Impact of hot injected beam on whistler mode with alternating electric field (AC) in the magnetosphere of Saturn

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Abstract - Whistlers are believed to be generated by its own and responsible to evolve dynamical properties of magnetized planetary environment. Growing whistler instability can cause other uncertainties in the magnetosphere and evident to be generated by mean of injection events and temperature variance in plasma environment. In this paper the empirical dispersion relation has developed for parallel propagating whistler mode instability in an infinite saturnian magnetoplasma in the presence of perpendicular electric field for ring distribution function having non-monotonous nature. Method of characteristics solutions alongside kinetic approach found to be most suitable in order to achieve perturbed plasma states. The perturbed and unperturbed particle trajectories have taken into consideration to determine perturbed distribution function. A remarkable growth rate expression with added hot plasma injection has been calculated in inner magnetosphere near 6.18 $R_s$. The results obtained using demonstrative value of the parameters suited to the Saturnian magnetosphere have been computed and discussed. Pressure (Temperature) anisotropy is found to be a peculiar source of free energy for whistler mode instability. The AC frequency irrespective of its magnitude, affects the growth rate significantly. The bulk of energetic hot electrons injection influences the growth rate by increasing its peak value. The result obtained provide the important view of wave particle interaction and useful to analyze the VLF emissions observed over a wide frequency range.

Key words: Saturn magnetospheric environment, Growth rate, Wave Particle Interaction, Whistler Mode Wave.

1. Introduction
Whistler was first coined by Barkhausen \cite{Barkhausen} in 1919 and found to be first ever discovered plasma waves. Studies tells that the Whistlers are dispersive in nature as travel through one hemisphere to another and Characteristic frequency dependence, interplay a major role in magnetosphere as its time of arrival increases with depreciating frequency \cite{Shukla}. Enormous emission of plasma and radio frequency range found to be dominant in Saturn magnetospheric environment \cite{Goertz, Shukla, Pandey}. Additionally, low ranged frequency
Whistlers can be used as a diagnostic tool to characterize the localized magnetospheric processes taking place in plasma environment. Study of whistlers are based on the fact that like EM electron cyclotron waves, usually these are sensed as right-hand Polarized waves but its polarization characteristics can be turned into left-handed in view of the frame of spacecraft on account of strongly reversed Doppler shift. Invoked weaker ‘Doppler shift’ may be because of larger angle as an interesting anomaly between the streaming solar wind velocity and magnetic field vectors (appx. At 10 AU). Whistler or lower hybrid waves particle interaction is of utmost importance as it propagates through the moderate angles (10° – 60°) with the magnetic field, driving vigorous wave amplification and high-energy tale electrons precipitation from the magnetospheric layers to the lower atmosphere/ionosphere. First ever detected lightning originated Whistlers at 6.18 Rs in Saturn magnetosphere well defined by Akali et al. [6], though Storey [7] in 1953 given exclusive generation mechanism for the first, concluding these whistler modes travel from one hemisphere to another along magnetic field lines.

Prior studies disclose that remarkable shift of k, achieved due to maximum growth rate change with respect to chief parameters such as propagation angle, magnetic fields, density variation and some other parametric parameters involved in local processes observed before [8, 9]. Similarly study of the modified wave becomes significant as it gives an important overview of magnetospheric unrevealed and complicated processes. Ample discussion on outcome of particle and wave resonant interaction reported by many researchers e.g., [10, 11], describing amplification of wave associated with particle precipitation. Sazhin and Hayakawa [12] in (1992) have given exclusive overview on chorus emission, considering anisotropic energetic particles as a main play factor for these VLF emissions. Extensive review on wave particle interaction done by many investigators e.g., [13]. Interplay between particle and wave, contributes in particle acceleration mechanism [14]. Saturn internal to middle layer of magnetosphere found to have a prominent injection influenced active zone. In inner Saturn environment, Menietti et al. [15] reported explanatory observation of existence of plasma species carrying lower energies about 1Kev inside the plasma injection alongside the Pancake like PAD (Pitch angle distribution).

Many other researchers e.g., [16] have done extensive study on PAS (Pitch angle scattering) of energetic electrons of radiation belt and concluded, whistler waves as a chief driving agent of these electrons into the loss cone and precipitation into the atmosphere. It is ubiquitous in magnetospheric plasma that Whistlers can significantly resonate with specific energy range of electrons i.e., unstructured hiss with, appx. 100 eV–1000 eV and structured chorus with, approx. 1–10 keV and can scatter these charged entities [17, 18]. Exclusive survey of whistler chorus at Saturn has done by Menietti et al. [19], reporting intense chorus near middle magnetic layers (4.5 < L < 7.5) with highest peak between 5.5 Rs - 6.5 Rs and latitude ranging 5° - 10°. Additionally, highly intense hiss greater than chorus also observed. Data released by Voyager 1 disclosed narrowband radio emission cantered close to 5KHz [3, 20]. Specific frequency band emission close to 5 kHz detected by Voyager 1, between 3.25 RS and 58 RS. Energetic particles of two cooler and hotter components (1 eV to 28 keV) observed within middle range of magnetospheric layer (5 < L < 12 Rs) [21- 24]. Clark et al. [25] proposed diffusion model demonstrating energisation of species undergoing radial diffusion mechanism due to centrifugally invoked interchanged instability and emphasized the need of deeper investigation referring interplay between wave and particle to demonstrate magnetospheric processes as inner zone local processes are still unclear. Many investigators examine pervasive interchanged instability driven by centrifugal forces. Mauk et al. [26] and many others reported inward radial diffusion of electrons limiting from 20 to 200 keV and energetic ions from 5 to 200 keV, using MIMI (Magnetospheric Imaging Instrument), found to be dominant between 3.8Rs to 11.2Rs. Chorus at Saturn, influenced by injection mechanism reported using RPWS (Cassini) data, characterising the wave property and generation mechanism [27]. Lightning originated two whistlers have been detected by RPWS on board Cassini in the Saturn magnetosphere in 2004, near 6.19 Rs. Lightning generated Sharp storm eruptions reported by ISS (Imaging Science Subsystem) on board Cassini through cloud motions analysis, believed to be associated with SED (Saturn's electrostatic discharges) [28]. It is observed, whistler mode chorus trapping bit of weakly relativistic electrons and accelerating with a rising tone [29]. Additionally, frequency found to be increased with elevated amplitude along with these rising tones.
The generation mechanism of whistler component still is of importance as it involves nonlinear processes causing evolution of wave growth and hump of waves of swiftly changing frequency. Menietti et al. [30] presented extensive survey on whistler emission mechanism and reported Saturn intrinsic environment as an active zone where whistler hiss found to be more intense at lower latitude as compare to chorus.

In this framework, eminence of whistlers in Kronian intrinsic magnetosphere is evaluated, employing benefits of spacecraft (Cassini) being present in the region of investigation where radial diffusion and thus injection processes must be taken as a rich feature in order to evaluate evoked whistler wave growth.

2. Dispersion Relation and Growth rate

Collision less, Uniform anisotropic space plasma, influenced by electric field \( E_\infty = (E_\omega \sin \nu t) \hat{e}_\omega \) and external magnetic field \( B_0 = B_0 \hat{e}_z \), are used to achieve numerical dispersion relation. The inhomogeneities in the interaction area are negligible. Technical and geometric principles being followed as given by Shukla et al. [31] and Kumari and Pandey [8]. Hence after lengthy calculation, using Vlasov equation -

\[
\varepsilon_{ij}(\kappa, \omega) = 1 + \sum_s \left\{ \frac{4e_s^2 \pi}{(\beta m_e)^2 \omega_s^2} \right\} \int \frac{d^3p}{\omega - k_s \omega_s - (n + g) \omega_s} \]

Considering \( k_\perp = 0 \), for parallelly propagating whistler mode wave and instability, the dispersion relation achieved (from equation 1):

\[
\varepsilon_{11} + i \varepsilon_{12} = N^2 \]

Here, \( N^2 = (\kappa^2 c^2)/\omega^2 \), is showing refractive index.

Hence for \( n=1 \), dispersion relation becomes:

\[
N^2 = 1 + \frac{4e_s^2 \pi}{(\beta m_e)^2 \omega_s^2} \int \frac{d^3p}{\omega - k_s \omega_s - (n + g) \omega_s} \]

Where,

\[
N_1 = \frac{(\beta m_e)^2}{\beta_p} \frac{\partial f_0}{\partial P_\perp} \left( \omega - \frac{\kappa ||P||}{\beta m_e} \right) \left( \frac{P_\perp}{\beta m_e} - \frac{v \Gamma_x}{\beta \left( \frac{\omega_e}{p^2} - v^2 \right)} \right)
\]

\[
N_2 = \beta m_e \kappa ||P|| \frac{\partial f_0}{\partial P_\parallel} \left( \frac{P_\perp}{\beta m_e} - \frac{v \Gamma_x}{\beta \left( \frac{\omega_e}{p^2} - v^2 \right)} \right)
\]

‘Maxwellian ring momentum distribution function’ is considered here (for trapped electron)

\[
f(P_\perp, P_\parallel) = \frac{n_e/n}{\pi^{3/2} p_\perp^{3/2} p_\parallel^{1/2}} \exp \left[ - \frac{(P_\perp - P_\perp_0)^2}{p_\perp^2} - \frac{(P_\parallel - P_\parallel_0)^2}{p_\parallel^2} \right]
\]
\[ B = \exp\left(-p_{0\perp}^2/p_{0\parallel}^2\right) + \sqrt{\pi} \frac{p_0}{p_{0\perp}} \text{erfc}\left(-p_{0\parallel}/p_0\right) \]  

(7)

Where

\[ p_{0\parallel} = \left(\frac{2k_BT_{\parallel}}{m_e}\right)^{1/2} \quad \text{and} \quad p_{0\perp} = \left(\frac{2k_BT_{\perp}}{m_e}\right)^{1/2}, \]

are showing relevant parallel and perpendicular electron thermal velocities accordingly.

Now putting, \(d^3p = 2\pi \int_0^\infty p_{\perp}^2 dp_{\perp} \int_{-\infty}^\infty dp_{\parallel}\) and keeping (6) in equation (3), then solving integration,

Dispersion relation for Whistler mode becomes:

\[
\frac{k^2c^2}{\omega^2} = 1 + \frac{4\pi e^2}{(Bm_e)\omega^2} \frac{n\varepsilon}{B} \left[ X_1 \frac{\beta m_e \omega}{k_{||}p_{0\parallel}} Z(\xi) + X_2 \left(1 + \xi Z(\xi)\right)\right] 
\]

(8)

\[
X_1 = 1 + \frac{P_{0\parallel}^2}{P_{0\perp}^2} \frac{p_0}{p_{0\perp}} \sqrt{\pi} \frac{(\beta m_e)v \Gamma_{\perp}}{\beta \left(\frac{\omega^2}{\beta^2} - v^2\right)} \left(\sqrt{\pi} \frac{1}{2} p_{0\parallel} - \frac{p_0}{P_{0\perp}}\right) 
\]

\[
X_2 = \left[ X_1 + \frac{P_{0\parallel}^2}{P_{0\perp}^2} \left(1 - \sqrt{\pi} \frac{p_0^2}{P_{0\perp}^2} \text{erf}\left(\frac{p_{0\perp}}{P_{0\perp}}\right) + 3 \frac{p_0^2}{P_{0\perp}^2} - 3 \frac{1}{2} \sqrt{\pi} \frac{p_0}{P_{0\perp}}\right) \right] - \frac{(\beta m_e)\omega}{\beta \left(\frac{\omega^2}{\beta^2} - v^2\right)} \left(\sqrt{\pi} \frac{1}{2} p_{0\parallel} + \sqrt{\pi} \frac{P_{0\parallel}^2}{P_{0\perp}^2} \text{erf}\left(\frac{p_{0\perp}^2}{P_{0\perp}^2}\right) - 2P_0\right) 
\]

Here function \(Z(\xi) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^\infty e^{-t^2} dt\), is relating plasma dispersion function alongside

\[ \xi = \frac{\beta m_e}{k_{||}p_{0\parallel}} \left(\omega - \frac{\omega_c}{\beta} \pm \frac{\omega_c}{\beta} + pv\right). \]

Applying condition \(\frac{k^2c^2}{\omega^2} \gg 1\) (Whistler mode wave)

Considering plasma frequency,

\[ \omega_p^2 = \frac{4\pi e^2 n_e/n}{B_0 m_e} \]

\[ \omega = \omega_r + i\gamma \]

The equation (8) turns into the expression-

\[ D(k,w) = \frac{-k^2c^2}{\omega_p^2} + \frac{1}{\beta} \left[ \frac{X_1 \omega}{k_{||}p_{0\parallel}} (\beta m_e) \left\{ -\frac{1}{\xi} - \frac{1}{2\xi^3}\right\} - \left( X_2 2\xi^2 \right) + \left[ \frac{(\beta m_e)\omega}{k_{||}p_{0\parallel}} X_1 + X_2 \xi \right] \left[ i\sqrt{\pi} \exp(-\xi^2) \right]\right] \]

(9)
Implementing dimensionless parameters as

\[ \tilde{k} = \frac{k|P_0|}{\omega cs} \]

Then, the growth rate with respect to the dimensionless parameters \( \tilde{k}, \beta_1, K_2, X_1 \) and \( X_2 \) is achieved here

\[ \frac{Y}{\omega_c} = \frac{\sqrt{R}}{\beta k} \left( \frac{X_2}{X_1} - \frac{\beta X_3}{1 - \beta X_3 + \beta X_4} \right) \left( 1 - \beta X_3 + \beta X_4 \right)^3 \exp \left[ \frac{\left( 1 - \beta X_3 + \beta X_4 \right)^2}{\tilde{k}} \right] \]

(10)

The real part of equation (9) is given by,

\[ X_3 = -\frac{\omega_r}{\omega_c} = \frac{\tilde{k}^2}{\beta_1} \left[ K_2 (1 + \beta X_4) + \frac{X_2}{X_1} \frac{\beta_1}{2 (1 + \beta X_4)} \right] \]

(11)

Where \( K_2 = \frac{1}{2X_1} \) and \( \beta_1 = \frac{4 \pi e_0 k B \mu_0 (n_e/n)}{m_e^2 B B_0^2} \)

\[ X_4 = -\frac{p v}{\omega_c} \]

(12)

3. Plasma Parameters – measured data set by Voyager 1, 2 [5] and Cassini [4, 22] have taken, for G R analysis. Dispersion model has been developed for bounded conditions- n=1, p=1 and q=0 using \( \sum J_p = 1 \) and \( \sum J_q = 1 \)

| Table 1. Plasma Parameters taken for the growth calculation |
|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Radial Distance, \( R_s \) | Magnetic Field, \( B_o \) (nT) | Temperature Anisotropy, \( A_T \) | Electric Field, \( E \) (mV/m) | Relativistic Factor, \( \beta \) | Density, \( n \) (m\(^{-3}\)) | \( K_B T_0 \) (eV) (Background) | Frequency (AC), \( \nu \) (kHz) | \( K_B T_{inj} \) (keV) (Injected hot beam) |
|-----------------|---------------|---------------|---------------|-----------------|---------------|-----------------|---------------|-----------------|
| 6.18 \( R_s \) | 73            | 1.5           | 0.01          | 0.5             | 5\times10\(^7\) | 100             | 3             | 200             |
4. Result and Discussion

Figure 1: (GR) Growth rate verses $\tilde{k}$ for different AC frequency (Keeping temperature, anisotropy, number density etc. constant).

Figure 2: (GR) Growth rate verses $\tilde{k}$ for numerous values of number density ratio (Keeping AC frequency values, temperature, anisotropy etc. constant).

Figure 3: GR (Growth rate) verses $\tilde{k}$ for numerous temperature anisotropy (Keeping AC frequency, relativistic factor, number density etc., constant).

Figure 4: GR (Growth rate) verses $\tilde{k}$ for numerous values of relativistic factor (temperature anisotropy, number density, AC frequency values etc. constant).
**Figure 1**, depicting the diversified view of GR- $\gamma/\omega_c$ (along y axis) verses WN (wavenumber $k$-along x axis), for numerous AC frequency value, in account of ‘ring distribution function’ for electrons in intrinsic magnetosphere of Saturn’s. Growth rate seems to be increased for increased AC frequency value, highest growth measured for frequency of 5 KHz. The enhancement occurs due to leading inverse landau damping in the interacting zone and imparting particle energy to wave. Conclusively, Interplay of AC frequency does a lot in whistler wave variation as it is clearly visible, peaks are shifting towards higher WN, both frequency and magnitude of growth seems to be elevated as increased frequency of the field may cause improvement in resonance condition.

**Figure 2**, depicting the variability in GR with warm electrons i.e., $n_w/n_c$. It is evident from the figure that the escalating ratio of number density causing growth rate. Additionally, the inner zone of kronian magnetosphere can be concluded as higher zone of density gradient, because of the hot injection events towards inside, which may refer as causing factor for whister growth.

**Figure 3**, demonstrating the enhancement in growth rate with respect to WN (wavenumber) for diverse value of TA (temperature anisotropy). It is found from the dispersion relation that as the TA (i.e., Temperature ratio -perpendicular to parallel - $T_L/T_i$) raises, growth rate also escalates in both the sense, frequency and magnitude by mean of hot ring’s electron alongside the presence of cold electron surrounding. Menietti et al. [15] reported growth of whistler due to increase in the ratio of temperature and PAN cake like distribution of hot component.

**Figure 4**, showing depreciated GR (growth rate) for increased value of relativistic factor ($\beta$) in view of WN (wavenumber) i.e., maximum peak is obtained for lowest value ($0.5$). Similarly, conclusion is made that smaller $\beta$ is measured for greater velocity of the highly energetic particles inferring more growth of whistlers. Thus, for ring distribution of particle this cannot be referred as the prime factor, responsible for growth of whister but can be salient for other kind of distribution as Maxwellian [29].

5. Conclusion

Inner magnetosphere of Saturn is influenced by many stochastic processes and forces, bring many uncertainties and instabilities that may play a major role in wave enhancement mechanism. The analysis done gives cognizance of process of dimensionless growth rate of whistler waves. Here, the theoretical study done characterizes the vitality of energetic electrons associated with ring to be a major factor resulting growth of these low frequency whistler waves alongside frequency of alternating current and temperature anisotropy of particles. The investigation of outer planets wave emission is still in its infancy and require a deeper groundwork to demonstrate local activity within the magnetized planets. The results on remarkable growth rate obtained statistically may carryout to understand wide range of VLF emissions within Saturn magnetospheric plasma environments.

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