Observational and Theoretical Study of Lower Hybrid Drift Waves

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Abstract: One of the most important diamagnetic current driven instability transverse to the magnetic field is lower hybrid drift instability (LHDI) which excites lower hybrid drift waves (LHDW). LHDI gives rise to anomalous resistivity which further leads to onset of magnetic reconnection. Because of its high anomalous collision frequency, LHDI enhances the rate of transverse diffusion. The lower hybrid frequency (LHF) ranges between electron and ion cyclotron frequency which is a natural resonance. LHDW is generally observed in transition layer regions and magnetic reconnection sites, where the gradient in density occurs. We are presenting electromagnetic kinetic model including gradients in density and magnetic field, finite parallel wavenumber and non-thermal particle distribution function or kappa velocity distribution function. The effect of the aforementioned factors on the growth rate of LHDI in different plasma beta circumstances has been thoroughly investigated and will be discussed. Space observation of drift driven wave using MMS spacecraft will also be discussed

01 DISPERSION EQUATION

Governing equations

- Vlasov equation:

$$\frac{\partial f_s}{\partial t} + \boldsymbol{v}_s.\nabla f_s + \frac{q_s}{m_s}\left[\boldsymbol{E} + \frac{\boldsymbol{v}_s}{c}\times \boldsymbol{B}\right].\nabla_v f_s = 0$$

$$f_s = f_{0s}(\boldsymbol{v}) + \delta f_{1s},\ (\delta f_{1s} \ll f_{0s})$$

is the velocity distribution function

- Maxwell's equations:

$$\nabla.\boldsymbol{E} = 4\pi\rho$$
$$\nabla.\boldsymbol{B} = 0$$
$$\nabla\times\boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}$$
$$\nabla\times\boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{J} + \frac{1}{c}\frac{\partial \boldsymbol{E}}{\partial t}$$

- Perturbed charge and current density:

$$\delta\rho = \sum_s e_s \int \boldsymbol{d^3v}\,\delta f_s \quad and \quad \boldsymbol{\delta J} = \sum_s e_s \int \boldsymbol{d^3v}\,\boldsymbol{v}\,\delta f_s$$

Methodology

Basic equations + unperturbed distribution function
↓
Linearization (higher order quantities are neglected)
↓
Fourier Transform (x → k, t → ω)
↓
obtained charge and current density
↓
Solve Maxwell equations
↓

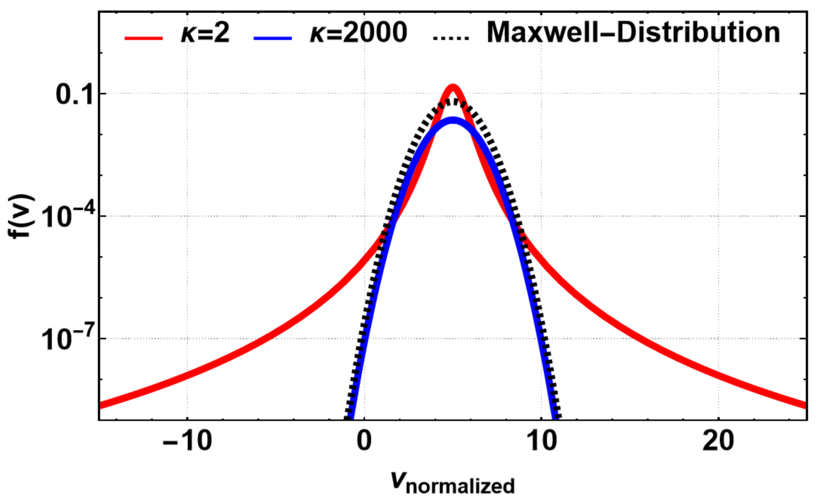
$$D_{ij} = \det\left[\delta_{ij} + \chi^{el}_{ij}(k,\omega) + \chi^{ion}_{ij}(k,\omega) - \frac{c^2k^2}{\omega^2}\left(\delta_{ij} - \frac{k_ik_j}{k^2}\right)\right] = 0$$

Distribution Function

$$f_s(v) = \frac{n}{(\pi\,\theta_s^2\,\kappa)^{\frac{3}{2}}}\frac{\Gamma(\kappa+1)}{\Gamma\left(\kappa-\frac{1}{2}\right)}\left(1 + \frac{v_x^2 + (v_y - V_{D,s})^2 + v_z^2}{\kappa\,\theta_s^2}\right)^{-(\kappa+1)}$$

$$v_{D,s} = -\frac{\nabla p\times B}{qnB^2}, \qquad \theta_s = \sqrt{\frac{2\kappa-3}{\kappa}}\sqrt{\frac{T_s}{m_s}},$$

$$s = ions, electrons \quad and \quad \kappa > \frac{3}{2}$$



Dispersion Elements

$$D_{xx} = \frac{k^2c^2}{\omega_{pe}^2} - \frac{\frac{m_e}{m_i}\left(1-\frac{1}{2\kappa}\right)\xi_{i1}Z_{\kappa-1}(\xi_{i1})}{\left(1-\frac{3}{2\kappa}\right)}$$

$$D_{xy} = -D_{yx} = i\frac{\omega}{\omega_{ce}}\left(1+\frac{1}{\kappa}\right)^{-1}$$

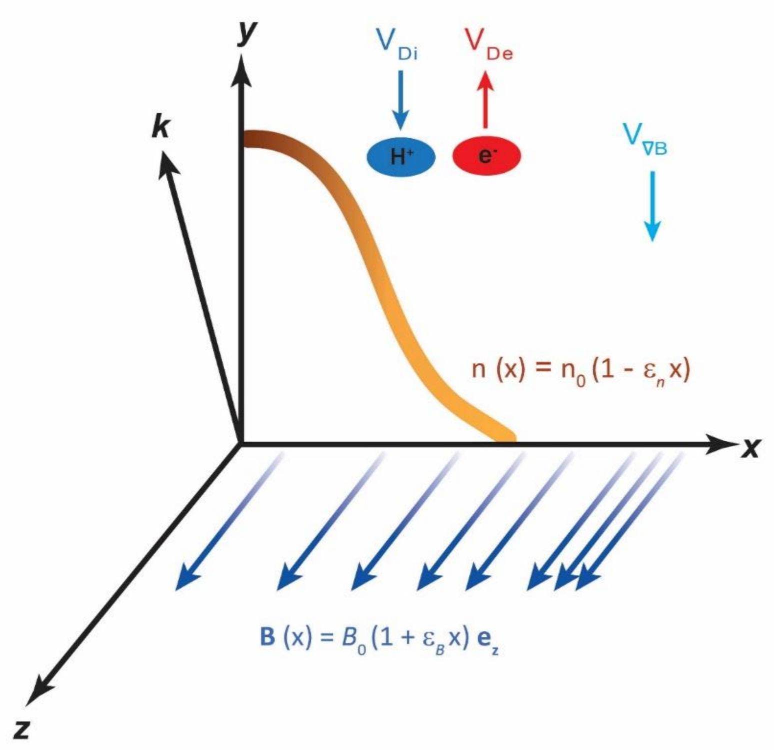
$$D_{yy} = \frac{\omega^2}{\omega_{LH}^2}\left[\frac{\left(1-\frac{1}{2\kappa}\right)\left(1+\frac{1}{\kappa}\right)}{\left(1+\frac{1}{2\kappa}\right)} + \frac{\omega_{ce}^2}{\omega_{pe}^2}\right] + \left[\left(1+\frac{1}{\kappa}\right)^{-1} + \frac{2}{\beta_i}\right]\frac{\omega}{k_yV_A}\frac{V_{di}}{V_A} - \frac{m_i}{m_e}\frac{k_z^2c^2}{\omega_{pe}^2} + \frac{k_z^2}{k^2}\xi_{i1}Z_{\kappa-1}(\xi_{i1})\frac{\left(1-\frac{1}{2\kappa}\right)}{\left(1-\frac{3}{2\kappa}\right)} + \left[\left(1-\frac{1}{2\kappa}\right) + \xi_iZ_\kappa(\xi_i)\right]$$

$$D_{yz} = D_{zy} = \frac{m_e}{m_i}\frac{k_z}{k}\xi_i\left\{2\left(-\frac{k_y}{k}\xi_i + \frac{V_{di}}{\theta_i}\right)\left[\left(1-\frac{1}{2\kappa}\right) + \xi_iZ_\kappa(\xi_i)\right] + \frac{k_y}{k}\frac{\xi_{i1}}{\xi_i}Z_{\kappa-1}(\xi_{i1})\frac{\left(1-\frac{1}{2\kappa}\right)}{\left(1-\frac{3}{2\kappa}\right)}\right\} + \frac{k_yk_zc^2}{\omega_{pe}^2}$$

$$D_{zz} = \frac{k_y^2c^2}{\omega_{pe}^2} - \frac{m_e}{m_i}\xi_i\left\{2\frac{k_z^2}{k^2}\xi_i\left[\left(1-\frac{1}{2\kappa}\right) + \xi_iZ_\kappa(\xi_i)\right] + \frac{k_y^2}{k^2}\frac{\xi_{i1}}{\xi_i}Z_{\kappa-1}(\xi_{i1})\frac{\left(1-\frac{1}{2\kappa}\right)}{\left(1-\frac{3}{2\kappa}\right)}\right\}$$

02 Plasma Model

- Linear kinetic treatment for the collisionless, two-component plasma consisting of electrons and ions.
- Gradient and magnetic field gradient and magnetic field directions shown in the figure.



03 NUMERICAL RESULTS

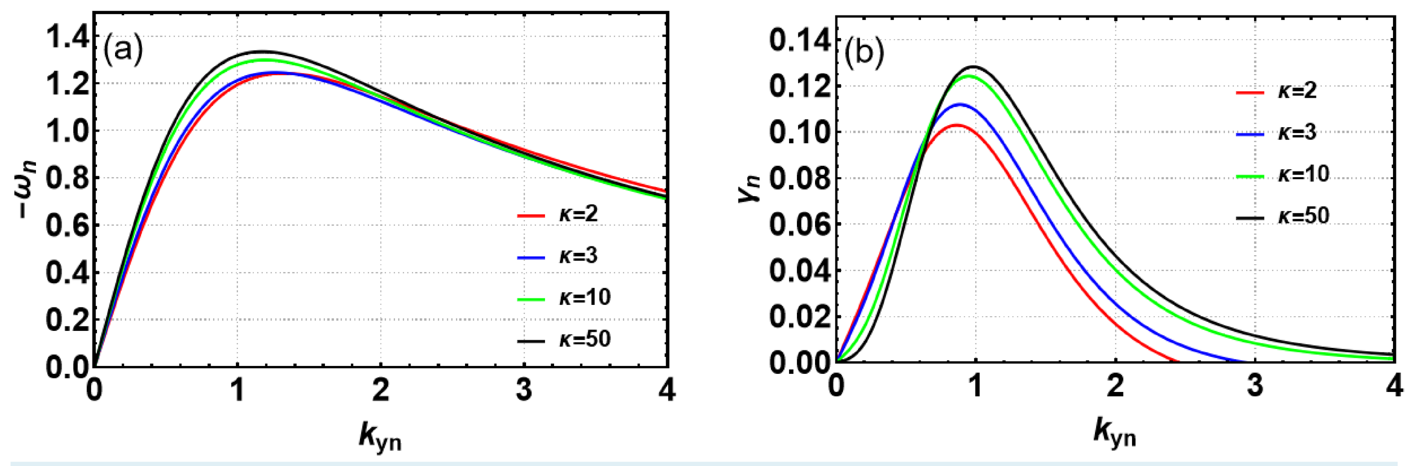


Fig1: Non-thermal electrons and ions $\omega_n \uparrow as\ \kappa \uparrow$ $\gamma_n \uparrow as\ \kappa \uparrow$

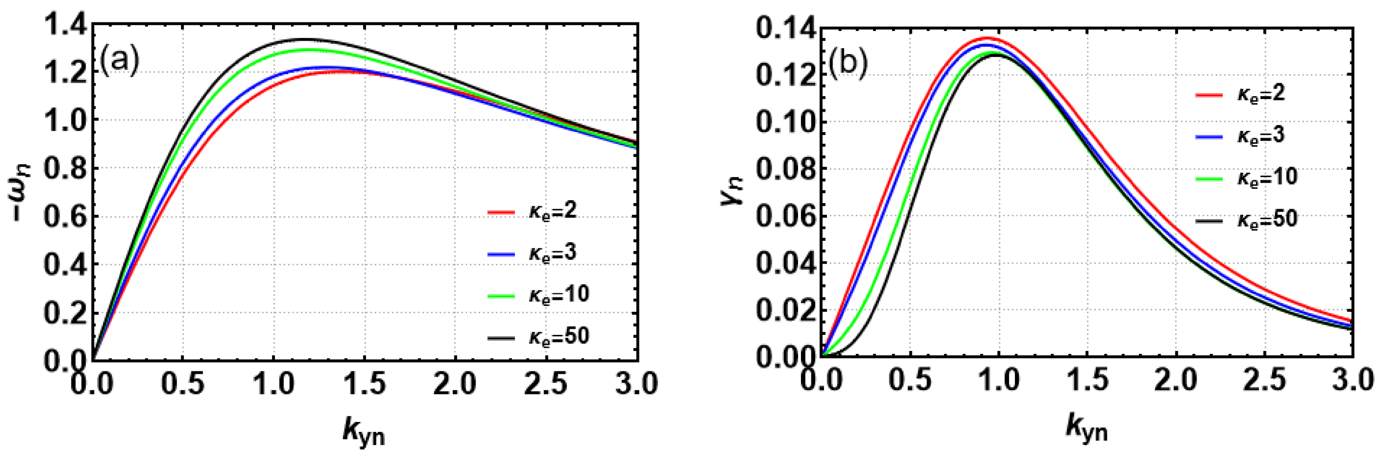


Fig2: Non-thermal electrons and thermal ions $\omega_n \uparrow as\ \kappa_e \uparrow$ $\gamma_n \uparrow as\ \kappa_e \downarrow$

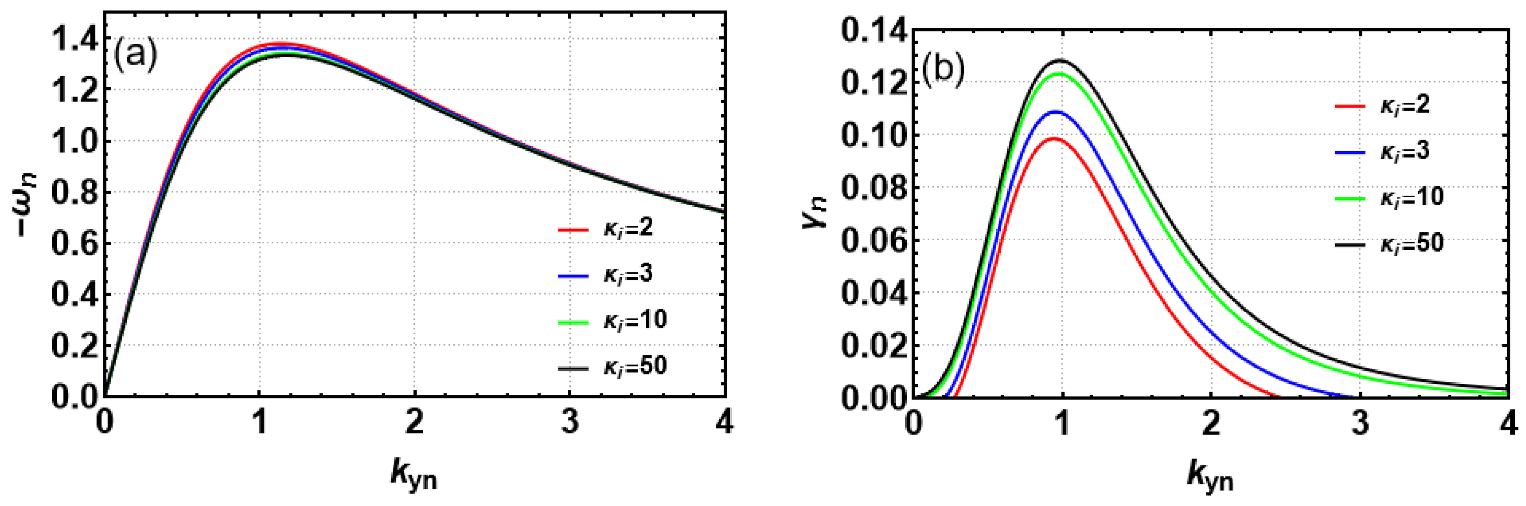


Fig3: Thermal electrons and non-thermal ions $\omega_n \uparrow as\ \kappa_i \downarrow$ $\gamma_n \uparrow as\ \kappa_i \uparrow$

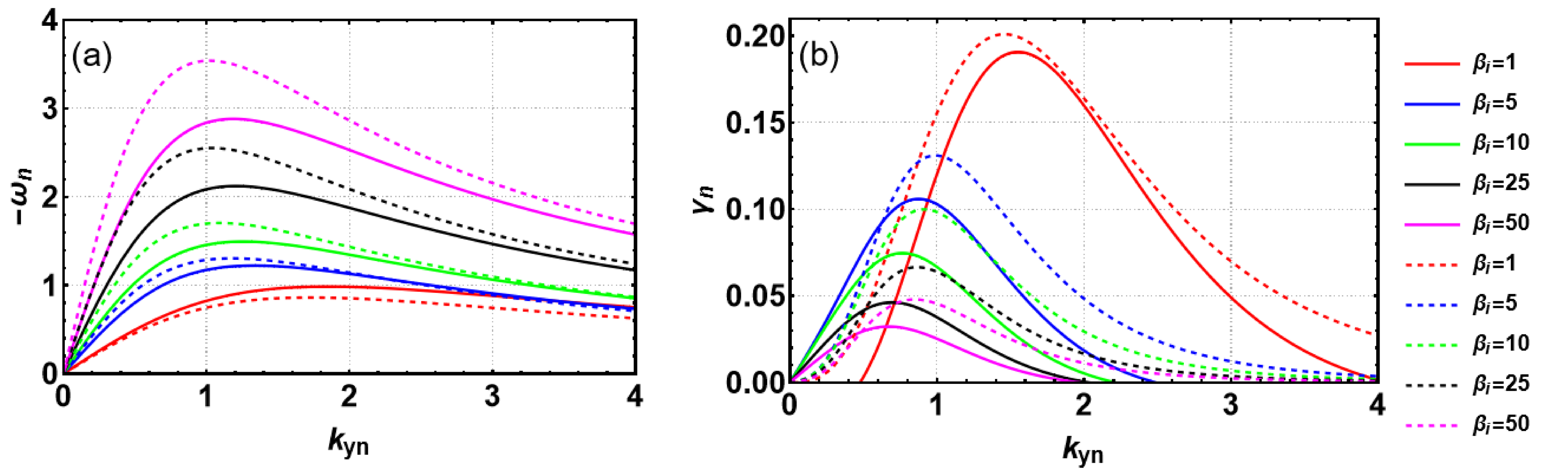
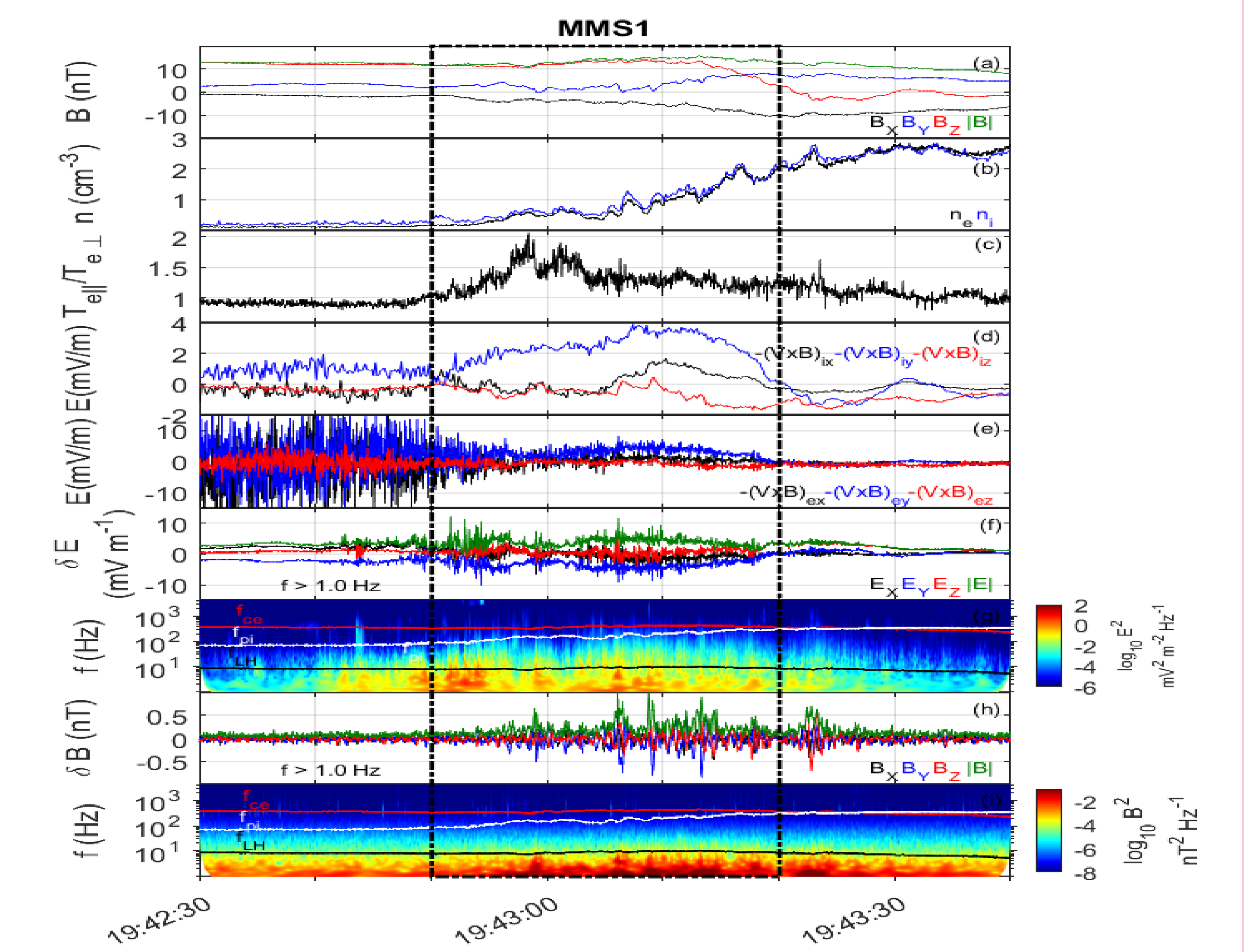


Fig4: Effect of β_i on thermal (dash lines) and nonthermal plasma population (solid lines) : $\omega_n \uparrow as\ \beta_i \uparrow$ $\gamma_n \uparrow as\ \beta_i \downarrow$

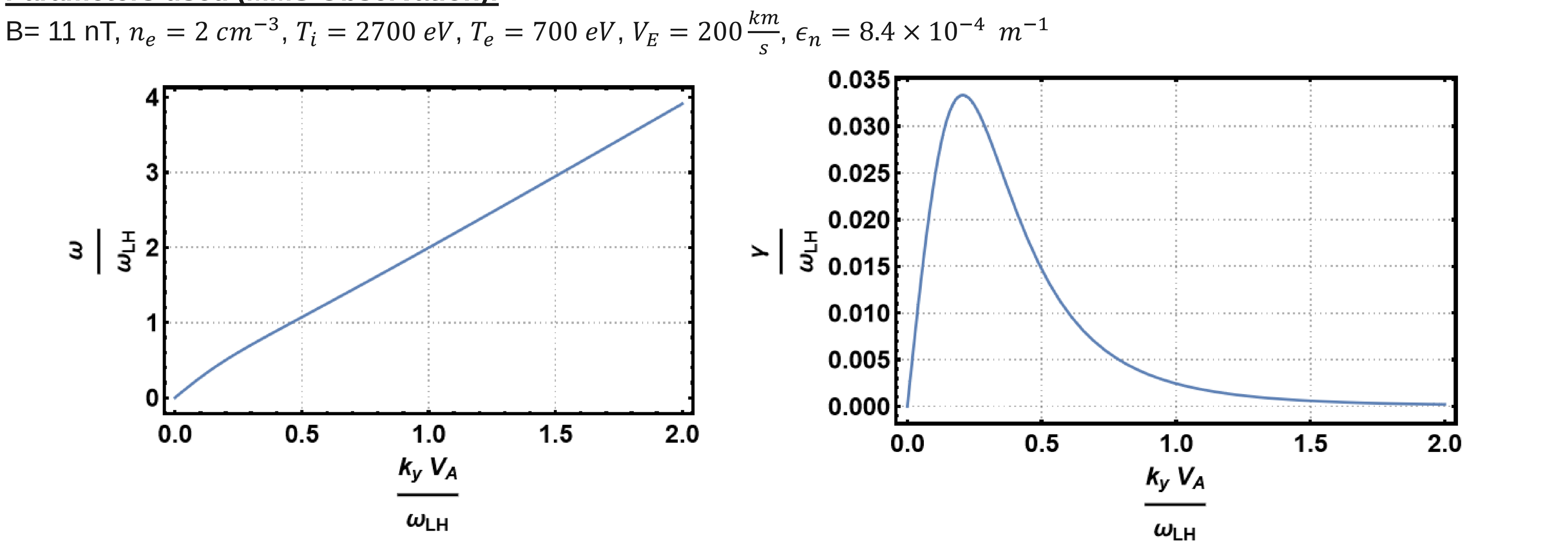
04 Observations of LHDW



05 Instability analysis of LHDI

Parameters used (MMS Observation):

B= 11 nT, $n_e = 2\ cm^{-3}$, $T_i = 2700\ eV$, $T_e = 700\ eV$, $V_E = 200\ \frac{km}{s}$, $\epsilon_n = 8.4\times10^{-4}\ m^{-1}$



06 Conclusions

Effect of nonthermal electrons and ions on LHDI: The maximum growth rate of the LHDI increases with the increases in κ index as shown in Fig1 and similarly the normalized negative maximum real frequency gradually increases with an increase of κ index

Effect of nonthermal electrons and thermal ions on LHDI: The maximum growth rate of the LHDI increases with the decrease in κ_e index as shown in Fig2 and normalized negative maximum real frequency gradually increases with an increase of κ index.

Effect of thermal electrons and nonthermal ions on LHDI:

γ(nonthermal electrons and thermal ions) $> \gamma$(thermal electrons and ions) $> \gamma$(nonthermal electrons and ions) $> \gamma$(thermal electrons and nonthermal ions)

Effect of ion plasma beta, β_i, on LHDI: The effect of ion beta on the LHDI growth rate is compared between nonthermal and thermal plasma distribution cases, it is found that the ion beta in presence of more nonthermal plasma population suppresses more growth rate than the case of thermal plasma as shown in Fig4.

Observation and Instability analysis of Lower hybrid waves:

- Lower hybrid drift waves are observed in the magnetopause region in the Earth's magnetosphere. The MMS was traversing from magnetosphere to magnetosheath.
- The presence of density gradient in the electron and ions gives rise to LHDI that can be seen in the section of Instability analysis using equation mentioned in *Davidson et. al., 1975*. This implies the generation mechanism of LH waves is LHDI.

Density gradient → **Lower Hybrid Drift Instability** → **Lower Hybrid Waves**