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Archives of Physics Research, 2011, 2 (1): 190-201
(http://scholarsresearchlibrary.com/archive.html)

Scholars Research Library
ISSN 0976-0970
CODEN (USA): APRRC7

Excitation of VLF mode instability with electric field by loss-cone distribution

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ABSTRACT

The excitation of electromagnetic whistler mode wave of low frequencies by loss-cone distribution function has been studied in the auroral region in the presence of perpendicular AC electric field. Method of characteristics solution and kinetic approach has been adopted to derive the dispersion and growth rate. In this paper the effect of AC field frequency, loss-cone angle and temperature anisotropy has been studied by using the method of characteristics solution in the auroral region of ionosphere.

INTRODUCTION

Whistler waves are believed to play an important role in the generation of the pulsating aurora. Naturally occurring plasma waves associated with Earth's auroral ionosphere include whistlers. The energy source for a whistler is a lighting discharge where the waves are generated over a wide frequency range in a very short time. These waves propagate from their source in all directions. Parts of their energy propagate in the earths ionosphere wave guide with a velocity close to the light and almost without frequency dispersion. Another part of the wave energy produced during a lighting discharge penetrates through the ionosphere into the magnetosphere. Part of energy of these waves may propagate almost parallel to the magnetic field lines of the magnetosphere in a duct of enhanced plasma density and even naturally reach the conjugate point on the earth's surface in the hemisphere. The travel time of the signal propagating through the magnetosphere is much greater than the travel time of the signal propagating in the earths ionosphere wave guide and is of the order of few seconds. Moreover, the time delay of the signal is frequency dependent, which results in the characteristic whistler frequency/ time profile.

Electrons can be scattered into the loss-cone by wave particle interaction between whistler mode radiation and energetic electrons in the magnetosphere. The scattering of electrons into the loss-cone by incoherent whistler radiation was considered by Kennel and Petschek [1] while the pitch angle scattering caused by coherent whistler emissions was treated by Inan et al [2]. The scattering mechanism is believed to occur in the equatorial plane. The ionosphere is believed to play some role in determine the spatial characteristics of the pulsating aurora [3]. While the pulsating aurora is one of the most common types of aurora, it can vary considerably in appearance. In general, it is characterized by irregularly shaped auroral patches with quasi – periodic intensity fluctuations [4].

The cyclotron wave particle interaction [5-10] such waves provide a viable mechanism for stochastic acceleration and pitch angle scattering loss of energetic trapped electrons in the earth radiation belt [11]. Natural whistler mode emissions have been found in radiation belt environment of all magnetized planets and analogous to other mode waves [12] they can easily propagated over a wide range of magnetosphere. Whistler mode waves can be generated by cyclotron resonant interactions with anisotropic energetic electrons [8]. The cyclotron resonant energies are capable of exceeding the electron rest mass under certain magnetospheric conditions. The loss-cone driven whistler instability is an attractive device for explaining auroral pulsations, because the instability is directly driven by the precipitation process [13, 14]. Huang et al [15] have observed that for the loss-cone angle is also large. Electric field measurements at magnetospheric heights and shock regions have given values of an a.c. field along and perpendicular to Earth's [16-18]. Electromagnetic ion –Cyclotron instability in the presence a.c. electric field in the ionosphere with observed superathermal electrons have been studied by Pandey et al [19].

Motivated by these findings whistler mode instabilities, having frequencies much smaller than the plasma frequency and gyro frequency have been studied in the magnetosphere, both in the presence of a parallel A.C. electric field [20] and also in presence of perpendicular A.C. electric field [21] in a situation where energetic electrons have a generalized distribution and positive index representing the strength of the loss-cone index. Recently Pandey and Misra [22] have studied the generation of loss-cone driven whistler instability in the auroral region for an anisotropic plasma having Bi- Maxwellian distribution with loss-cone in the presence of Parallel A.C. electric field.

The purpose of this paper is to extend the investigation of the role of generating whistler mode wave of low frequencies by loss-cone distribution in particular and by other factors in general in the auroral region in the presence of perpendicular AC electric field. Method of characteristics solution and kinetic approach has been adopted to derive the dispersion and growth rate.

II. Dispersion Relation

A homogeneous collision less ionospheric plasma subjected to an external magnetic field $B_0 = B_0$ e_x and an electric field E_0=(E_0 sin υ t $\hat{e}_x$) has been considered in order to obtain the relation .In case, the Vlasov-Maxwell equations are liberalized. The linear zed equations obtained after neglecting the higher order terms and separating the equilibrium and non- equilibrium parts, following the techniques of Pandey and Misra [22] are given as:

$$v\frac{\partial f_{s0}}{\partial r}.+\frac{e_s}{m_s}\left[E_o \sin\upsilon t+(v\times B_o)\right]\left(\frac{\partial f_{so}}{\partial v}\right)=0 \qquad ...(1)$$

$$\frac{\partial f_{s1}}{\partial t}+v.\frac{\partial f_{s1}}{\partial r}+\left(\frac{F}{m_s}\right)\left(\frac{\partial f_{s1}}{\partial v}\right)=S(r,v,t) \qquad ...(2)$$

where force is defined as F= mdv/dt

$$F=e_s\left[E_o \sin\upsilon t+(v\times B_o)\right] \qquad ...(3)$$

The particle trajectories are obtained by solving the equation of motion defined in equ.(3) and S(r,v,t) is defined as.

$$x_0=x+\left(\frac{v_y}{\omega_{cs}}\right)+\left(\frac{1}{\omega_{cs}}\right)\left[v_x \sin\omega_{cs}t'-v_y\cos\omega_{cs}t'\right]+\left(\frac{\Gamma_x}{\omega_{cs}}\right)\left[\frac{\omega_{cs}\sin\nu t'-\nu\sin\omega_{cs}t'}{\omega_{cs}^2-\nu^2}\right]$$

$$y_0=y+\left(\frac{v_x}{\omega_{cs}}\right)-\left(\frac{1}{\omega_{cs}}\right)\left[v_x \cos\omega_{cs}t'-v_y\sin\omega_{cs}t'\right]-\left(\frac{\Gamma_x}{\nu\omega_{cs}}\right)\left[1+\frac{\nu^2\cos\omega_{cs}t'-\omega_{cs}^2\cos\nu t'}{\omega_{cs}^2-\nu^2}\right]$$

$$z_0=z-v_z t' \qquad ...(4)$$

and the velocities are

$$v_{x0}=v_x\cos\omega_{cs}t'-v_y\sin\omega_{cs}t'+\left\{\frac{\nu\Gamma_x(\cos\nu c'-\cos\omega_{cs}t')}{\omega_{cs}^2-\nu^2}\right\}$$

$$v_{y0}=v_x\sin\omega_{cs}t'+v_y\cos\omega_{cs}t'-\left\{\frac{\Gamma_x(\omega_{cs}\sin\nu t'-\nu\sin\omega_{cs}t')}{\omega_{cs}^2-\nu^2}\right\}$$

$$v_{z0}=v_z \qquad ...(5)$$

Where $\omega_{cs}=\frac{e_s B_0}{m_s}$ is the cyclotron frequency of species s and $\Gamma_x=\frac{e_s E_0}{m_s}$ and a.c. electric field is varying as $E=E_{0x}\sin\nu t$, ν being the angular a-c frequency.

$$S(r,v,t)=\left(-\frac{e_s}{m_s}\right)\left[E_1+v\times B_1\right]\left(\frac{\partial f_{so}}{\partial v}\right) \qquad ...(6)$$

where s denotes species and E_1 ,$B_1$and f_{s1} are perturbed and are assumed to have harmonic dependence in f_{s1},B_1 and $E_1 \cong \exp i(k.r-\omega t)$.The method of characteristic solution is used to determine the perturbed distribution function.f_{s1}, which is obtained from eq. (2) by

$$f_{s1}(r,v,t)=\int_{\circ 0^\circ}^{\infty} S\{r_0(r,v,t^{`}),v_0(r,v,t^{`}),t-t^{`}dt^{`}. \quad (7)$$

The phase space coordinate system has been transformed from (r,v,t) to (r_0,v_0,t-t`).The particle trajectories which have been obtained by solving eq.(3) for the given external field configuration and wave propagation $k=\left[k_\perp e_{x,}\, 0, k_\parallel\, e_z\right]$.After doing some lengthy algebraic simplification and carrying out the integration similar to Pandey and Misra [22], the perturbed distribution function f_1 is written as:

$$f_{s1}(r,v,t)=-\frac{e_s}{m_s\omega}\sum_{m,n,p,q}^{\infty}\frac{J_p(\lambda_2)J_m(\lambda_1)J_q(\lambda_3)e^{i(k.r-\omega t)}}{\{\omega-k_\parallel\, v_\parallel\ -(n+q)\omega_{cs}+p\nu\}}\left[E_{1x}J_nJ_p\left\{(\frac{n}{\lambda_1})U^*+D_1(\frac{p}{\lambda_2})\right\}\right.$$
$$\left.-iE_{1y}\left\{J_n^{'}J_pC_1+J_nJ_p^{'}D_2\right\}+E_{1z}J_nJ_pW^*\right]$$

Where the Bessel identity

$$e^{i\lambda\sin\theta}=\sum_{k=-\infty}^{\infty}J_k(\lambda)\,e^{ik\theta}$$

has been used, the arguments of the Bessel functions are

$$\lambda_1=\frac{k_\perp v_\perp}{\omega_{cs}},\lambda_2=\frac{k_\perp\Gamma_x\nu}{\omega_{cs}^2-\nu^2},\lambda_3=\frac{k_\perp\Gamma_x\omega_{cs}}{\omega_{cs}^2-\nu^2}$$

where

$$C_1=\frac{1}{v_\perp}\left(\frac{\partial f_0}{\partial v_\perp}\right)(\omega-k_\parallel\ .v_\parallel\ )+\left(\frac{\partial f_0}{\partial v_\parallel}\right)k_\parallel$$

$$U^*=C_1\left[v_\perp-\left\{\frac{\nu\Gamma_x}{\omega_{cs}^2-\nu^2}\right\}\right]$$

$$W^*=\left[\left(\frac{n\omega_{cs}v_\parallel}{v_\perp}\right)\left(\frac{\partial f_0}{\partial v_\perp}\right)-n\omega_{cs}\left(\frac{\partial f_0}{\partial v_\parallel}\right)\right]+\left[1+\left\{\frac{k_\perp\nu\Gamma_x}{\omega_{cs}^2-\nu^2}\right\}\{(p/\lambda_2)-(n/\lambda_1)\}\right]$$

$$D_1=C_1\left\{\frac{\nu\Gamma_x}{\omega_{cs}^2-\nu^2}\right\},D_2=C_2\left\{\frac{\omega_{cs}\Gamma_x}{\omega_{cs}^2-\nu^2}\right\}$$

$$J_n^{'}=\frac{dJ_n(\lambda_1)}{d\lambda_1},J_p^{'}=\frac{dJ_p(\lambda_2)}{d\lambda_2} \quad \ldots(8)$$

Following [14] the conductivity tensor $\|\sigma\|$ is written as

$$\|\sigma\| = -\sum \frac{e_s^2}{m_s \omega} \sum_{m,n,p,q}^{\infty} \int \frac{J_q(\lambda_3) S_{ij} d^3v}{\omega - kv - (n+q)\omega_{cs} + pv}$$

Where

$$S_{ij} = \begin{Vmatrix} v_\perp \frac{n}{\lambda_1}(J_n)^2 J_p A & iv_\perp J_n B & v_\perp W^* \frac{n}{\lambda_1} J_n^2 J_p \\ v_\perp J_p A J_n J'_n & v_\perp J'_n B & iv_\perp W^* J_p J_n J'_n \\ v_\parallel J_n^2 J_p A & -iv_\parallel J_n B & v_\parallel W^* J_n^2 J_p \end{Vmatrix}$$

$$A = \left(\frac{n}{\lambda_1}\right) U^* + \left(\frac{p}{\lambda_2}\right) D_1, \qquad B = J'_n J_p C_1 + J'_n J_n D_2$$

From $J = \|\sigma\|.E_1$ and two Maxwell's curl equations for the perturbed quantities, we have

$$\left[k^2 - k.k - \frac{\omega^2}{c^2}\varepsilon(k,\omega)\right].E_1 = 0$$

where

$$\varepsilon(k,\omega) = 1 - \frac{4\pi}{i\omega}\|\sigma(k,\omega)\| \text{ is dielectric tensor}$$

The Maxwellian distribution function with loss-cone angle θ_c taken from Huang et al [15] is written as:

$$f_{so} = \frac{n_0}{M\pi^{3/2}\alpha_\perp^2 \alpha_\parallel} \exp\left[-\left(\frac{v_\perp}{\alpha_\perp}\right)^2 - \left(\frac{v_\parallel}{\alpha_\parallel}\right)^2\right] \qquad \left|\frac{v_\perp}{v_\parallel}\right| > \tan\theta_c$$

Where normalization constant M is given as

$$M = \frac{1}{\sqrt{\frac{1+\tan^2\theta_c}{A_T + 1}}}$$

$$\|\varepsilon_{ij}(k,\omega)\| = 1 + \sum \frac{4\pi\pi_s^2}{m_s \omega^2} \int \frac{J_q(\lambda_3)\|S_{ij}\| d^3v}{\omega - kv - (n+q)\omega_{cs} + pv}$$

$$\varepsilon_{11} \pm \varepsilon_{12} = N^2$$

Now the dispersion relation of oblique whistler wave is obtained from above for

$n = 1, p = 1$ and $J_p = 1, J_q = 1$

$$\frac{k^2c^2}{\omega^2} = 1 + \frac{\omega_p^2}{\omega^2}\left[\left(1+\frac{X_{ac}}{\alpha_\perp}\right)\left\{\frac{\omega}{Mk_\parallel\, \alpha_\parallel} Z(\xi(+ A_T\left(1+\xi Z(\xi)\right)\right\} + \tan^2\theta_c \left\{\left(\frac{1}{2}\right) + \xi^2\left(1+\xi Z(\xi) + \frac{X_{ac}}{\alpha_\perp}\xi\left(1+\xi Z(\xi)\right)\right)\right\}\right]$$

where

$$X_{ac} = \frac{\nu\Gamma_x}{\omega_c^2 - \nu^2} \qquad X_3 = \frac{\omega_r}{\omega_c} \qquad X_4 = \frac{-\nu}{\omega_c} \qquad k_3 = 1 - X_3 + X_4 \;,\; k_4 = \frac{X_3}{k_3}$$

$$k_1 = k$$

The required expression for growth rate and real frequency are obtained as

$$\frac{\gamma}{\omega_c} = \frac{\dfrac{\sqrt{\lambda}}{Mk_1}\left[\left(1+\dfrac{X_{ac}}{\alpha_\perp}\right)\left(A_T - k_4\right) + \left(\dfrac{\tan\theta_c k_3}{Mk}\right)^2 - \dfrac{X_{ac}\tan\theta_c{}^2 k_3}{\alpha_\perp Mk_1}\right]k_3^3\exp\left(-\left(\dfrac{k_3}{Mk_1}\right)\right)}{\left(1+\dfrac{X_{ac}}{\alpha_\perp}\right)\left\{1 + X_4\dfrac{M^2A_T\left(1+X_4\right)}{2k_3^2} - \dfrac{M^2k_1^2}{k_3}\left(A_T - k_4\right)\right\} + \dfrac{X_{ac}\tan\theta_c{}^2}{2\alpha_\perp}}$$

$$X_3 = \frac{k_1^2}{2\beta}\left[1 + X_4\frac{M^2A_T\beta\left(1+\dfrac{X_{ac}}{\alpha_\perp}\right)}{\left(1+X_4\right)^2} + \frac{X_{ac}\tan\theta_c{}^2 M}{2\alpha_\perp k_1\left(1+X_4\right)}\right]$$

where

$$\beta = \frac{k_\beta T_\parallel\, n_0 \mu_0}{B_0^2}$$

RESULTS AND DISCUSSION

Plasma parameters suited to the auroral ionosphere has been adopted to calculate the growth rate and real frequency of the loss-cone driven whistler instability in the presence of perpendicular AC electric field. Ambient magnetic field $B_0 = 1\times10^{-7}$ T electron density to vary from $n_0 = 1\times10^{9}$ m-3 to 4×10^{9} m-3 electron energy $K_B T_\parallel$ from 6eV t0 12 eV. Temperature anisotropy is supposed to vary from 0.25 to 1. The value of perpendicular AC electric field has been taken as E_0=20 mV/m having frequency varying from $\upsilon = 0$ to 6kHZ and loss –cone angle is supposed to vary from $\theta_c = 0$ to 30^0.

Fig1. shows the variation of growth rate and real frequency with respect to k for various values of temperature anisotropy in presence of Perpendicular AC field magnitude E_0=20mV/m with frequency $\upsilon = 2\text{kHZ}$ and other plasma parameters shown in the caption of the figure. It is obvious from the figure that with the increase of temperature anisotropy the growth rate increase of temperature anisotropy the growth rate increases significantly, indicating that the temperature anisotropy is main driving force proving energy for the growth rate of instability. This effect is more prominent in the presence of perpendicular A.C. electric field, as compared to the case when parallel A.C. electric field is present as reported by Pandey and Misra [22]. Fig 2 shows the growth rate and real frequency with respect to k for various values of loss-cone angle in the presence of anisotropy A_T=1.5 and A.C. Field E_0 =20mV/m. It is obvious that as the loss-cone angle increase, the growth rate goes on increasing. The value of pitch angle distribution is more effective in the presence of perpendicular AC field in comparison to parallel AC field as reported by Pandey and Misra [22]. Pitch angle anisotropy works as free energy source to drive instability. Fig 3 shows the effect of AC frequency variation in the presence temperature anisotropy A_T=1.5 and loss-cone $\theta_c = 10^0$. The increase of frequency exhibits increase of growth rate and shifting of the maxima of the lower values of k. Resonance velocity is modified by the of AC frequency as it is represented by the factor $\frac{\omega - \omega_c + \omega'}{\omega_c}$ as such the real frequency decreases with the increases of AC frequency, but the effect of the magnitude of Ac Field has no effect. Fig 4 shows the effect of frequency variation in the presence of temperature anisotropy and in the absence of loss-cone. This figure shows that in the absence of loss-cone the role of frequency variation is more prominent in comparison to the case when loss-cone is present but the value of the maxima of the growth rate is less in comparison to the case when loss-cone is present, this shows that the loss-cone angle behaves as free energy source. In fig 5 the effect of frequency variation is shown in the presence of loss-cone but the temperature anisotropy is absent. In this case the maxima um value of the growth rate is significantly reduced and although the increase of frequency s the growth rate but this contribution is not that much effective. Significant reduction in the growth rate maxima indicates the major contribution of the temperature anisotropy in the growth rate of the instability rather than pitch angle anisotropy. In fig 6 the growth rate and real frequency variation is shown with respect to k for various values of the density n_0. It is obvious that as the density increases the growth rate as well as the band width increases significantly. This shows that the number density of plasma particle has important role in this region of ionosphere. Fig 7 shows the growth rate and real frequency with respect to k. As the energy of the energetic electrons increase there is increase of the growth rate and also the increases in band width with gradual shift of the maxima towards higher wave length k. This shows that in this region thermal energy is less effective.

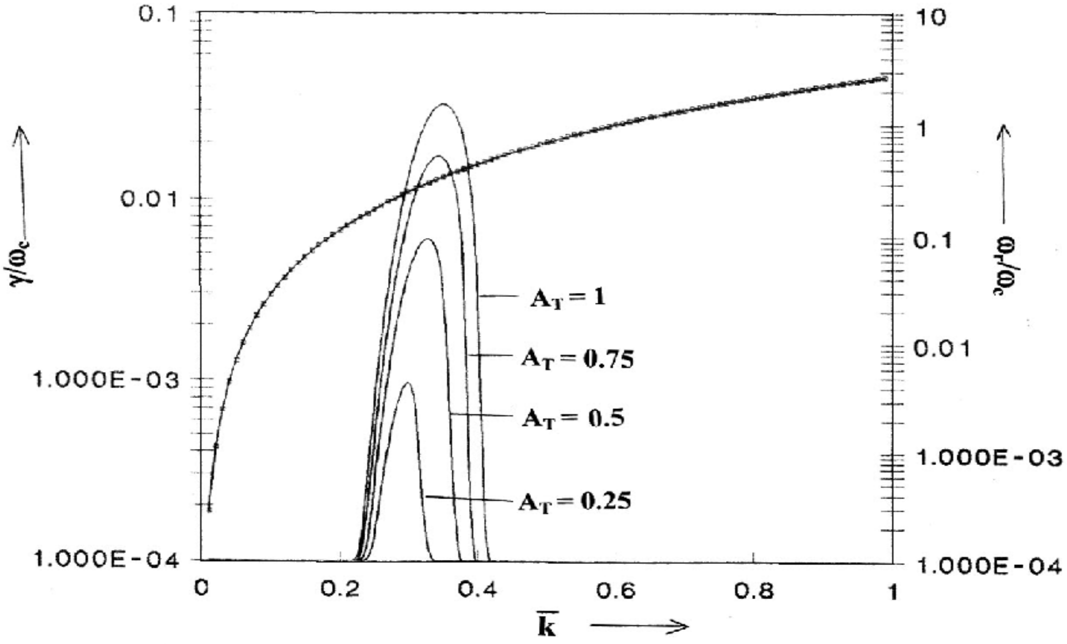

Fig. 1: Variation of growth rate γ/ω_{ci} verses $\vec{k}$ for different value of Temperature anisotropy and others parameters $B_0 = 1\times10^{-7}\,T$, $n_0 = 1\times10^{9}\,m^{-3}$, $\theta_c = 10^0$, $E_0 = 2\times10^{-3}\,v/m$, $K_B T_{\|} = 10eV$, $\nu = 2kHz$.

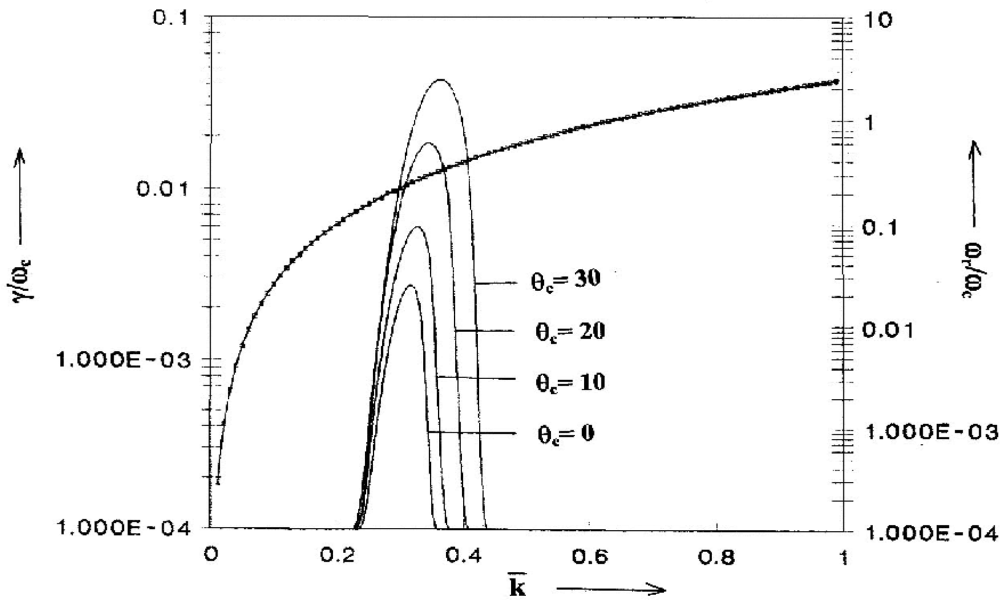

Fig.2: Variation of growth rate γ/ω_{ci} verses $\vec{k}$ for different value of loss-cone angle and others parameters $B_0 = 1\times10^{-7}\,T$, $n_0 = 1\times10^{9}\,m^{-3}$, $A_T = 1.5$, $E_0 = 2\times10^{-3}\,v/m$, $K_B T_{\|} = 10eV$, $\nu = 2kHz$.

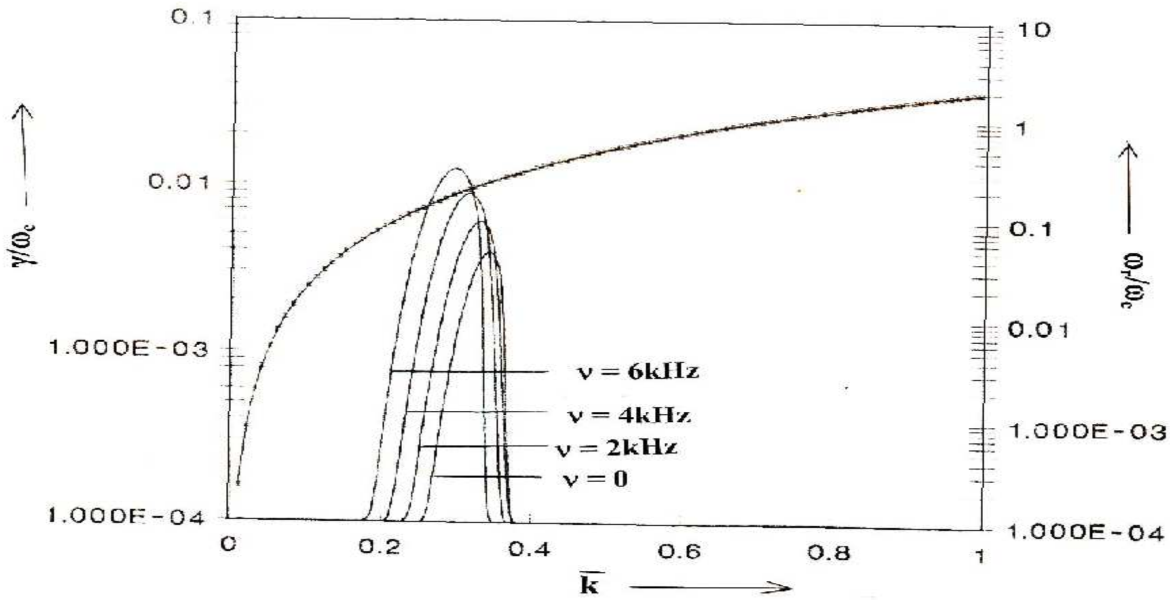

Fig.3: Variation of growth rate γ/ω_{ci} **verses** $\vec{k}$ **for different value of A.C. frequency and others parameters** $B_0 = 1\times10^{-7}\,T$, $n_0 = 1\times10^{9}\,m^{-3}$, $A_T = 1.5$, $E_0 = 2\times10^{-3}\,v/m$, $K_B T_{\|} = 10eV$, $\theta_c = 10^0$.

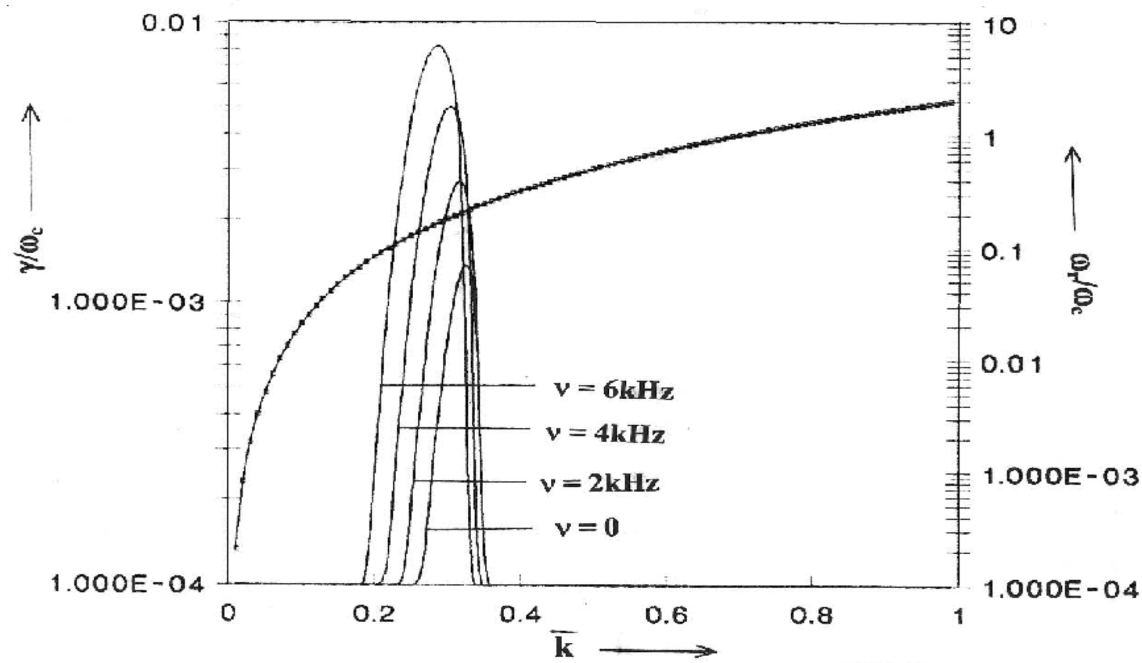

Fig.4: Variation of growth rate γ/ω_{ci} **verses** $\vec{k}$ **for different value of A.C. frequency In the absence of loss-cone angle and others parameters** $B_0 = 1\times10^{-7}\,T$, $n_0 = 1\times10^{9}\,m^{-3}$, $A_T = 1.5$, $E_0 = 2\times10^{-3}\,v/m$, $K_B T_{\|} = 10eV$.

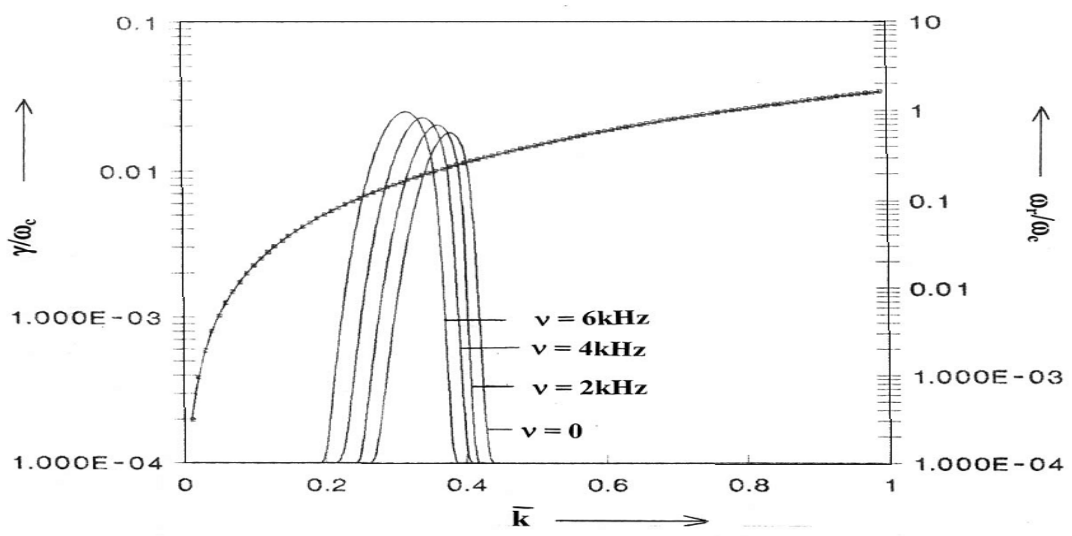

Fig.5: Variation of growth rate γ/ω_{ci} verses $\vec{k}$ for different value of A.C. frequency In the absence of loss-cone angle and Temperature anisotropy, others parameters
$B_0 = 1\times10^{-7}\,T$, $n_0 = 1\times10^{9}\,m^{-3}$, $E_0 = 2\times10^{-3}\,v/m$, $K_B T_\parallel = 10eV$.

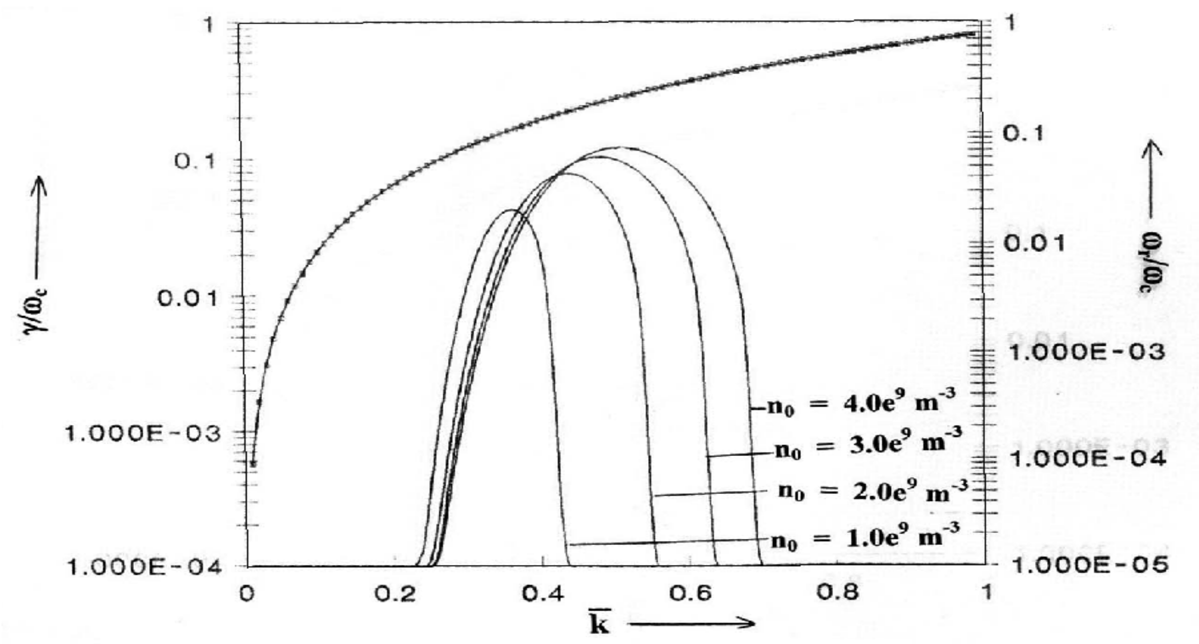

Fig.6: Variation of growth rate γ/ω_{ci} verses $\vec{k}$ for different value of number density and others parameters $B_0 = 1\times10^{-7}\,T$, $A_T = 1.5$, $E_0 = 2\times10^{-3}\,v/m$, $\theta_c = 30^0$
$K_B T_\parallel = 10eV$, $\nu = 2kHz$.

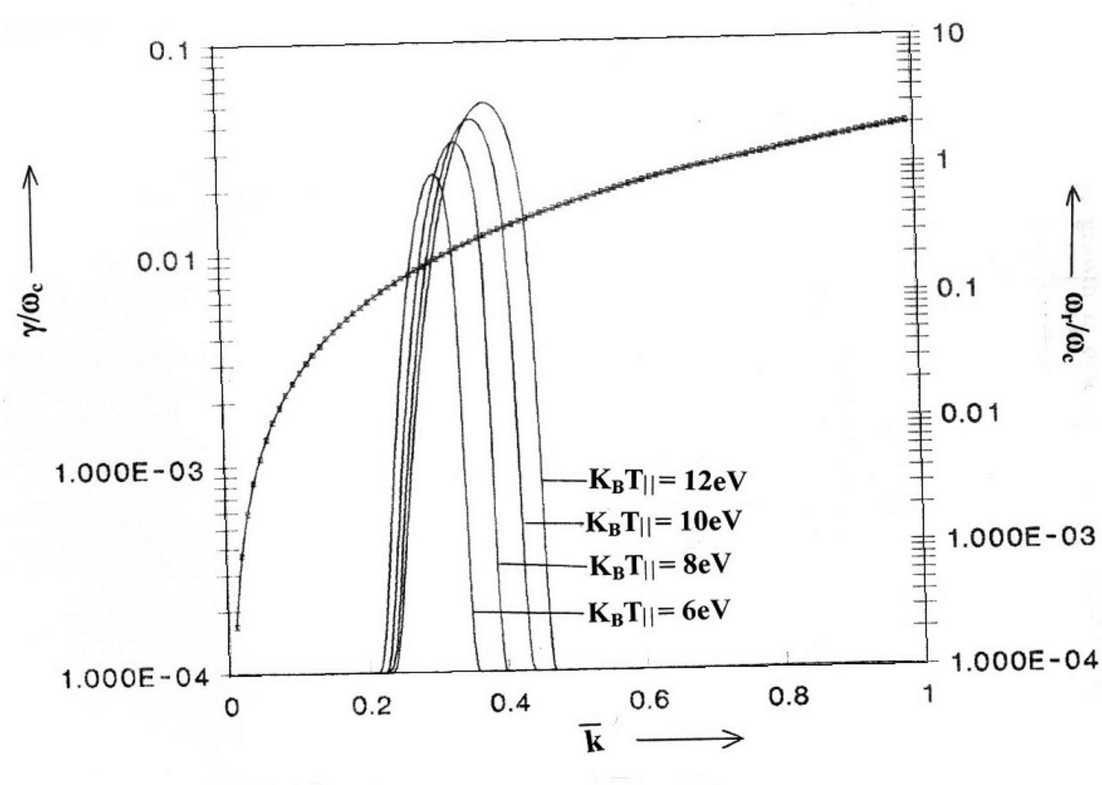

Fig.7: Variation of growth rate γ/ω_{ci} verses $\vec{k}$ for different value of $K_B T_{\parallel}$ and others parameters $B_0 = 1\times10^{-7}\,T$, $A_T = 1.5$, $E_0 = 2\times10^{-3}\,v/m$, $\theta_c = 30^0$ $K_B T_{\parallel} = 10eV$, $n_0 = 1\times10^9 m^{-3}$, $\nu = 2kHz$.

CONCLUSION

Whistler mode instability has been studied for anisotropic plasma having bi- Maxwellian velocity distribution with loss-cone in the presence of perpendicular AC electric field. Method of characteristic solutions has been used to derive the dispersion relation and growth rate. The role of the excitation of whistler instability has been discussed by loss-cone in particular and by other factors in general in the auroral region of the ionosphere. It is observed that the presence of perpendicular AC electric field plays prominent role in providing additional energy for the enhancement of the growth rate. It is not the magnitude but the frequency of the AC field which plays significant role in the growth of the wave. In its presence the wave growth is obtained at lower value of the wave number.

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