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Thermal effects on parallel resonance energy of whistler mode wave

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Abstract. In this short communication, we have evaluated the effect of thermal velocity of the plasma particles on the energy of resonantly interacting energetic electrons with the propagating whistler mode waves as a function of wave frequency and L-value for the normal and disturbed magnetospheric conditions. During the disturbed conditions when the magnetosphere is depleted in electron density, the resonance energy of the electron enhances by an order of magnitude at higher latitudes, whereas the effect is small at low latitudes. An attempt is made to explain the enhanced wave activity observed during magnetic storm periods.

Keywords. Dispersion relation; parallel resonance energy; VLF emissions; whistler waves; magnetic storms.

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1. Introduction

Wave–particle interactions play a crucial role in the formation of the magnetopause boundary layer, generation of VLF emissions, precipitation of energetic charged particles leading to auroras [1–3] etc. The charged particles in the ionosphere and magnetosphere exhibit anisotropic distribution in momentum space, which is suitable for cyclotron instability leading to wave-growth and hence to particle precipitation into the atmosphere. Thus, there is continuous loss of particles from the ionosphere and magnetosphere, which is balanced by the injection of particles at different latitudes and radial distances via slow processes such as radial convection, diffusion and azimuthal drifts. During magnetic storm and substorm periods, the transfer of energy from the solar wind to the magnetosphere is significantly enhanced. The effects include dramatic changes and intensification of the particle population, the magnetic and electric fields and the electric currents in the ionosphere and magnetosphere, as well as Joule heating of the upper atmosphere. In addition, magnetic storms are often associated with the fast and large fluctuations of the electric and magnetic fields. The duration of a storm can vary from hours to days. Park [4] analysed whistlers recorded at a large number of stations extended over $L \sim 2$ to 6 and showed that during the substorm periods the plasma from the plasmasphere in the forenoon sector was convected inward across L shells and drained rapidly through the ionosphere. This was corroborated by the *in-situ* ionosonde measurements of enhanced f_0F_2 in a limited local time sector [4]. Based on the measurement of number density and temperature of cold H^+ ions, Bezrukikh *et al* [5] have reported that the number density of cold plasma inside the daytime plasmasphere could significantly change, either decrease or increase, during moderate geomagnetic storms. Both decreasing and increasing number density inside the plasmasphere are explained by the variations in the ionosphere parameters during ionospheric storms initiated by the geomagnetic storms. Ho *et al* [6] observed enhancements of total electron contents in the large-scale ionospheric structures during geomagnetic storms, while Szuszczewich *et al* [7] reported about the decreased electron density in the F-layer.

The generation of the field aligned currents, electric fields, injection of particles, enhancement of ring current etc. modify the generation processes of VLF emissions and as a result emission activity is intensified during magnetic disturbances [8,9]. Das and Kulkarni [10] studied the resonant interaction between whistler mode waves and the energetic electrons in the presence of field aligned current present during substorm activity and tried to explain the intense VLF emissions observed during substorm activity near the plasmapause. Smith *et al* [11] have reported a number of intense chorus emissions at the start of the expansion phase of the substorm and called it substorm chorus events (SCEs), which have been observed near $L = 4$ at Halley, Antarctica (76°S, 27°W), by the VELOX instrument during 1992–1995.

In this short communication, we have tried to show the effect of plasma temperature on the resonance energy of electrons interacting with the propagating whistler mode VLF waves during quiet and disturbed magnetosphere conditions. In the case of disturbed conditions we have considered only the effect of plasma density depletion on the generation of the VLF waves. The role of parallel current, electric field, ring current etc. on the generation of waves is qualitatively discussed. Using the resonance condition and dispersion relation of the interacting wave, an expression for the parallel resonance energy of the interacting electron has been derived. The effect of thermal velocity of the ambient plasma is included through the dispersion relation. Numerical computations for the parallel resonance energy of the electrons have been made for different values of wave frequency, L-values and pitch angles.

2. Resonance energy

Whistler mode waves propagating along geomagnetic field line interact with counterstreaming electrons and the interaction becomes more effective when resonance condition $\omega - kv = n\omega_H/\beta$ is satisfied, where ω_H is the electron gyrofrequency, k is wave vector, $\beta = (1 - v^2/c^2)^{-1/2}$, v is the electron velocity and n is an integer equal to $0, \pm 1, \pm 2$, etc. $n = 0$ corresponds to the Landau resonance and $n = 1$ represents Doppler shifted cyclotron resonance, which has been discussed in the present paper. The interaction is most effective near the equatorial region [12], which has been indirectly confirmed from the particle and wave measurements [13,14]. The wave vector k and wave frequency ω are related through dispersion relation [15]

$$\frac{k^2c^2}{\omega_{\mathrm{P}}^2} + \frac{k^2 v_{\mathrm{t}\parallel}^2}{(\omega-\omega_H)^2}\left[A_{\mathrm{T}} + \frac{\omega}{(\omega-\omega_H)}\right] + \frac{\omega}{\omega-\omega_H} = 0, \tag{1}$$

where ω_{P} is the plasma frequency, $v_{\mathrm{t}\parallel} = (2K_{\mathrm{B}}T_\parallel/m_{\mathrm{e}})^{1/2}$ is the parallel thermal velocity, K_{B} is the Boltzmann constant and anisotropy factor, $A_{\mathrm{T}} = (T_\perp/T_\parallel) - 1$, $T_\perp$ and $T_\parallel$ are the average perpendicular and parallel temperatures of the plasma. The second term is the thermal correction term in the dispersion relation. The above equation is solved for k, which is substituted in the resonance condition to obtain the expression for resonance velocity as

$$\begin{aligned} v_\parallel \cong v_{\mathrm{R}\parallel} &= \omega c\mu \pm \omega_H c[\mu^2 \\ &\quad +(\omega_H^2/\omega^2-1)/\cos^2\alpha]^{1/2}/\omega(\mu^2+\omega_H^2/(\omega^2\cos^2\alpha))^{1/2}, \end{aligned} \tag{2}$$

where $\mu = [c^2\omega_{\mathrm{P}}^2(\omega_H-\omega)/\{c^2\omega(\omega_H-\omega)^2 + v_{\mathrm{t}\parallel}^2\omega\omega_{\mathrm{P}}^2(A_{\mathrm{T}}-\omega/(\omega_H-\omega))\}]^{1/2}$.

Equation (2) yields two values of $v_{\mathrm{R}\parallel}$. For the whistler mode propagation $\omega \ll \omega_H$ and according to resonance condition $v_\parallel$ is negative implying that the resonantly interacting electrons and whistler waves move in the opposite direction [12]. Hence we consider negative sign in eq. (2) and compute the parallel resonance energy of the electrons $W_\parallel = mv_\parallel^2/2$, which is shown in figure 1 for $T_\parallel = 1200$ K, pitch angle $\alpha = 30°$ as a function of wave frequency and L-value. The equatorial electron density used in the computation is taken to be 1200, 550, 400 and 80 cm^{-3} for $L = 2$, 3, 4 and 5 respectively and may be considered as a representative of normal conditions. We have also calculated the resonance energy at different plasma temperatures (1600 K, 2000 K), but no appreciable changes are found both at the low and high latitudes. Hence, these results are not given.

The resonance energy for a given frequency range decreases as L-value is increased. For example, in the frequency range 1–5 kHz, the resonance energy is of the order of 10^2 keV at $L = 2$; whereas for $L = 5$ it varies between 8 and 0.02 keV. As frequency increases, resonance energy decreases. The decrease is more rapid at higher L-values as compared to the lower L-values. At $L = 2$, the decrease is seen at higher frequencies (>50 kHz). Rice and Hughes [16] have also shown that the resonant electron energy decreases as frequency increases from 2 to 10 kHz and L-value increases from 2.68 to 3.05. The present results agree well with that reported by Singh [2] for the low latitude Indian station, Varanasi ($L = 1.07$, geomag. lat. = 14°55′).

We have also computed $W_\parallel$ for the depleted condition of plasmasphere, which may represent disturbed geomagnetic condition [5,17,18]. For the computation the equatorial electron densities are taken as 315, 25, 6 and 1 cm^{-3} respectively [17,18]. The results are also shown in figure 1. It is noted that although the equatorial electron density decreases during the geomagnetic disturbed conditions, the energy of the resonant electrons, if the parameters remain the same, increases almost by an order of magnitude as compared to the normal conditions. The changes in $W_\parallel$ are more visible at higher frequencies and higher L-values. This is expected because as one moves closer to the Earth, the effect of solar disturbances will go on decreasing, which is in accordance with the present computation. If the energetic electrons follow Maxwellian velocity distribution function, then the number of

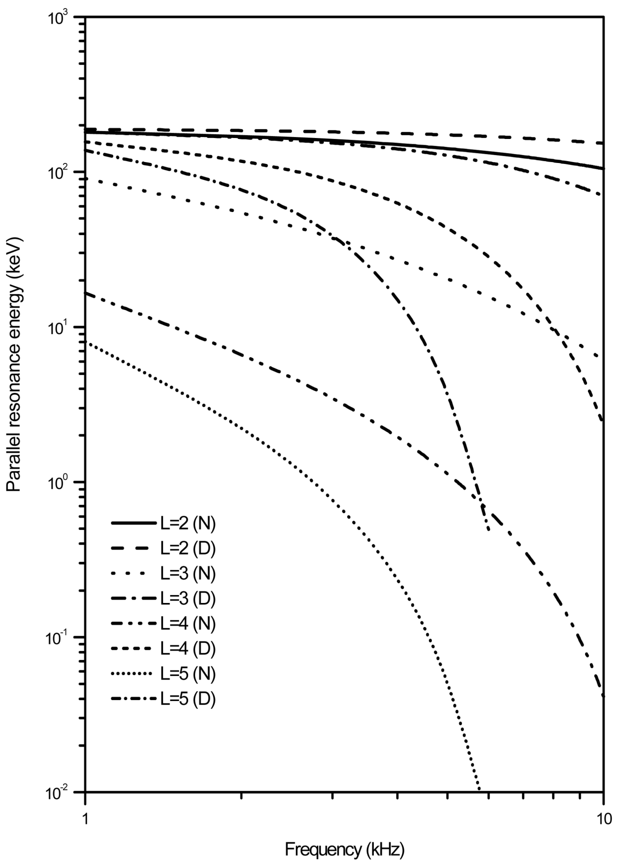

Figure 1. Variation of parallel resonance energy of electrons with wave frequency during normal (N) and disturbed (D) magnetospheric conditions for $L = 2$, 3, 4 and 5. $T_{\|} = 1200$ K, $A_{\rm T} = 0.5$, pitch angle $\alpha = 30°$.

available resonant electrons decreases as resonance energy increases. The clouds of energetic electrons injected from the plasma-sheet during the substorm expansion phase compensate over the decrease in energetic electron density and enhance the wave activity. The injected clouds of energetic electrons have been established to be associated with substorm chorus events [11]. The electric fields and currents set up during the storm periods may accelerate the low-energy electrons and enhance the number density of resonant electrons. Further, the electric field may also amplify the generated VLF emissions [15]. Thus, the overall wave activity is enhanced during magnetic storm periods [10,19]. Summers *et al* [20] have reported the occurrence of enhanced relativistic electron flux only during the enhanced substorm and chorus activity at $L = 5$. The electrons are accelerated by stochastic gyroresonance with whistler-mode chorus waves [20]. Thus, enhanced chorus waves generated during prolonged substorm activity can generate relativistic electron flux which increases in the outer radiation zone.

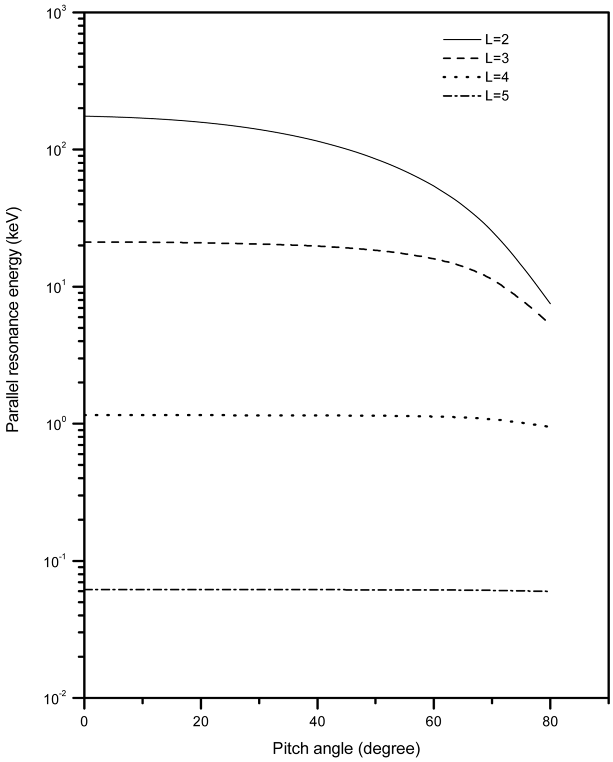

Figure 2. Variation of parallel resonance energy with pitch angle α for $L = 2$, 3, 4 and 5. $T_{\|} = 1200$ K and wave frequency $\omega = 5$ kHz.

Figure 2 shows variation of resonant energy of electrons with pitch angle for different L-values (2–5). We note that an increase in pitch angle causes small decrease in resonance energy at the mid-latitudes ($L = 2, 3$), whereas at high latitudes practically no changes have been obtained. Energy and pitch angle of resonantly interacting electrons along with density distribution in the magnetosphere show that the occurrence of gyro–resonant interaction is more probable near $L = 4$ and 5, whereas it becomes less favorable for $L > 5.5$ as well as for $L < 3$.

3. Conclusion

In this paper, we have derived the expression for resonance energy of electrons containing the thermal velocity term in the dispersion relation, which has been used to study the variation of the resonance energy with frequency, L-value and pitch angle of the energetic electrons. The computation is made for the normal and disturbed conditions. The effect of magnetic disturbances on the resonant interaction is discussed and an attempt is made to explain the enhanced wave activity observed during magnetic storm periods. The present study may find its application in the modeling of VLF emissions and dynamics of precipitating electrons into the atmosphere; the latter may trigger lightning discharges from the atmosphere.

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References

[1] D K Singh, Ashok K Singh, R P Patel, R P Singh and A K Singh, *Ann. Geophys.* **17**, 1260 (1999)
[2] D K Singh, *Study of whistler waves and VLF emissions observed at Varanasi*, Ph.D. Thesis (Banaras Hindu University, India, 1999)
[3] V Y Trakhtengerts and M J Rycroft, *J. Atmos. Solar Terr. Phys.* **62**, 1718 (2000)
[4] C G Park, *J. Geophys. Res.* **78**, 672 (1973)
[5] V V Bezrukikh, M I Verigin, G A Kotova, L A Lezhere, Yu I Venediktov and J Lemaire, *J. Atmos. Solar Terr. Phys.* **63**, 1179 (2001)
[6] C M Ho, A J Manucci, L Sparks, X Pi, U J Linqwister, B D Wilson, B A Iijima and M J Reyes, *J. Geophys. Res.* **103**, 26409 (1998)
[7] E P Szuszczewich, M Lester, P Wilkinson, P Blanchard, M Abdu, R Hanbaba, K Igrashi, S Pulinets and B M Reddy, *J. Geophys. Res.* **103**, 11665 (1998)
[8] M Hayakawa, Y Tanaka, S S Sazhin, T Okada and K Kurita, *Planet Space Sci.* **34**, 225 (1986)
[9] D K Singh and R P Singh, *Pramana – J. Phys.* **59**, 563 (2002)
[10] A C Das and V H Kulkarni, *Planet. Space Sci.* **25**, 261 (1977)
[11] A J Smith, M P Freeman, M G Wickett and B D Cox, *J. Geophys. Res.* **104**, 1235 (1999)
[12] B T Tsurutani and G S Lakhina, *Rev. Geophys.* **35**, 491 (1997)
[13] M J LeDocq, D A Gurnett and G B Hospodarsky, *Geophys. Res. Lett.* **25**, 4063 (1998)
[14] O Santolik, D A Gurnett and J S Pickett, *Ann. Geophys.* **22**, 2555 (2004)
[15] I M L Das and R P Singh, *J. Geophys. Res.* **87**, 2369 (1982)
[16] W K M Rice and A R W Hughes, *J. Atmos. Solar Terr. Phys.* **60**, 1149 (1998)
[17] M J Rycroft, Whistlers and discrete ELF/VLF emissions, J A Holtet (ed) *Proc. of NATO Advanced Study Institute*, *Norway* (D. Reidel Publishing Company, Dordrecht, Holland, 1974)
[18] M J Rycroft, *J. Atmos. Terr. Phys.* **38**, 1211 (1976)
[19] Devendraa Siingh, Shubha Singh and R P Singh, *Indian J. Radio Space Phys.* **34**, 305 (2005)
[20] D Summers, C Ma, N P Meredith, R B Horne, R M Thorne and R R Anderson, *J. Atmos. Solar Terr. Phys.* **66**, 133 (2004)