispersion relation that k ~ 0.54km^{-1}. The wave group velocity V_g ~ 2.33× 10^7 m s^{-1}, the electronparallel velocity $v_{ÐÐ}$ ~ 6.97× 10^7 ms^{-1} and the electron perpendicular velocity $v_{4\%}$ ~ 34. 7 ms^{-1}. We find the dimensionless parameters ä² and î² from equations (5) and (6) as 0.99 and 0.114, respectively. The value of ã ~ 1.04 and $\Omega_{\omega} = \dfrac{eB_{\omega}}{m_o}$ = 26.36, considering that the maximum wave amplitude B_w ~ 150pT observed by Cluster spacecraft (Santolik et al, 2004).Using equation (10), we have computed $\left(1 - \dfrac{V_R}{V_g}\right)$ ~ 2.35. Substituting all the above computed parameters in equation (8), we find $\dfrac{\partial \omega}{\partial t}$ ~ 30.87 kHz s^{-1}. Hence the frequency sweep rate, " f/"t ~5.00 kHz s^{-1}, which is very much comparable to our observed frequency sweep rate of 4.25 kHz s^{-1}. Thus, our result confirmed that the above theory of chorus generation is consistent with the analysis of chorus emissions recorded at Indian ground station Nanital. (Omura *et al.* 2008) successfully applied this theory to reproduce the formation of rising tone chorus elements propagating away from the equator using a self-consistent particle simulation (Katoh and Omura, 2006). Recently, (Hikiahima *et al* 2009) successfully performed an electromagnetic full-particle simulation to study the generation mechanism of VLF whistler-mode chorus emissions in the equatorial region of the magnetosphere using parabolic variation of the static magnetic field.

The concept of nonlinear growth rate based on the second-order resonance condition was used by (Nunn, 1974), (Nunn *et al.* 1997) and (Trakhtengerts, 1999; 1995) to explain chorus generation. However these authors have not determined the relative roles of temporal frequency variation and spatial variation of gyrofrequency in contribution to the formation of chorus elements.

5. CONCLUSION

The characteristics of VLF chorus emissions recorded at Nainital are reported. Analysis of the observed dynamic spectra of chorus emissions shows that each chorus element originated from the underlying hiss band. Thesechorus emissions may have been generated near the equatorial region of L-value corresponding to the recording station and have propagated in whistler-mode to be received at the Nainital Station. A generation mechanism for various temporal and spectral features of recorded VLF chorus emissions is presented on the basis of the recent nonlinear theory of (Omura *et al.* 2008). It is observed that the seed of the chorus elements is formed solely by the temporal frequency variation or the second-order phase variation in time, which maximizes the nonlinear growth rate at the magnetic equator. The frequency sweep rate of chorus element calculated from the theory is consistent with observations. Thus, our result conformed that the above theory of chorus generation is consistent with the analysis of chorus emissions recorded at Nainital. Further experimental and theoretical studies of VLS chorus emissions using some more long data sets are required for a complete understanding of this phenomenon.

ACKNOWLEDGEMENT

The author is grateful to Director, N I T, Srinagar-190006. J & K for his encouragement and keen interest in publishing this research work.

REFRENCES

Bortnik, J., Thorne, R.M. and Meredith, N.P., The unexpected origin of plasma spheric his from discrete chorus emissions, *Nature*., 452, 62 (2008).

Burtis, W.J. and Helliwell, R.A., Magnetospheric chorus: occurrence pattern and normalized frequency, *Planet. Space Sci*., 24, 1007 (1976).

Carpenter, D.L. and Anderson, R.R., An ISEE/whistler model of equatorial density in the magnetosphere, *J. Geophys. Res*., 97, 1097 (1992).

Chum, J., Santolik, O., Breneman, A.W., Kletzing, C.A., Gurnett, D.A. and Pickett, J.S., Chorus source properties that produce time shifts and frequency range differences observed on different cluster spacecraft, *J. Geophys. Res*., 112 A 06206 (2007). doi: 10 1029/2006JA012061.

Hattori, K. and Hayakawa, M., Consideration of dynamic spectra and direction finding results of hiss-triggered chorus emissions, *Proc. NIPR Symp. Upper Atmos. Phys*., 7, 40 (1994).

Hattori, K., Hayakawa, M., Lagoutte, D., Parrot, M. and Lefeuvre, F., Further evidence of triggered chorus emissions from wavelet in the hiss band Planet, *Space Sci*., 39, 1465 (1991).

Helliwell, R., Whistlers and related ionospheric phenomena, *J. Geophys. Res*., 72, 4273 (1967).

Helliwell, R.A., Whistler and Related Ionospheric Phenomena (Stanford, C.A, USA: Stanford University Press) 1965,

Hikishima, M., Yagitani, S., Omura, Y. and Nagano, I., Full particle simulation of whistler-mode rising chorus emissions in the magnetosphere, *J. Geophys. Res*., 114 A01203 (2009). doi.1029/2008JA013625.

Katoh, Y. and Omura, Y., A study of generation mechanism of VLF triggered emissions by self-consistent particle code, *J. Geophys. Res*., 111, A12207 (2006). doi: 10. 1029/2006JA011704.

Katoh, Y. and Omura, Y., Computer simulation of chorus wave generation in the earths inner magnetosphere, *Geophys. Res. Lett*., 34, L03102 (2007). doi: 10. 1029/2006GL028594.

Lauben, D.S., Inan, U.S., Bell, T.F. and Gurnett, D.A., Source characterizations of ELF/VLF chorus, *J. Geophys Res*., 107, A12 1429 (2002). doi: 10. 1029/2000JA 003019.

Lauben, D.S., Inan, U.S., Bell, T.F., Kirchner, D.L., Hospodarsky, S.B. and Pickett, J.S., VLF chorus emission observed by POLAR during the January 10, 1997 magnetic cloud, *Geophys. Res. Lett*., 25, 2995 (1998).

Meredith, N.P., Horne, R.B. and Anderson, R.R., Substorm dependence on chorus amplitudes: implications for the acceleration of electrons to relativistic energies, *J. Geophys Res*., 106, 13165 (2001).Nunn, D., A self-consistent theory of triggered VLF emissions, *Planet. Space Sci*., 22, 349 (1974).

Nunn, D., Omura, Y., Matsumoto, H., Nagano, I. and Yagitani, S., The numerical simulation of VLF chorus and discrete emissions observedon Geotail satellite using a Vlasov code, *J. Geophys. Res*., 102, 27083 (1997).

Omura, Y. and Matsumoto, H., Computer simulations of basic process of coherent whistler wave-particle interactions in the magnetosphere, *J. Geophys. Res*., 87, A6 4435 (1982).

Omura, Y. and Summers, D., Computer simulation of relativistic whistler-mode wave-particle interactions, *Phys. Plasma*., 11, 3530 (2004).

Omura, Y., Furuya, N. and Summers, D., Relativistic acceleration of resonant electrons by coherent whistler mode waves in a dipole magnetic field, *J. Geophys. Res*., 112, A06236 (2007). doi. 1029/2006JA012243.

Omura, Y., Hikishima, M., Katoh, Y., Summers, D. and Yagitani, S., Nonlinear mechanisms of lower band and upper band VLF chorus emissions in the magnetosphere, *J. Geophys Res*., 114 A07217 (2009). doi: 10.1029/2009JA014206.

Omura, Y., Katoh, Y. and Summer, D., Theory and simulation of the generation of whistler-mode chorus, *J. Geophys. Res*., 113 A04223 (2008). doi: 10. 1029/2007JA012622.

Patel, R.P., Singh, R.P., Singh, A.K., Gwal, A.K. and Hammar, D., Observation of very low frequency emission at Indian Antarctic station Maitri Pramana, *J.Phys*., 61, 4773 (2003).

Santolik, O., Gernet, D.A., Pickett, J.S., Parrot, M. and Cornilleau-Wehrlin, N., A mocroscopic and nanoscopic view of storm-time chorus on 31 March 2001, *Geophys. Res. Lett*., 31 L02801 (2004). doi: 10. 1029/2003 GL018757.

Santolik, O., Gernet, D.A., Pickett, J.S., Parrot, M. and Cornilleau-Wehrlin, N., Central position of the source region of storm-time chorus planet, *Space Sci*., 53, 299 (2005).Santolik, O., New results of investigations of whistle-mode chorus emissions nonlin, Process. Geophys., 15, 621 (2008).

Santolik, O., Parrot, M. and Lefeuvre, F., Singularvalue decomposition methods for wave propagation analysis, *Radio Sci*., 38 1 1010 (2003). doi: 10. 1029/2000RS002523.

Sazhin, S.S. and Hayakawa, M., Magnetospheric chorus emission, *Planet Space Sci*., 40, 681 (1992).

Singh, A.K. and Ronnmark, K., Generation mechanism for VLF chorus emissions observed at a low-latitude ground station, *Ann. Geophys*., 22, 2849 (2004).

Singh, A.K., Singh, S.B. and Patel, R.P., An explanation of the observation of whistler-mode chorus emissions at the Indian Antarctic station, Maitri (L = 4.5), *Phy. Scr.* 81, 2010.

Singh, K.K., Singh, J., Patel, R.P., Singh, A.K., Singh, R.P., Singh, R. and Ganai, P.A., Quasi periodic VLF emissions observed during daytime at a low latitude Indian ground station Jammu, *J. Earth Syst. Sci*., 118, 31 (2009).

Singh, R., Patel, R.P., Singh, R.P. and Lalmani., An experimental study of hiss triggered chorus emission at low latitudes, *Earth Planets space*., 52, 37 (2000).

Singh, R.P., Patel, R.P., Singh, A.K., Effects of solar and magnetic acyivity on VHF scintillations near the equatorial anomaly crest, *Ann. Geophys*., 22, 2849 (2004).

Singh, S.K., Kumar, S. and Gwal, A.K., Daytime very low frequency (VLF) emissions observed at Maotri station Antarctica, *Ind. J. Phys*., 77, B4451 (2003).

Smirnova, N.A., Fine structure of the ground observed VLF chorus as an indicator of the wave particle interaction process in the magnetosphere, *Planet. Space Sci*., 32, 425 (1984).

Summers, D., Mace, R.L. and Hellberg, M.A., Pitch-angle scattering rates in planetary magnetospheres, *J. Plasma Phys*., 71, 3237 (2005).

Thorne, R.M., Obrien, T.P., Shprits, Y.Y., Summers, D. and Horne, R.B., Timescale for MeV electron microburst loss during geomagnetic storm, *J. Geophys. Res*., 110 A09202 (2005). doi: 10. 1029/ 2004JA010882.

Trakhtengerts, V.Y., A generation mechanism for chorus emissions, *Ann. Geophys*., 17, 95(1999).

Trakhtengerts, V.Y., Magnetospheric cyclotron maser: backward wave oscillator generation regime, *J. Geophys. Res*., 100, 17205 (1995).