Inspired from work compiled by Friedel et al. [2002], who presented the current state of research into relativistic electron dynamics, covering diffusion, substorm acceleration, wave acceleration etc., we have made an attempt to do numerical analysis of relativistic electromagnetic electron-cyclotron harmonics in various magnetospheric regimes. The various flyby and orbiter missions, accomplishing the development of technology, have explored the complex and vast magnetospheres of various planets. The data sent by Pioneer, Voyager, Ulysses and Cassini has enriched the space science community in numerous ways. We, therefore mention some of the relevant observations made by Cassini, Voyager 1 and 2 and other terrestrial spacecraft to study EMEC instability in magnetosphere of Jupiter, Saturn and Uranus.

7.1.1. Saturn

Out of several types of plasma waves observed in the outer magnetosphere, with the Voyager flybys [Gurnett et al. 1981; Scarf et al. 1982], the most complex and strongest plasma wave emissions has been reported in the inner region of the magnetosphere, inside of ~10 Rs [Gurnett et al. 2005]. Cassini showed that extensive electron-cyclotron harmonics (ECH) were observed inside ~8 Rs [Zarka 2004; Kurth and Gurnett 1991]. Rs is conventional equatorial radius of Saturn, to be approximately equal to 58,232 km. Voyager observed fluctuations in the intensity range of 20 to 30KeV indicate that electrons are on high energy tail of resonant spectrum [Kurth and Gurnett 1991]. Various radial distances in Saturn’s magnetosphere were investigated during Voyager and Cassini missions. Voyager 1 provided information on number densities and energies of hot and cold components of electron distribution function, in 6 – 18 Rs. Magnetic field magnitude was found to be 80 – 4.4 nT for that radial distance [Sittler at al. 1983]. Cassini served us with the data of same variables in the range of 5.5 – 2.2 Rs. In 5.5 - 2.2 Rs range of distance, the magnetic field values increased rapidly from 100 – 1400 nT respectively [Gurnett et al. 2005, Young et al. 2005]. Detailed discussion done by Wahlund et al. [2005] explains four magnetospheric regions identified by the Cassini’s Radio and Plasma Wave Science (RPWS) cold plasma results. Each region characterized by different ion composition, plasma temperature and densities.

A survey of plasma electron environment concludes that electron distribution functions are found to be non-Maxwellian in nature. The hotter components (~100 –
1000 eV) can be modelled by kappa distribution [Summers and Thorne 1991]. Therefore, since Maxwellian distribution cannot be applied as electron distribution function, the background plasma can be modelled by Kappa distribution function. The existence of hotter components (\(\sim 100 - 1000\) eV) justify the use of Kappa distribution function [Summers and Thorne 1991; Pierrard and Lazar 2010] to study the dynamics of Saturn’s magnetosphere.

7.1.2. Jupiter

Kurth et al. [1980] first reported the Voyager observations of strong electron-cyclotron harmonic emissions at Jupiter. More plasma waves and radio waves observations were made by Ulysses [Stone et al. 1992] and Galileo [Gurnett et al. 1996] providing opportunity to study magnetosphere of Jupiter in detail. In 1980, Barbosa and Kurth [1980] presented brief encounters with ECH emissions found at larger radial distances at frequencies above electron cyclotron frequency. It has been rightly said, that the most intense radiation belt out of all the magnetized planets is that of Jupiter, with electron energies in excess of 50 MeV at \(L=1.4\) [de Pater and Dunn 2003]. ECH waves with electric field amplitude of \(\sim 100\ \mu\text{V/m}\) exist inside \(\sim 23\ R_J\) [Zarka 2004]. The work of Menietti et al. [2012] showing the plot of electric field intensity, gives the clear examples of ECH oscillations observed above \(f_c\). The plot shows the active enhancements near and between cyclotron harmonics. Average peak power calculated by them for ECH emissions was reported as \(5.53 \times 10^{-10}\) watts/m². Recently, Woodfield et al. [2013] explained that cyclotron-resonant wave acceleration provides a population of few MeV electrons at \(10 - 14\ R_J\), which in turn provides the source of particles for transportation to \(\sim 1.5\ R_J\). \(R_J\) is conventional equatorial radius of Jupiter, \(\sim 69,911\) km.

7.1.3. Uranus

The Voyager 2 flyby of Uranus revealed that the planet has an unusual magnetosphere. The reports from Voyager 2 plasma wave observation instrument, during the encounter at Uranus [Gurnett et al. 1986] presented the evidence of existence of electrostatic and electromagnetic plasma turbulences, low frequency radio emissions and also non-Maxwellian high-energy tail distribution. The observations made by Plasma Wave Instrument showed important processes regarding radio emissions, local wave-particle interactions and plasma waves [Scarfe et
al. 1987; Kurth et al.1987; Kurth et al. 1989]. Presence of electron-cyclotron waves in
the region of inner magnetosphere of Uranus were also observed [Gurnett et al. 1986].
And Krimigis et al. [1986] explains how electron intensities substantially exceed
proton intensities at a given energy. The evidences given by Voyager 2 suggest that
the particle distribution functions at Uranus should be characterized by a ‘warm’ core
and a non-Maxwellian tail that varied significantly along the spacecraft trajectory.

Inspired from above mentioned literature and understanding the importance of
ECH waves in interplanetary space, we present the comparative investigation of
electron-cyclotron waves in magnetosphere of Jupiter, Saturn and Uranus.

7.2. Dispersion Relation and Growth Rate

A homogeneous anisotropic collisionless plasma in the presence of an external
magnetic field $B_o = B_o \hat{e}_x$ and an electric field $E_{ox} = E_o \sin(\omega t) \hat{e}_x$ is assumed.
Following the methodology of section 2.2 of chapter 2, the dielectric conductivity
using particle trajectories for relativistic plasma, is written as:

$$\varepsilon_{ij} = 1 + \sum \frac{4\pi e_i^2}{(\lambda m_j)^2} \frac{d^3 P J (\lambda_i) \| S \|}{\omega - \frac{k_i P_1}{\lambda m_j} - \frac{(n + g) k_0}{\lambda}} + p u \quad \text{(7.1)}$$

Where

$$\| S \| = \begin{pmatrix}
P_{J^2} J_p \left( \frac{n}{\lambda_1} \right) U^* & iP_{J^2} J_p \left( \frac{n}{\lambda_1} \right) W^* \\
iP_{J^2} J_p \left( \frac{n}{\lambda_1} \right) U^* & P_{J^2} J_p \left( \frac{n}{\lambda_1} \right) W^* \\
P_{J^2} J_p \left( \frac{n}{\lambda_1} \right) U^* & iP_{J^2} J_p \left( \frac{n}{\lambda_1} \right) W^* \\
\end{pmatrix} \quad \text{(7.2)}$$

$$U^* = \left( \frac{c_i P_1 n}{\lambda_i m_i \lambda} \right) \left( \frac{mu_i D}{\lambda_1} \right) + \left( \frac{p u c_i D}{\lambda_2} \right)$$

$$V^* = \frac{c_i J_n J_p}{\lambda_i m_i \lambda} + c_i DJ_p J_n \omega_e$$

$$W^* = \left( \frac{nu e F m_i}{k_z P_1} \right) + \left( \frac{\lambda m_i P \omega \phi_{f_0}}{\partial p_z} \right) + G_i \left( \frac{p}{\lambda_2} - \frac{n}{\lambda_1} \right)$$

3
\[
C_1 = \left\{ \frac{(\lambda m_e)}{P_\perp} \right\} \left\{ \frac{\partial f_0}{\partial P_\perp} \right\} \left( \omega - \frac{k_1 P_z}{\lambda m_e} \right) + \lambda m_e \left\{ \frac{\partial f_0}{\partial P_\perp} \right\}
\]

\[
D = \left[ \frac{\Gamma_x}{\lambda} \left\{ \frac{(\omega_c)}{\lambda} \right\}^2 - v^2 \right], \quad G = \left\{ \frac{H k_\perp u \Gamma_s}{\lambda} \left\{ \frac{(\omega_c)}{\lambda} \right\}^2 - v^2 \right\}
\]

\[
H = \left\{ \frac{(\lambda m_e)}{P_\perp} \right\} \left\{ \frac{\partial f_0}{\partial P_\perp} \right\} \left( \frac{P_z}{\lambda m_e} \right) + \lambda m_e \left\{ \frac{\partial f_0}{\partial P_z} \right\}, \quad F = \frac{H k_\perp P_z}{\lambda m_e}
\] 

\[ J_n'(\lambda_1) = \frac{dJ_n(\lambda_1)}{d\lambda_1} \text{ and } J_p'(\lambda_2) = \frac{dJ_p(\lambda_2)}{d\lambda_2} \]

The Bessel function arguments are defined as

\[
\lambda_1 = \frac{k_\perp P_\perp}{\omega_c m_e}, \quad \lambda_2 = \frac{k_\perp \Gamma_x}{\lambda} \left\{ \frac{(\omega_c)}{\lambda} \right\}^2 - v^2 \quad \text{and} \quad \lambda_3 = \frac{k_\perp u \Gamma_s}{\lambda} \left\{ \frac{(\omega_c)}{\lambda} \right\}^2 - v^2
\]

Substituting the values in eq. (7.1), the resulting dispersion relation for oblique propagating electron-cyclotron waves is approximated as:

\[
\varepsilon_{11} \pm \varepsilon_{12} = N^2 \cos^2 \theta
\] 

Hence the following dispersion relation is obtained from eq. (7.3) for relativistic case with perpendicular AC electric field for g= 0, p = 1, n = 1 is written as:

\[
\frac{k^2 c^2 \cos^2 \theta}{\omega^2} = 1 + 4 \pi c^2 \int \frac{dP}{\gamma} \left[ P_\perp \left( \frac{u \Gamma_s m_e}{2 (\omega_c^2 - v^2)} \right) \left( \frac{k_\perp P_\perp}{\lambda m_e} \right)^2 \left( \frac{k_\perp P_\perp}{\lambda m_e} \right) \left( \frac{\partial f_0}{\partial P_\perp} \right) \right] \frac{1}{\lambda \omega - k_\perp P_\perp \omega - \omega_\alpha + \lambda \nu}
\]

Now, we apply the approximation for electron-cyclotron range of frequencies. Ion temperature are assumed isotropic with T_{i\perp} = T = T_i and magnetized with |\omega_c + i\gamma| << \omega_\alpha and |k_\parallel \omega | << |\omega_c, \omega_\alpha i \gamma|. EMEC instability driven by more perpendicular electron kinetic energy, T_{i\perp} > T_{i\parallel e} is considered in present investigation [Davidson, 1983].
The Lorentzian Kappa distribution function to be applied in case of electron-cyclotron waves is written as:

\[
f_\omega = \frac{n_o}{\pi^{3/2}P_{0i} P_{fi} \kappa^{3/2}} \frac{\Gamma(\kappa + 1)}{\Gamma(\kappa + 1/2)} \left[ 1 + \frac{P_{f}^2}{\kappa P_{di}} + \frac{P_{f}^2}{\kappa P_{di}} \right]^{-\kappa+1/2} ...
\]

(7.5)

And associated parallel and perpendicular effective thermal speeds are

\[
P_{0i} = \left[ \frac{2\kappa - \frac{3}{2}}{\kappa} \right]^{1/2} \left( \frac{T_{\perp}}{m_i} \right)^{1/2}, \hspace{1cm} P_{0i} = \left[ \frac{2\kappa - \frac{3}{2}}{\kappa} \right]^{1/2} \left( \frac{T_{\parallel}}{m_i} \right)^{1/2}
\]

Using equation (7.5), equation (7.4) becomes:

\[
D(k, \omega_i + i\gamma) = 1 - \frac{k^2 c^2}{\omega_i + i\gamma} + \sum J_p (\lambda_c) J_q (\varphi_c) \left\{ \frac{\omega_i^2}{\omega_{ce}^2} - \frac{\omega_p^2}{\omega_{pe}^2} \right\} \left\{ X_{1i} \left( \frac{\omega_{pe}^2}{\omega_{ce}^2} \right) \right\} \times
\]

\[
\times \frac{\omega_i + i\gamma}{\kappa_0 \theta_i} \left[ \frac{2\kappa - \frac{3}{2}}{\kappa} \right]^{1/2} \left( \frac{\omega_i}{\kappa - 3/2} \right) Z_{k-1} \left[ \frac{\omega_i}{\kappa - 1} \right]^{1/2} \xi_i \left[ 1 + \xi_i \left[ \frac{\omega_i}{\kappa - 1} \right]^{1/2} Z_{k-1} \left[ \frac{\omega_i}{\kappa - 3/2} \right] \xi_i \right] \right]
\]

(7.6)

Where

\[
X_{1i} = \frac{P_{0i}^2}{P_{0i}^2} - \frac{\nu \lambda m_i \Gamma_{xi}}{\lambda \left( \frac{\omega_{ce}^2}{\lambda^2} - \nu^2 \right)} \frac{P_{0i}^2}{P_{0i}^2} \sqrt{\pi}
\]

\[
X_{1e} = \frac{P_{0e}^2}{P_{0e}^2} - \frac{\nu \lambda m_i \Gamma_{xe}}{\lambda \left( \frac{\omega_{ce}^2}{\lambda^2} - \nu^2 \right)} \frac{P_{0i}^2}{P_{0i}^2} \sqrt{\pi}
\]

\[
A_T = \frac{P_{0i}^2}{P_{0e}^2} - 1
\]

Plasma dispersion function \(Z_{k-1}\) and its derivative are the one used by Hellberg and Mace [2002] and Summers and Thorne [1991].

Applying condition \(\frac{k^2 c^2}{\omega^2} >> 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2}\) with p=1, n=1 and q=0 we can get the growth rate and real frequency using

\[
K_4 = \frac{X_4}{1 - X_4 + \lambda X_4}, \hspace{1cm} K = \frac{K_4 P_{DL}}{\omega_{cs}}, \hspace{1cm} \beta = \frac{K_4 T_{D} \mu_o n_o}{B_0} \Gamma_{xi} = \frac{eE_i}{m_i}, \hspace{1cm} X_i = \frac{\lambda \omega}{\omega_{ce}}
\]

The growth rate and real frequency are given in dimensionless form as:
\[
\gamma = \frac{\sqrt{\pi}}{k \cos \theta} \left( \frac{(\kappa - 1) \kappa^{-1/2}}{(\kappa - 3/2) \kappa} \right) (A_T - K_i) K_i^3 \left\{ - \left( \frac{K_i}{k \cos \theta} \right) \right\}^{-2e}
\]

\[
\omega_{ce} = \frac{1 + X_4}{1 + X_4} + \frac{k \cos \theta}{k - 3/2} \left( \frac{1 + X_4}{2K_i^2} + \frac{k^2 (A_T - K_i)}{K_i} \right) - \frac{X_{1e} X_i}{X_{1i}} K_i^2
\]  

\[
X_i = \frac{\omega_{ce}}{\omega_{ce}} = \frac{k^2 \cos^2 \theta}{\beta} \left[ \frac{X_{1e} (1 + X_4)}{X_{1e} - X_{1i} (1 + X_4)} + \frac{A_T \beta X_{1e}}{2(1 + X_4) (X_{1e} - X_{1i} (1 + X_4))} \right]
\]

\[\cdots(7.7)\]

\[\cdots(7.8)\]

7.3. Result and Discussions

7.3.1. EMEC waves in magnetosphere of Saturn

To investigate the magnetosphere of Saturn, we consider the most recent measurements made by Cassini spacecraft [Gurnett et al. 2005]. As the radial distance changes from 3.5 R_s to 10 R_s, the density of electrons is observed to vary from 200 to 0.50 cm\(^{-3}\). And also thermal energy of electrons ranges from 40 to 360 eV. The magnitude of magnetic and electric field has been taken as 36 nT and 0.01mV/m respectively at 8 R_s [Gurnett et al. 2005]. Therefore, we calculated the growth rate by substituting the parameters observed at 8 R_s with electron density of 0.75 cm\(^{-3}\). At this radial distance, we take 300 eV as thermal energy of electrons (\(K_B T_{\perp e}\)) and 100 eV as thermal energy of ions (\(K_B T_{\perp i}\)) so that investigation can be made with considerable ratio of \(T_{\perp e}/T_{\perp i}\) greater than 1, suitable for study of EMEC waves. **Figure 7.1** shows the variation of dimensionless growth rate with respect to wave number (\(\tilde{k}\)) for different values of \(T_{\perp e}/T_{\perp i}\). Since \(T_{\perp e}/T_{\perp i} - 1 = \kappa_T\), the magnitude of growth rate is .0157, 0.0235 and 0.0638 for temperature anisotropy (\(\kappa_T\)) 0.25, 0.5 and 0.75 respectively. The graph displays how significantly EMEC waves grow when temperature anisotropy increases with other parameters fixed. Lazar et al. [2013] performed the refined analysis of electron – whistler cyclotron instability with electron temperature anisotropy in plasma far from Maxwellian equilibrium for bi-kappa distribution. The derived solutions provided accurate correlation between maximum growth rate and threshold conditions. Referring to the conclusions drawn by them, it can be inferred that lowest thresholds of temperature anisotropy decreases with increase in density of suprathermal electrons. In **figure 7.2**, the variation of AC field leads to changes in plasma properties thus varying the resultant growth rate. The magnitude of AC
frequency has been taken well below the calculated gyro frequency of EMEC waves. The magnitude of growth rate varies from 0.0235 to 0.0379 as AC frequency increases from 1 kHz to 2 kHz. The relativistic factor plays a crucial role in damping of EMEC waves in magnetospheric plasma. In, figure 7.3 with increasing value of relativistic factor as $\lambda = 0.5, 0.6$ and $0.7$, damping of electron-cyclotron waves is shown as $\gamma/\omega_c = 0.0235, 0.0105$ and $0.0057$ respectively. This can be explained mathematically referring to expression of $\lambda$. The increase in relativistic factor implies decrease in value of velocity of charged electrons. So as $\lambda$ increases the decrease in growth rate can be seen. Therefore, it can be concluded that for non-relativistic case, the growth of EMEC waves will be less than in present case of relativistic study of EMEC waves. Figure 7.4 shows the variation of propagation angle ($\theta$) with respect to wave number for other parameters fixed. It is clearly seen that growth rate increases from 0.0295 to 0.0732 for $\theta$ ranging from $5^\circ$ to $20^\circ$. Results can be compared with those of dispersion relation and growth rate calculated done by Ahirwar [2013] for parallel propagating EMIC waves in Saturn’s magnetosphere.

### 7.3.2 EMEC waves in magnetosphere of Jupiter

We now discuss the variation in growth rate of EMEC waves for magnetosphere of Jupiter at $L=17$ R$_J$. The plasma parameters were provided by Voyager’s encounter with planet [Bagenal 1994]. After thorough literature survey and depending on the availability of data, the dispersion relation has been found at radial distance 17 R$_J$. At this distance from the planet, number density and thermal energy of electrons were reported as $3.0 \text{ cm}^{-3}$ and $1000 \text{ eV (} K_B T_e \text{)}$ respectively [Bagenal et al., 1997]. According to discussions made by Clark [1987], the approximate magnitudes are taken to be 0.1 mV/m and 51 nT. With $K_B T_i$ as 100 eV, we deal with suitable $T_e/T_i$ more than 1. The sensitivity of results to the temperature anisotropy is considered in figure 7.5. For $A_T=0.25$, peak value is 0.0566, when $A_T$ increases to $0.5$, maximum peak of 0.1484 is observed at $\vec{k} = 0.3$. And as $A_T$ becomes $0.75$, phenomenal increase in maximum growth rate 0.7738 is shown in the graph. Figure 7.6 shows the variation of growth rate for different values of AC frequency with respect to wave number ($\vec{k}$). As AC frequency increases from 1.5 kHz to 2.5 kHz, magnitude of growth rate increases from 0.1167 to 0.1961. Therefore, it is inferred
that temperature anisotropy serves as a free source of energy. The work has been done for magnetosphere of Jupiter and Saturn, when polarization electric field occurs, even in the absence of electric currents. The study of plasma equilibrium has also been done by varying influential parameters like plasma anisotropy and temperature of all species [Maurice et al. 1997]. In figure 7.7, similar behaviour of relativistic factor is shown. Growth rate becomes 0.1484, 0.0324 and 0.0156 for relativistic factor = 0.5, 0.6 and 0.7 respectively. So, it can be seen as the value of relativistic factor increases, growth rate decreases. The relativistic effects on dispersion and Landau damping of Langmuir waves in a relativistic Kappa-distributed plasma have been studied by Podesta [2008]. Results were found to be a good match for the electron velocities with the phase speed of weakly damped plasma waves, thus providing a plausible mechanism for their acceleration. Oblique propagation of EMEC waves at various values of angle of propagation (θ) is calculated and graph has been plotted in figure 7.8. The maximum peak value increases in each case as 0.1484, 0.1912 and 0.3239 for θ = 10°, 15° and 20° respectively. Shklyar and Matsumoto [2009] presented an account of resonant interaction between obliquely propagating waves and energetic charged particles. The work has also discussed two important applications of this theory. One of them being calculating growth (or damping) rate of obliquely propagating waves, just as we have presented in this chapter, and other one to investigate proton precipitation into upper atmosphere.

7.3.3 EMEC waves in magnetosphere of Uranus

To investigate the growth rate of EMEC waves in magnetosphere of Uranus, we consider parameters at 11 R_U. The analysis have been performed with 0.01 mV/m and 11 nT field magnitudes [Hudson, 1989]. At 11 R_U, \( K_n T_{ei} \) is 1500 eV and \( K_n T_{ji} \) has been considered of the order of 100 eV [Pandey et al. 2003] with electron density as 0.05 cm\(^{-3}\). Figure 7.9 shows the variation of growth rate at different temperature anisotropies. For \( \delta_T = 0.25, 0.5 \) and 0.75 growth rate varies as 0.0024, 0.0036 and 0.0054 respectively. Recently, work done by Pandey et al. [2014] shows comparable results where non-relativistic EMEC waves were analyzed for terrestrial magnetosphere. In figure 7.10, we can see different values of growth rate at different frequencies. As AC frequency increases from 200Hz to 800 Hz, growth rate increases from 0.0027 to 0.0051. Importance of variation of AC frequency has been discussed
by Pandey et al. [2013] for bi-subtracted Maxwellian plasma and can be applied in present case too. Figure 7.11 shows the effect of relativistic factor on the growth rate of EMEC waves in magnetosphere of Uranus. The damping of waves is clearly shown in graph with growth rate decreasing from 0.0036 to 0.0011 as relativistic factor increases from 0.5 to 0.7 respectively. The comparative study of relativistic and non-relativistic whistler waves can be referred [Pandey and Kaur 2012]. The value of propagation angle varies as 10°, 15° and 20° in figure 7.12. The maxima occuring at $\tilde{k} = 0.2$, increases as 0.0036, 0.0041 and 0.0049 for above mentioned values respectively. Whether EMEC wave grows or damps is produced depends on many factors including the density, energy, and temperature anisotropy of the energetic electrons, as well as the ambient cold plasma density and ion composition. In similar phenomena for dominating ions, the work was done by Hu and Fraser, [1994] explaining growth and damping of EMIC waves. They concluded that generation and propagation of EMIC waves depends strongly on the characteristics of both cold and energetic ions in the magnetospheric plasmas.

7.4. Conclusion

In this chapter, oblique relativistic electron-cyclotron waves are analyzed in presence of external AC field in the magnetosphere of Jupiter, Saturn and Uranus. The expression for dispersion relation, real frequency and growth rate is evaluated using Kappa distribution function, following linear kinetic approach. Analyzing the effect of temperature anisotropy, AC electric field and angle of propagation of relativistic EMEC waves at different radial distances, it is concluded that these parameters support the growth of waves. Though there exist huge differences in origin, form and contents of the planetary magnetospheres [Bagenal 1992], the magnetosphere of Jupiter, Saturn and Uranus exhibit similar behavior of EMEC waves with temperature anisotropy in presence of AC field. While studying EMEC waves in magnetosphere of Saturn, it is inferred that growth rate attains maxima when angle of propagation increases, and for Jupiter and Uranus maximum magnitude of growth rate is achieved when temperature anisotropy increases. Increase in growth rate with increasing angle of propagation implies that electrostatic component of the propagating wave is stronger than the electromagnetic component. Literature explains that as the propagation angle exceeds 40°, the electrostatic component starts
dominating the wave nature [Pandey et al. 2012]. As seen in case of Saturn, the most possible reason for increase in growth rate for higher value of θ can be either the reversed polarization [Misra and Pandey 2002] or the dominating presence of electrostatic electron-cyclotron waves in spectrum observed in Saturn’s magnetosphere [Kurth et al. 1983; Barbosa and Kurth 1993; Gurnett et al. 1981]. Whereas, temperature anisotropy remains the main parameter effecting the wave growth in magnetosphere of Jupiter and Uranus.

Since the presence of different drifting ion species affect cold plasma dispersion relation and growth rate [Gomberoff and Neira 1983; Gomberoff et al. 1996], therefore the work provides the basic model which is appropriate for application to space plasma environments and various magnetospheric regimes for detailed study of cyclotron waves with more dominant and energetic charged particles than electrons.
Fig. 7.1: Variation of Growth Rate with respect to \( \tilde{k} \) for various values of \( T_\perp/T_i \) at \( \nu = 1.5 \) kHz, \( \theta = 10^\circ \), \( \lambda = 0.5 \), \( \kappa = 2 \) and other fixed plasma parameters at 8 Rs.

Fig. 7.2: Variation of Growth Rate with respect to \( \tilde{k} \) for various values of AC Frequency (\( \nu \)) at \( T_\perp/T_i = 1.5 \), \( \theta = 10^\circ \), \( \lambda = 0.5 \), \( \kappa = 2 \) and other fixed plasma parameters at 8 Rs.
Fig. 7.3: Variation of Growth Rate with respect to $\tilde{k}$ for various values of Relativistic Factor ($\lambda$) at $v=1.5$ kHz, $T_{i}/T_{e}=1.5$, $\theta=10^\circ$, $\kappa=2$ and other fixed plasma parameters at $8 R_s$.

Fig. 7.4: Variation of Growth Rate with respect to $\tilde{k}$ for various values of Propagation Angle ($\theta$) at $\lambda=0.5$, $v=1.5$ kHz, $T_{i}/T_{e}=1.5$, $\kappa=2$ and other fixed plasma parameters at $8 R_s$. 
Fig. 7.5: Variation of Growth Rate with respect to $\vec{k}$ for various values of $T_{\perp}/T_{\parallel}$ at $\nu = 2 \text{ kHz}$, $\theta = 10^\circ$, $\lambda = 0.5$, $\kappa = 2$ and other fixed plasma parameters at 17 $R_J$.

Fig. 7.6: Variation of Growth Rate with respect to $\vec{k}$ for various values of AC Frequency ($\nu$) at $T_{\perp}/T_{\parallel} = 1.5$, $\theta = 10^\circ$, $\lambda = 0.5$, $\kappa = 2$ and other fixed plasma parameters at 17 $R_J$. 
Fig. 7.7: Variation of Growth Rate with respect to \( \tilde{k} \) for various values of Relativistic Factor (\( \lambda \)) at \( \nu = 2 \text{ kHz} \), \( T_{\perp}/T_i = 1.5 \), \( \theta = 10^\circ \), \( \kappa = 2 \) and other fixed plasma parameters at 17 R_J.

Fig. 7.8: Variation of Growth Rate with respect to \( \tilde{k} \) for various values of Propagation Angle (\( \theta \)) at \( \lambda = 0.5 \), \( \nu = 2 \text{ kHz} \), \( T_{\perp}/T_i = 1.5 \), \( \kappa = 2 \) and other fixed plasma parameters at 17 R_J.
Fig. 7.9: Variation of Growth Rate with respect to $\tilde{k}$ for various values of $T_\perp/T_\parallel$ at $\nu = 500$ Hz, $\theta = 10^\circ$, $\lambda = 0.5$, $\kappa = 2$ and other fixed plasma parameters at 11 $R_U$.

Fig. 7.10: Variation of Growth Rate with respect to $\tilde{k}$ for various values of AC Frequency ($\nu$) at $T_\perp/T_\parallel = 1.5$, $\theta = 10^\circ$, $\lambda = 0.5$, $\kappa = 2$ and other fixed plasma parameters at 11 $R_U$. 
Fig. 7.11: Variation of Growth Rate with respect to $\tilde{k}$ for various values of Relativistic Factor ($\lambda$) at $\nu = 500$ Hz, $T_{\perp}/T_i = 1.5$, $\theta = 10^\circ$, $\kappa = 2$ and other fixed plasma parameters at $11 R_U$.

Fig. 7.12: Variation of Growth Rate with respect to $\tilde{k}$ for various values of Propagation Angle ($\theta$) at $\lambda = 0.5$, $\nu = 500$ Hz, $T_{\perp}/T_i = 1.5$, $\kappa = 2$ and other fixed parameters at $11 R_U$. 