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# SELF HEATING OF CORONA BY SHEARED FLOW-DRIVEN ELECTROSTATIC INSTABLITIES

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# SELF HEATING OF CORONA BY SHEARED FLOW-DRIVEN ELECTROSTATIC INSTABLITIES


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# Layout:-

1. Introduction
2. Wave Heating Models
3. Drift Wave as a Heating Mechanism
4. Sheared Flow as a Heating Mechanism
5. Present Mathematical Model
6. Application to Solar Corona
7. Role of Collisions in Corona
8. Summary

# 1. INTRODUCTION:

(a) Regions of Sun:

i. Interior: Core; Radiative Zone; Convection Zone

ii. Outer Atmosphere: Photosphere; Chromosphere; Corona (Boundaries are not well-defined).

The density $n$ decreases rapidly with height above solar surface,

| | |
|---|---|
| | $10^{23} m^{-3}$ photosphere |
| | $10^{15} m^{-3}$ transition region |
| $n \approx$ | $10^{12} m^{-3}$ at height of 1 $R_\odot$ (From Surface) |
| | $10^{7} m^{-3}$ at 1 AU |
| | $10^{6} m^{-3}$ in interstellar medium |

Air density at Earth's Surface $\simeq 10^{25}$particles$/m^3 = 10^{19} cm^{-3}$.
Electron density $n_e \simeq 10^{14} m^{-3}$ in inner corona but falls rapidly with distance.
AU = Astronomical Unit = $1.5 \times 10^{11}$ m = $1.5 \times 10^{8} km$
Light takes to travel 1 AU $\simeq$ 8 minutes

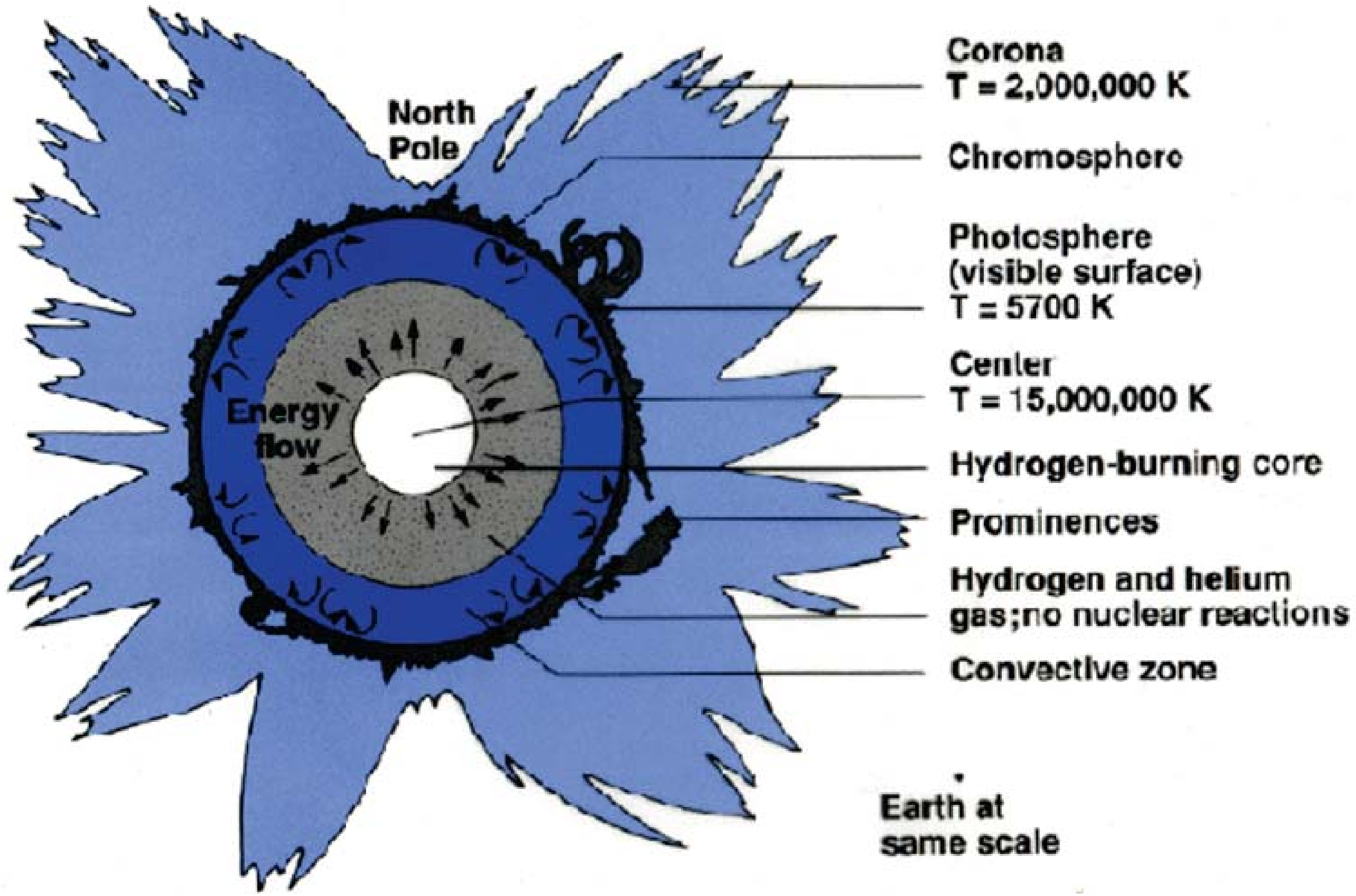

North
Pole
Energy
flow
Corona
T = 2,000,000 K
Chromosphere
Photosphere
(visible surface)
T = 5700 K
Center
T = 15,000,000 K
Hydrogen-burning core
Prominences
Hydrogen and helium
gas;no nuclear reactions
Convective zone
Earth at
same scale

**Figure 1.1**

## Problem:-

Chromosphere $T \sim (10^4)$K

Transition Layer $\sim 500km$

Corona (fully ionized H) plasma $T \sim 2,000,000\ {}^0K$ So corona is about 200 times hotter than chromosphere (counter intuitive).

**Major question of solar physics:**

**How T increases tremendously within a layer of 500 km.**

Then T decreases slowly in outer Corona with increasing distance.

At distance 1 AU away from Sun, Solar Wind $T \simeq 10^5\ K$

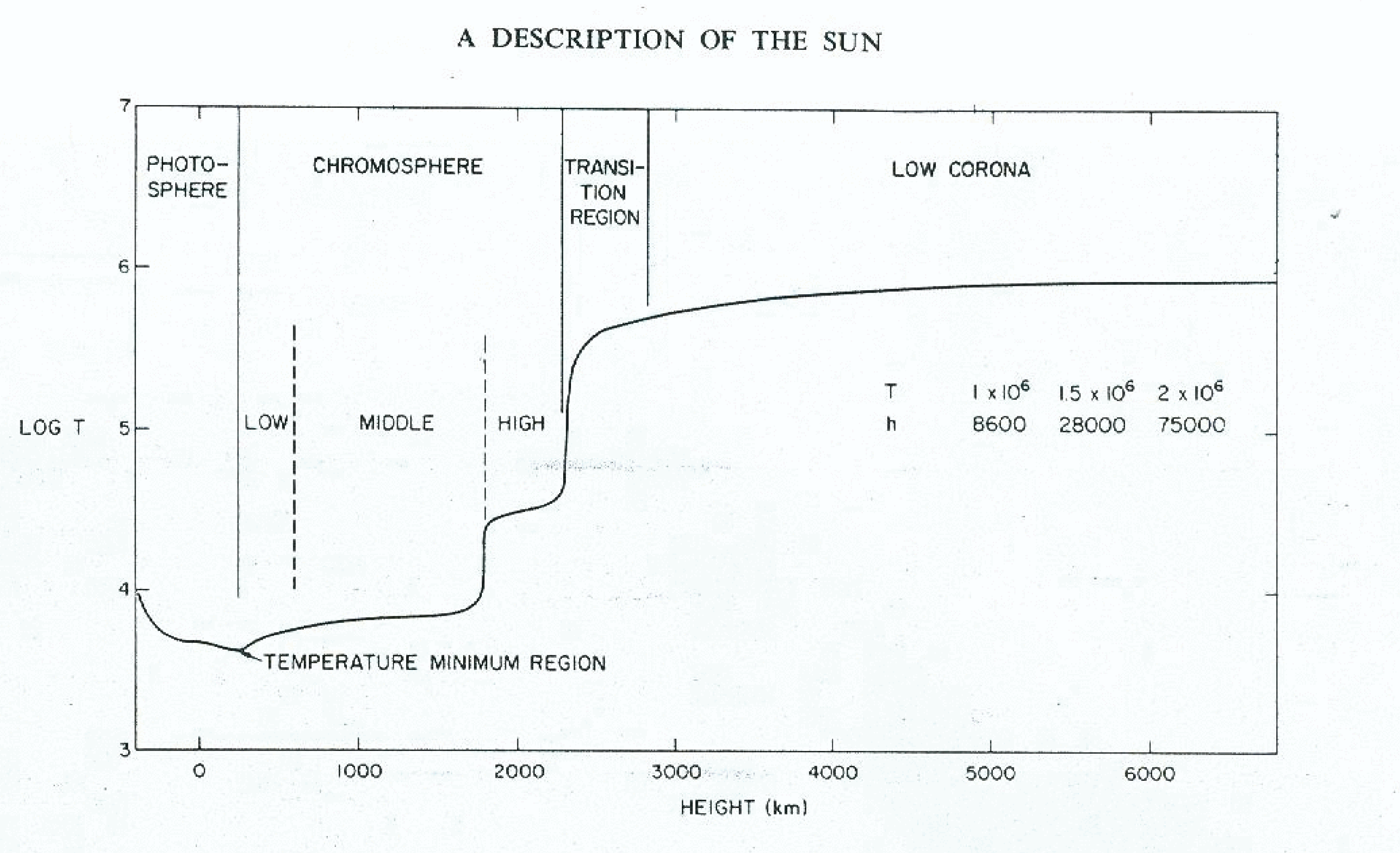



**Figure 1.2:** An illustrative model to show the sudden rise in temperature of Corona through transition region. (Priest 1982)

## 2. WAVE HEATING MODELS:-

- Proposed wave heating mechanisms assume that waves originate in the lower regions and deposit their energy in the corona. Any unstable wave can cause plasma heating through wave-particle interaction or by dissipation. But corona is considered to be almost collision-less.

- Coronal loops may cause localized heating. The bright coronal loops have higher densities compared to the ambient faint coronal plasma, which indicates that the heated plasma originates from the dense chromosphere.

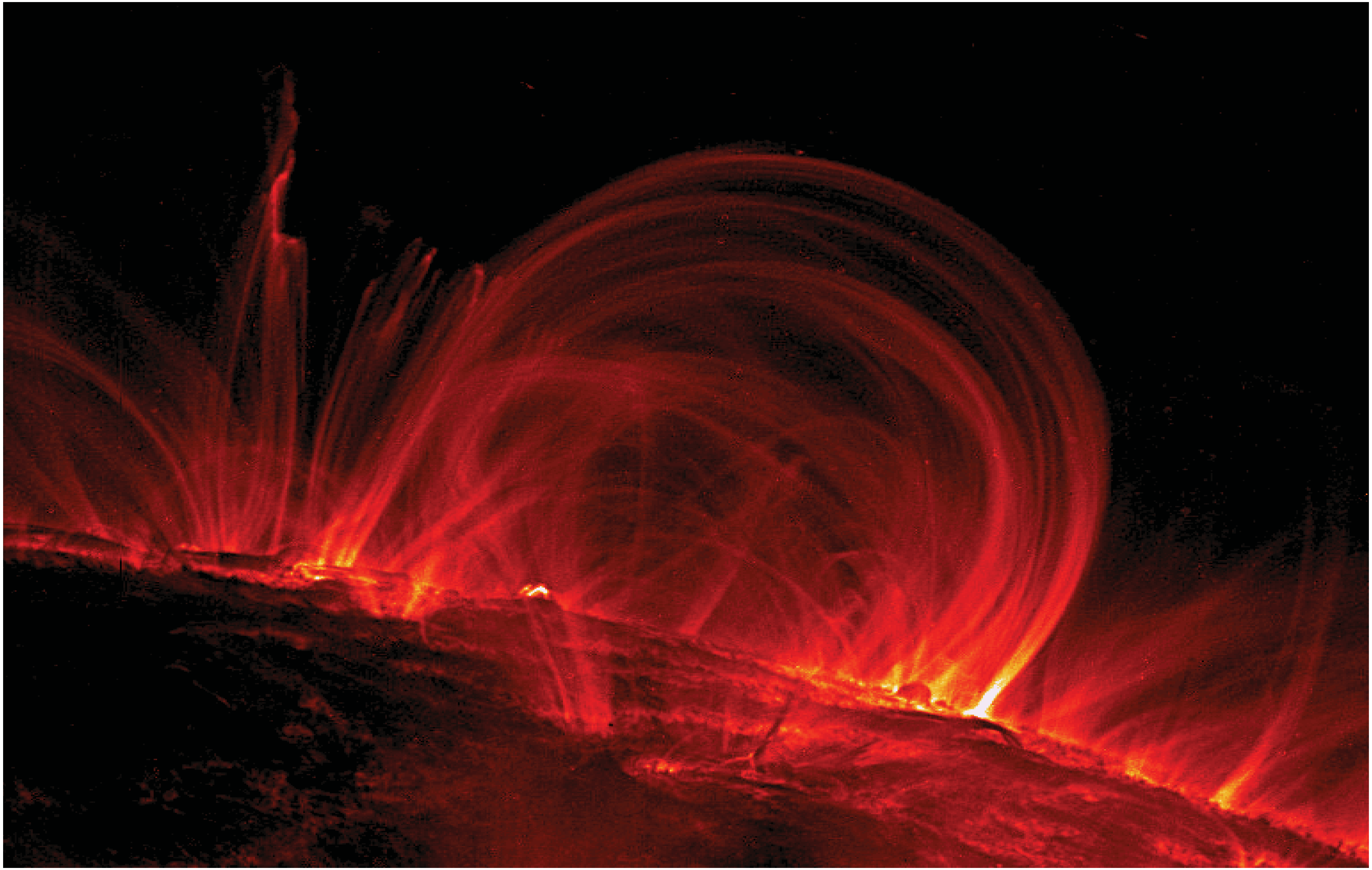


**Figure 2.1 Loops carry energy from lower regions to corona**

- Alfven waves carry energy fluxes from chromosphere to corona (Hollweg & Sterling 1994; Ionson 1983; Mok 1987; Steinolfson & Davila 1993; Helberstadt & Goed Bloed 1945).

**Alfven Waves:**

**Simplest Dispersion Relations:**

$$v_A^2 = \left(\frac{B_0^2}{\mu_0 n_0 m_i}\right)$$

$$\rho_s = \frac{c_s}{\Omega_i}; \quad c_s = \sqrt{\frac{T_e}{m_i}}; \quad \Omega_i = \frac{eB_0}{m_i}; \quad \lambda_e = \frac{c}{\omega_{pe}}$$

$$\omega^2 = v_A^2 k_z^2 \quad (MHD)$$

$$\omega^2 = \frac{v_A^2 k_z^2 (1 + \rho_s^2 k_\perp^2)}{1 + \lambda_e^2 k_\perp^2} \quad \text{(Two-fluid)}$$

- Coronal heating by acoustic waves originating from global oscillations has been ruled out (Aschwanden 2001).

- In almost all of the suggested wave mechanisms for coronal heating, the main energy source is located in other regions. The waves carry energy from lower atmospheric layers.

- Many Mechanisms have been proposed. Most of the theories of coronal heating by waves are based on magnetohydrodynamics (MHD) which cannot investigate electrostatic waves.

- Vranjes and Poedts (2009a, 2009b) proposed coronal heating by electrostatic drift waves using the results of kinetic theory.

## 3. DRIFT WAVE AS A HEATING MECHANISM:-[Vranjes & Poedts 2009]

Self-consistent coronal heating model should

1. Contain source of energy
2. Work everywhere in corona (in different magnetic structures)
3. Should be able to explain $T_e < T_i$
4. Should be able to explain how energy is dissipated in the highly conductive corona (which is generally considered to be collision-less).

- The plasma is continuously enentring into corona from lower regions (chromosphere and photosphere) which are highly inhomogeneous.
- Extremely fine density filaments and threads have been observed in solar atmosphere (Fig. 3.1)
- Drift waves of different wavelengths can exist in corona which has density gradients of many different lengths scales.

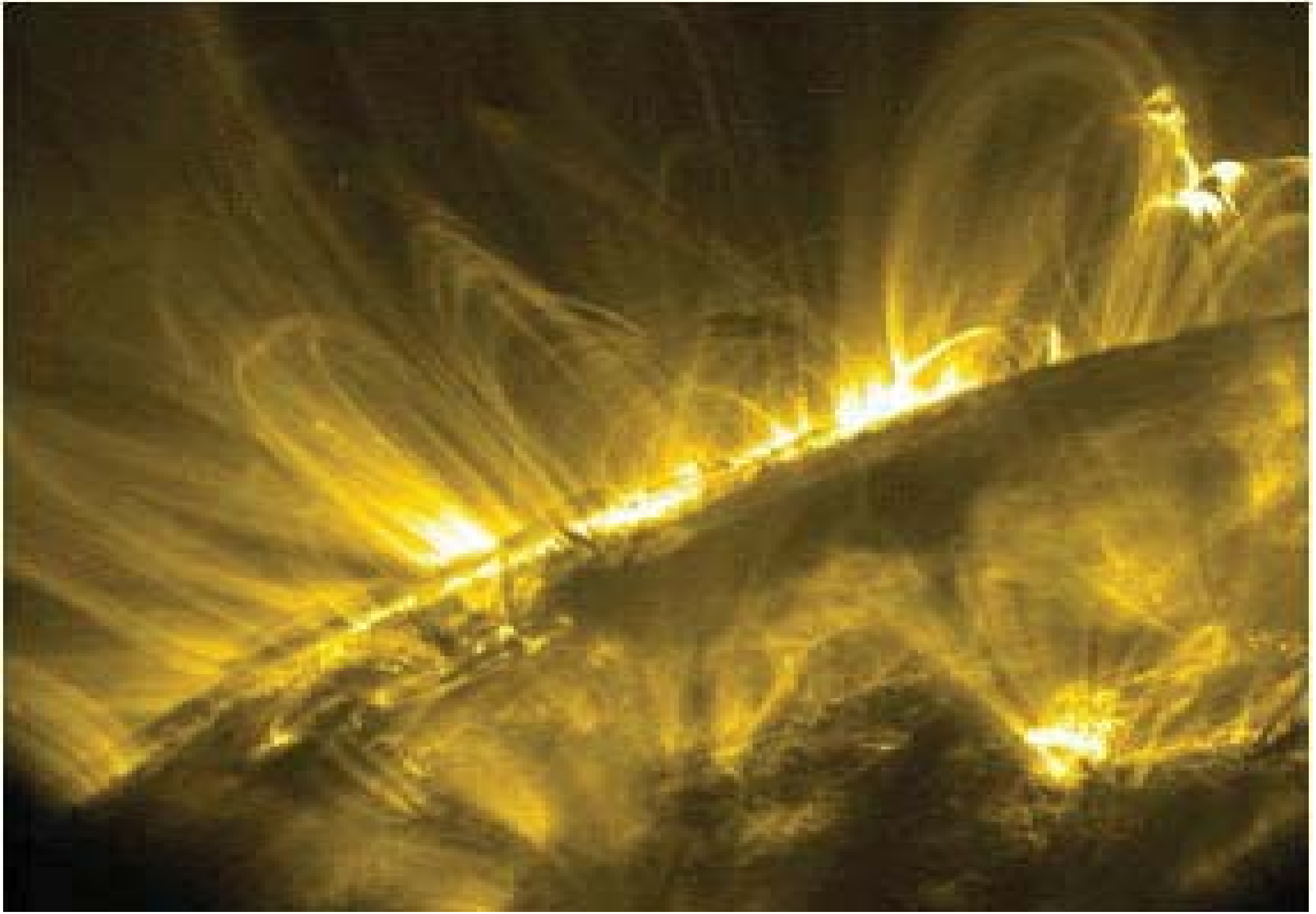


Figure 3.2 An image of the Sun taken by the Transition Region and Coronal Explorer (TRACE)

- Drift waves can grow under certain conditions.

- Drift waves can heat the plasma through two mechanisms, experimentally verified in case of tokamak plasma (Sanders et. al. Phys. Plasmas 7, 716 (1998))

1. Ion Landau damping ($\rho_i k \simeq 1$):
   This helps in parallel ion heating $T_{\parallel}$.

2. Stochastic Heating:
   Ions move in $\perp$ direction and feel time-varying electric field due to polarization drift. The motion becomes stochastic.

The heating mechanisms predominantly act upon the ions. These mechanisms explain

$$T_{i\parallel} < T_{i\perp}$$

$$T_e < T_H < T_{He}$$

in agreement with observations.

In this work, as an example, drift wave has been considered with $\mathbf{B}_0 = B_0\hat{\mathbf{z}}$; $\lambda_z \simeq \frac{2\pi}{k_z}$; $k_z \ll k_y$; $\nabla n_0 = -\hat{\mathbf{x}}\left|\frac{dn_0}{dx}\right|$; $L_n = \left|\frac{1}{n_0}\frac{dn_0}{dx}\right|^{-1} = 100m$; $\lambda_y \simeq 0.5m$ and $\lambda_z = 20km$. It has been shown that drift wave can become unstable at different wavelengths by varying S. Therefore, heating occurs everywhere along a given flux tube i.e. when the radial density gradient varies with increased altitude.

$\frac{\lambda_z}{L_n}$ = Fixed; $L_n = (S \times 100)m$ $\lambda_z = (S \times 40,000)m$; $1 \leq S \leq 1000$; $\frac{\omega_r}{\omega_i} \simeq 1$ and $\lambda_y = 0.5m$ (fixed).

## 4. SHEARED FLOW AS A HEATING MECHANISM:-

Plasma is flowing into the corona from chromosphere & photosphere.
We point out that a major energy source for heating is located within the corona to excite the short wavelength electrostatic perturbations, namely the sheared flows. Extremely fine density filaments and threads have been observed in the solar atmosphere (November & Koutchmy 1997) as shown in Fig. 3.2. Filamentary structures with length scales $\simeq$ 1m have been discussed (Woo 1996).
**Suggestion: Free energy available in the form of sheared flows is the major source of coronal heating.**
Sheared flows can excite the short-scale electrostatic perturbations continuously throughout the Corona. These electric fields accelerate charged particles and hence Corona is heated.
Two types of electrostatic instabilities are expected to occur in Corona.

1. Purely growing sheared flow-driven instability (D'Angelo 1965), which exists even if the plasma density is uniform $(\nabla n_{j0}) = 0$.

•November L. J. and Koutchmy S, Astrophys. J. 446, 512 (1997).
•Woo R., Nature, 379, 321 (1996).

2. The drift wave needs a plasma density gradient ($\nabla n_{j0} \neq 0$) for it's existence (Kadomtsev & Timofeev 1963) and sheared flow $(\mathbf{v}_0) = \mathbf{v}_0(x) \neq 0$ for instability (Saleem, Vranjes & Poedts 2007).

Some other mechanisms can also excite electrostatic wave.

# Drift Wave:

- Assume electron-ion collision-less plasma:
  $\mathbf{B}_0 = B_0\hat{\mathbf{z}}$ ; $n_{e0} = n_{i0} = n_0$
  $\nabla n_{j0} = -\left|\frac{dn_{j0}}{dx}\right|\hat{\mathbf{x}}$ ; $\mathbf{k} = k_y\hat{y} + k_z\hat{z}$
  $\mathbf{v}_{De0} = -\left(\frac{T_e}{eB_0}\right)\nabla lnn_0 \times \hat{\mathbf{z}}$
  $T_e =$ electron temperature ; $T_i =$ ion temperature
  $\nu_{ti}^2 = T_i/m_i$ ; $c_s^2 = \frac{T_e}{m_i}$; $\rho_s = \frac{c_s}{\Omega_i}$; $\Omega_i = \frac{eB_0}{m_i}$.
  $\nu_{te}^2 = T_e/m_e$
  $(\omega, \mathbf{k}) \rightarrow$ frequency and wave vector of the perturbation.
  $E = -\nabla\varphi$

## Electrons:

$$m_e n_e(\partial_t + \mathbf{v}_e.\nabla)\mathbf{v}_e = -en_e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \nabla p_e \tag{4.1}$$

$k_z \neq 0$, $\omega << \Omega_i$, imply

$$n_e \simeq n_{e0}(x)e^{e\varphi/T_e} \tag{4.2}$$

**Ions:**

$$m_i n_i(\partial_t + \mathbf{v}_i.\nabla)\mathbf{v}_i = en_i(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}) \tag{4.3}$$

$$\partial_t n_i + \nabla.(n_i \mathbf{v}_i) = 0 \tag{4.4}$$

**Quasi-neutrality:**

$$n_e \simeq n_i \tag{4.5}$$

$\lambda = \frac{2\pi}{k}$ wavelength of perturbation frequency; $\omega = \omega_r$ (basic drift wave has only real frequency). Then within the frame work of fluid theory,
$\nu_{ti}k_z << \omega_r << \nu_{te}k_z$ ; $\rho_e << \lambda$ ; $\rho_e = \nu_{te}/\Omega_e$ ; $\Omega_e = \frac{eB_0}{m_e}$ ; $\rho_s = c_s/\Omega_i$.
$k_z << k_y$ and $k_x = 0$ (local approximation)
Fourier analysis gives linear dispersion relation as,

$$(1 + \rho_s^2 k_y^2)\omega^2 - \omega\omega_e^* - c_s^2 k_z^2 = 0 \tag{4.6}$$

$$\mathbf{v}_{De0} = -\frac{T_e}{eB_0}\nabla ln n_o \times \hat{\mathbf{z}} = \left(\frac{T_e}{eB_0}\kappa_n\right)\hat{\mathbf{y}} \tag{4.7}$$

$\kappa_n = \left|\frac{1}{n_0}\frac{dn_0}{dx}\right|$ ; $L_n = \frac{1}{\kappa_n}$ ; $\kappa_n << k_y$ ; $\rho_s k_y < 1$.
For $\lambda_{De}^2 k_y^2 << 1$; $\lambda_{De}^2 = \frac{T_{e0}}{4\pi n_0 e^2}$.

Drift wave dispersion relation ($\nabla n_{j0} \neq 0$) for $c_s k_z << \omega_e^*$,

$$\omega = \omega_e^* = \mathbf{v}_{De0}.\mathbf{k} = \left( \frac{T_e}{eB_0} \kappa_n k \right) \tag{4.8}$$

Ion Acoustic wave ($\nabla n_{j0} = 0$), for $k_y = 0$,

$$\omega^2 = \omega_s^2 = c_s^2 k_z^2 \tag{4.9}$$

where $c_s^2 = T_e/m_i$.
If polarization drift is taken into account above relations modify as,

$$\omega = \frac{\omega_e^*}{1 + \rho_s^2 k_y^2} \tag{4.10}$$

$$\omega^2 = \frac{c_s^2 k_z^2}{1 + \rho_s^2 k_y^2} \tag{4.11}$$

where $\rho_s = \frac{c_s}{\Omega_i}$ and $\Omega_i = \frac{eB_0}{m_i}$.
$\rho_s^2 k_y^2$ - dispersive effect.

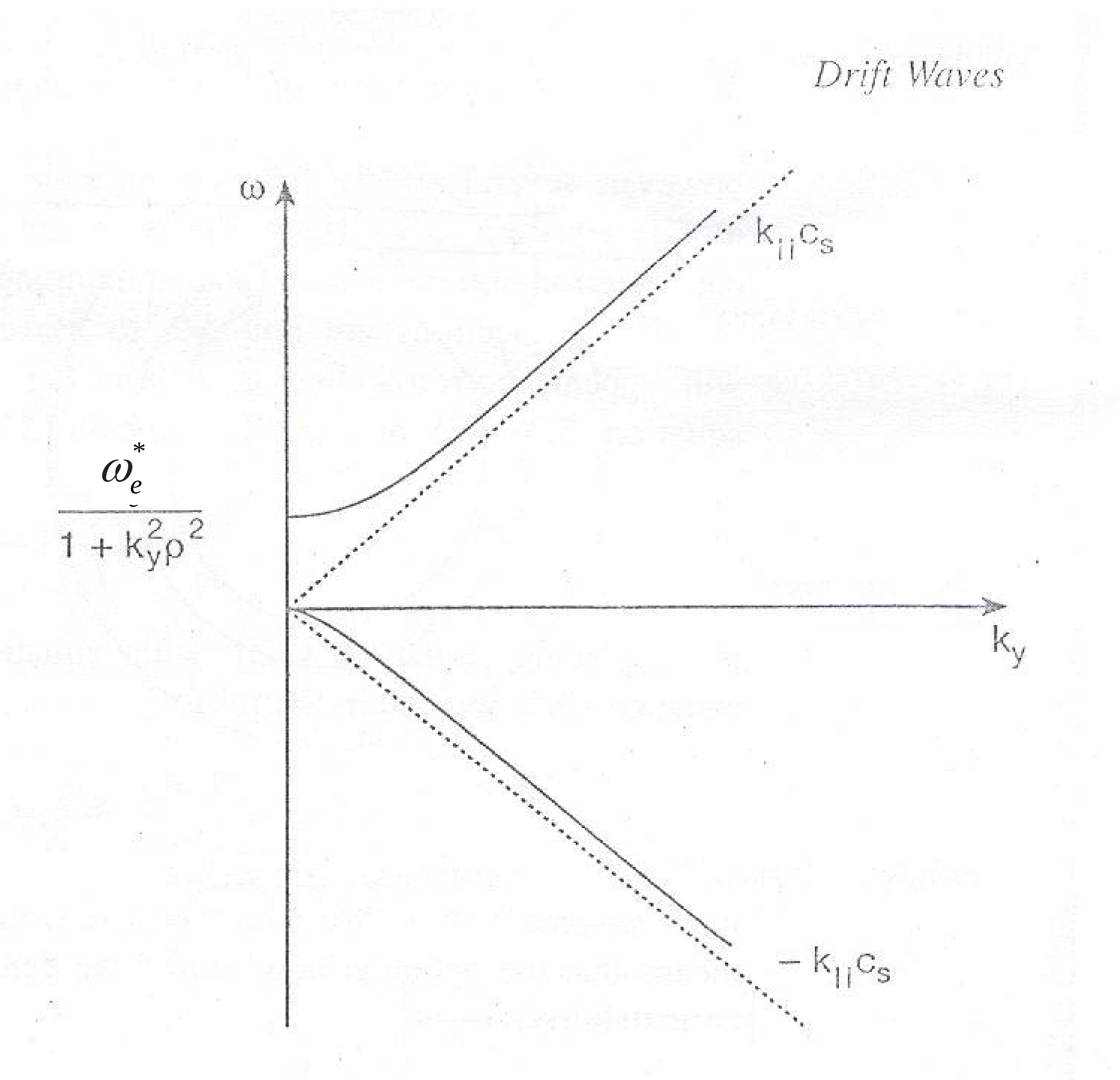



**Figure 4.1:** Dispersion diagram of drift  waves (Weiland 2000)

## D'Angelo Mode: (Phys. Fluids 1965)

$$\mathbf{B}_0 = B_0 \hat{\mathbf{z}} \equiv \text{constant}$$

$$v_{e0} = v_{i0} = v_0(x)\hat{\mathbf{z}}$$

Thus $\mathbf{J}_0 = 0$, low frequency perturbation $\omega << \Omega_i, \;\; k_y << k_z$

$$\mathbf{v}_{i\perp} = \frac{1}{B_0}(\mathbf{E}_\perp \times \hat{\mathbf{z}}) - \frac{1}{\Omega_i}\partial_t(\mathbf{v}_{i\perp}) = \mathbf{v}_E + \mathbf{v}_p \tag{4.12}$$

$$(\partial_t + v_0\partial_z)v_{iz} = \frac{e}{m_i}E_z - \frac{T_{i0}}{m_i n_{i0}}\partial_z n_{i1} - v_E d_x v_0(x) \tag{4.13}$$

$$\partial_t n_i + \frac{n_{i0}}{B_0\Omega_i}\partial_t(\nabla.\mathbf{E}_\perp) + n_{i0}\partial_z v_{iz} = 0 \tag{4.14}$$

$$n_e \simeq n_{e0}e^{\frac{e\varphi}{T_e}} \tag{4.15}$$

$$n_e \simeq n_i$$

$$(1+\rho_i^2 k_y^2 + \rho_s^2 k_y^2)\Omega_\omega^2 - c_s^2 k_y k_z [A_i - (1+\sigma)\frac{k_z}{k_y}] = 0 \qquad (4.16)$$

$$\rho_i = \frac{\nu_{ti}}{\Omega_i}\ ;\rho_s = \frac{c_s}{\Omega_i};\ ;\nu_{ti} = \sqrt{\frac{T_i}{m_i}};\ ;c_s = \sqrt{\frac{T_e}{m_i}}$$

$$\sigma = \frac{T_i}{T_e}$$

$$A_i = \frac{1}{\Omega_i}\left|\frac{dv_0(x)}{dx}\right|$$

$$\Omega_\omega = (\omega - \omega_0);\ \omega_0 = v_0 k_z$$

$\Omega_\omega \rightarrow$ Doppler-shifted frequency

Let $\rho_i^2 k_y^2, \rho_s^2 k_y^2 << 1$ and $T_i << T_e$

$$\Omega_\omega^2 = c_s^2 k_y k_z (A_i - \frac{k_y}{k_z}) \qquad (4.17)$$

(instability condition)

$$\frac{k_z}{k_y} < A_i \qquad (4.18)$$

# 5. PRESENT MATHEMATICAL MODEL:-

Coronal Plasma: electrons + H ions (90%) + He ions (10%), low density, hot, collision-less, magnetized, inhomogeneous and has sheared flows.
Let $j = a(H)$ ; $b(He)$
Simple physical picture of low frequency electrostatic instabilities is presented.

$$\mathbf{v}_{\perp j} = \frac{1}{B_0}(\mathbf{E}_\perp \times \hat{\mathbf{z}}) - \frac{T_j}{q_j B_0}(\nabla ln n_j \times \hat{\mathbf{z}}) - \frac{1}{q_j B_0}\left(\frac{\nabla.\mathbf{\Pi}_j}{n_j}\right) - \frac{1}{\Omega_j}(\partial_t + \mathbf{v}_j.\nabla)\mathbf{v}_j \times \hat{\mathbf{z}}$$

$$= \mathbf{v}_E + \mathbf{v}_{Dj} + \mathbf{v}_{\Pi j} + \mathbf{v}_{pj} \tag{5.1}$$

where $\mathbf{v}_E, \mathbf{v}_{Dj}, \mathbf{v}_{\Pi j}$ and $\mathbf{v}_{pj}$ are the electric, diamagnetic, stress tensor and polarization drifts, respectively. Note: $\Omega_j = eB_0/m_j$ is charge dependent. Stress tensor contains a collision-less part.

$$(\partial_t + v_{j0z}\partial_z)v_{jz1} + v_E d_x \nu_{joz}(x) = \frac{q_j}{m_j}E_{z1} - \frac{T_{j0}}{m_j n_{j0}}\partial_z n_{j1} \tag{5.2}$$

$$\partial_t n_{j1} + v_{0jz}\partial_z n_{j1} + \nabla n_{j0}.\mathbf{v}_E + \frac{n_{j0}}{B_0\Omega_j}(\partial_t + v_{j0z}\partial_z)\nabla_\perp.\mathbf{E}_\perp$$

$$-\frac{T_j}{q_j B_0 \Omega_j}(\partial_t + \nu_{j0z}\partial_z)\nabla_\perp^2 n_{j1} + n_{j0}\partial_z v_{jz1} = 0 \tag{5.3}$$

where $\nabla\nu_{0z}(x) = +\hat{\mathbf{x}}\left|\frac{d\nu_0(x)}{dx}\right|$.

$$\nabla.\mathbf{E}_1 = \frac{e}{\epsilon_0}(n_{a1} + n_{b1} - n_{e1}) \tag{5.4}$$

$k_z \neq 0$ ; $k_z << k_y$ ; $m_e \to 0$ imply,

$$n_{e1} \simeq n_{e0}e^{\Phi} \tag{5.5}$$

$\kappa_v = \left|\frac{1}{\nu_0}\frac{d\nu_0}{dx}\right|$ ; $\Phi = e\varphi/T_e$, $A_j = \frac{1}{\Omega_j}\frac{d\nu_0}{dx}$.
One obtains a fourth order dispersion equation for low frequency electrostatic perturbations in two-ion component plasma.

$$L_4\Omega_\omega^4 + L_3\Omega_\omega^3 + L_2\Omega_\omega^2 + L_1\Omega_\omega + L_0 = 0 \tag{5.6}$$

$\Omega_\omega = (\omega - \omega_0)$ and $\omega_0 = v_0 k_z$, If we assume only Hydrogen plasma, (5.6) becomes,

$$\Lambda_0 \Omega_\omega^2 - \omega_a^* \Omega_\omega + k_z k_y c_{as}^2 \left\{ A_a - (1 + \nu_{aT}^2 / c_{as}^2) \frac{k_z}{k_y} \right\} = 0 \tag{5.7}$$

$$\Lambda_0 = (1 + \rho_{aT}^2 k_y^2 + \rho_{as}^2 k_y^2).$$

$$(\Omega_\omega)_{1,2} = \frac{1}{2\Lambda_0} \left[ \omega_a^* \pm \left\{ (-\omega_a^*)^2 + 4\Lambda_0 c_{as}^2 k_z^2 k_y^2 \left( (1 + \sigma_a) - A_a \frac{k_y}{k_z} \right) \right\}^{1/2} \right] \tag{5.8}$$

where $\Lambda_0 = (1 + \rho_{aT}^2 k_y^2 + \rho_{as}^2 k_y^2)$.
Instability conditions $(0 < \omega_i)$,

$$(1 + \sigma_a) \frac{k_z}{k_y} < A_a \tag{5.9a}$$

$$(\omega_a^*)^2 < 4\Lambda_0 c_{as}^2 k_z^2 \left| \left( (1 + \sigma_a) - A_a \frac{k_y}{k_z} \right) \right| \tag{5.9b}$$

**Note:**
(5.9) predicts drift wave instability in single ion (j=a) component plasma (Saleem, Vranjes, Poedts 2007).

Assume $L_{jn} = \left| \frac{1}{n_{j0}} \frac{dn_{j0}}{dx} \right| = L_n$ (same for all species).
For homogeneous plasma ($\nabla n_{a0} = 0); \nabla n_{b0} = 0$ and $\nabla n_{e0} = 0$, Eq. (5.6) reduces to,

$$L_4 \Omega_\omega^4 + L_2 \Omega_\omega^2 + L_0 = 0 \tag{5.10}$$

Perturbation $\Psi = \Psi_0 e^{i\{\mathbf{k}.\mathbf{r}-(\omega_r+i\omega_i)t\}} = \Psi_0 e^{i(\mathbf{k}.\mathbf{k}-\omega_r t)}.(e^{\omega_i t})$
$e^{\omega_i t} \rightarrow \tau = \frac{1}{\omega_i}$ is e-folding time.
For $n_{b0} = 0$, (5.10) becomes

$$\Lambda_0 \Omega_\omega^2 + k_z k_y c_{as}^2 \left\{ A_a - \left(1 + \frac{T_a}{T_e}\right) \frac{k_z}{k_y} \right\} = 0 \tag{5.11}$$

Purely growing instability (D'Angelo's mode) for

$$(1+\sigma_a)\frac{k_z}{k_y} < A_a \tag{5.12}$$

$\sigma_a = \frac{T_a}{T_e}$.

# 6. APPLICATION TO SOLAR CORONA

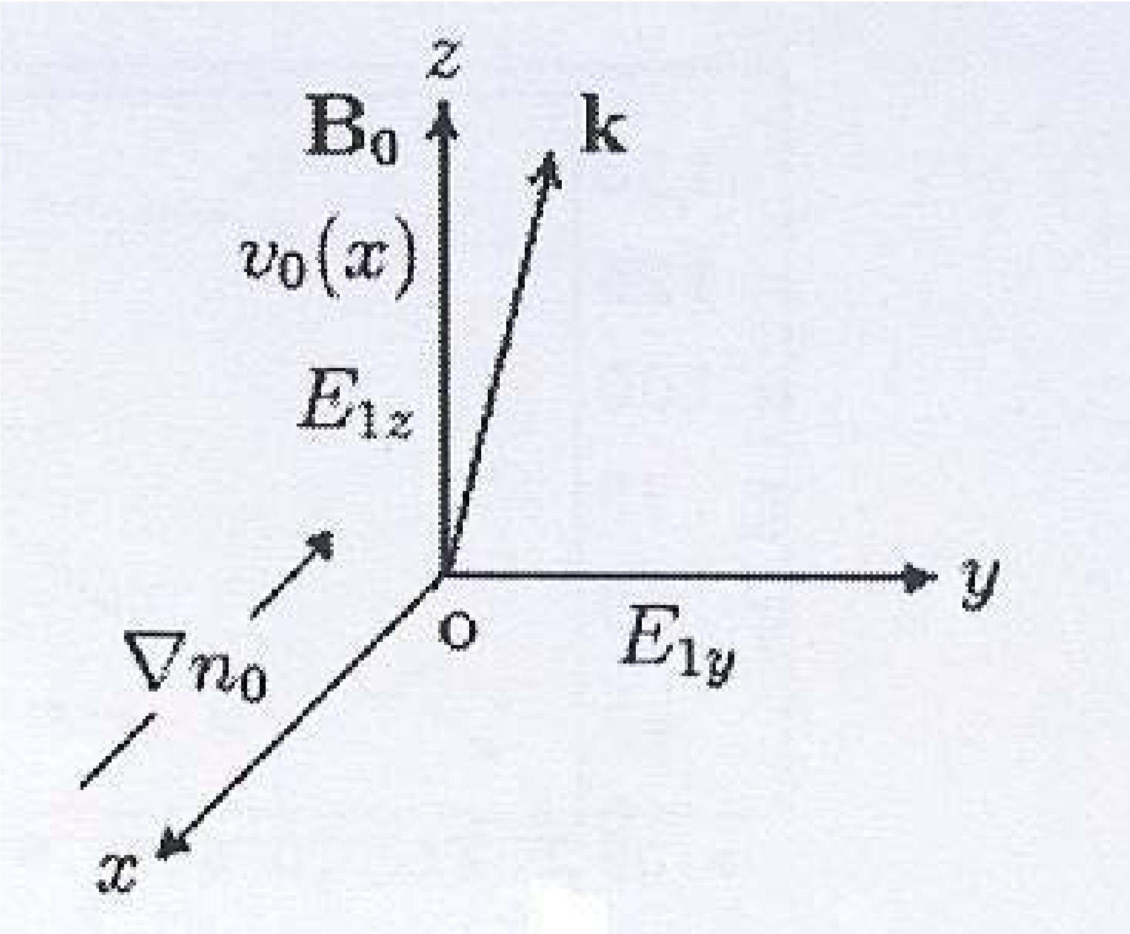



Figure 6.1(a): Directions of shear flow $\nu_0(x)$, the wave propagation with respect to density gradient and the external magnetic field are shown.

# Solar Coronal Parameters:

$$T_e \simeq (10^6)K$$

$$T_a \simeq (2 \times 10^6)K$$

$$n_e \simeq 10^{15} m^{-3}$$

$$B_0 \simeq 10^{-2} T = 200G$$

$$c_{as} = 9 \times 10^4 cm/sec; \ \Omega_a = 9.58 \times^5 rad/s$$

$$v_{eT} = 3.87 \times 10^6 cm/sec; \ v_{Aa} = 6.85 \times 10^6 cm/sec$$

$$c_{aT} = 1.28 \times 10^5 cm/sec = v_{Ta}$$

$$\rho_{as} = 0.094cm$$

$$\rho_{aT} = \frac{v_{Ta}}{\Omega_a} \simeq 0.133$$

# Shear Flow Driven Instability (H-plasma)

(growth rates for different length scales of sheared flow $L_\nu = \kappa_\nu^{-1}$);

$$\kappa_v = \left| \frac{1}{v_0} \frac{dv_0}{dx} \right|$$

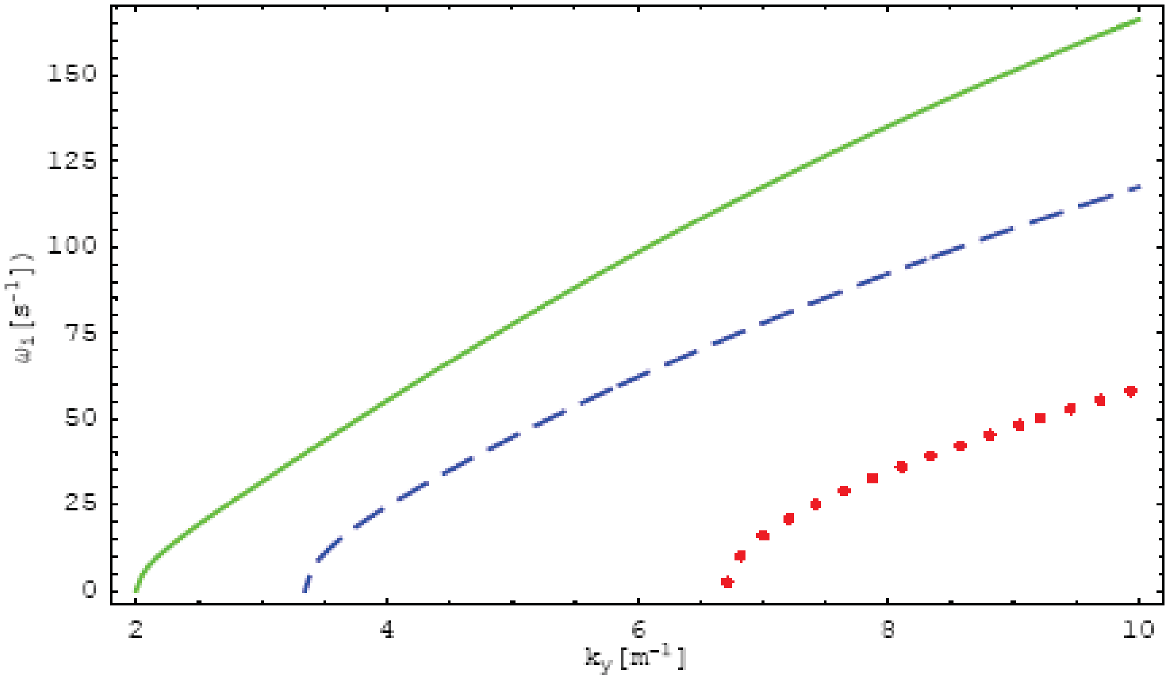



Figure 6.1(b): $\kappa_\nu = k_y/60$ (solid curve), $\kappa_\nu = k_y/100$ (dashed curve), and $\kappa_\nu = k_y/200$ (dotted curve), for $n_{e0} \sim n_{a0} \sim 10^{15} m^{-3}$, $T_e = 10^6 K$, $T_a = 2.5 T_e$, $B_0 \sim 10^{-2} T$ and $v_0 = 10 kms^{-1}$, using $\kappa_n = 0$, $n_{b0} = 0$, $k_z = 10^{-4} k_y$ and local approximation $\kappa_v << k_y$.

# Drift Wave Instability in (H-Plasma)

In Fig 6.2(a): For $2 < k_y < 3$; drift wave is unstable and linear theory is valid $\omega_i < \omega_r$. For $3 < k_y$ (shear flow instability dominates).
In Fig. 6.2(b): Same situation for $4 < k_y < 4.5$.

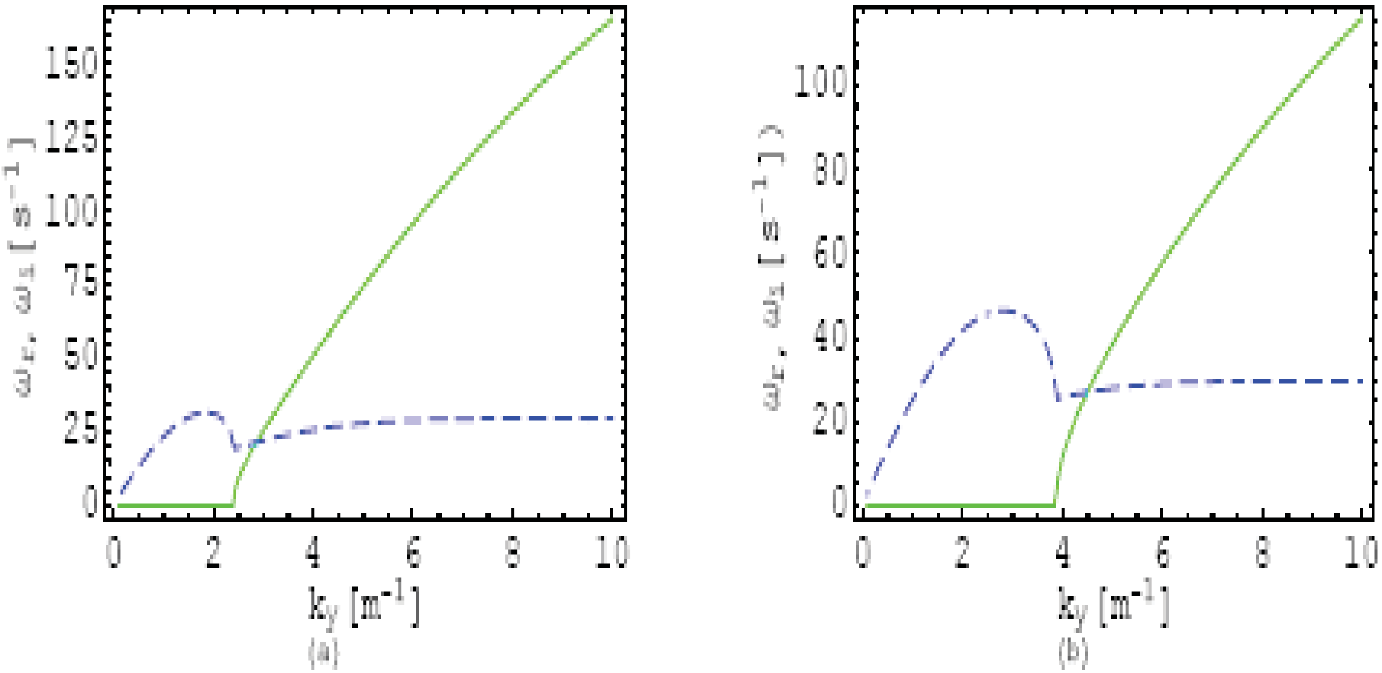
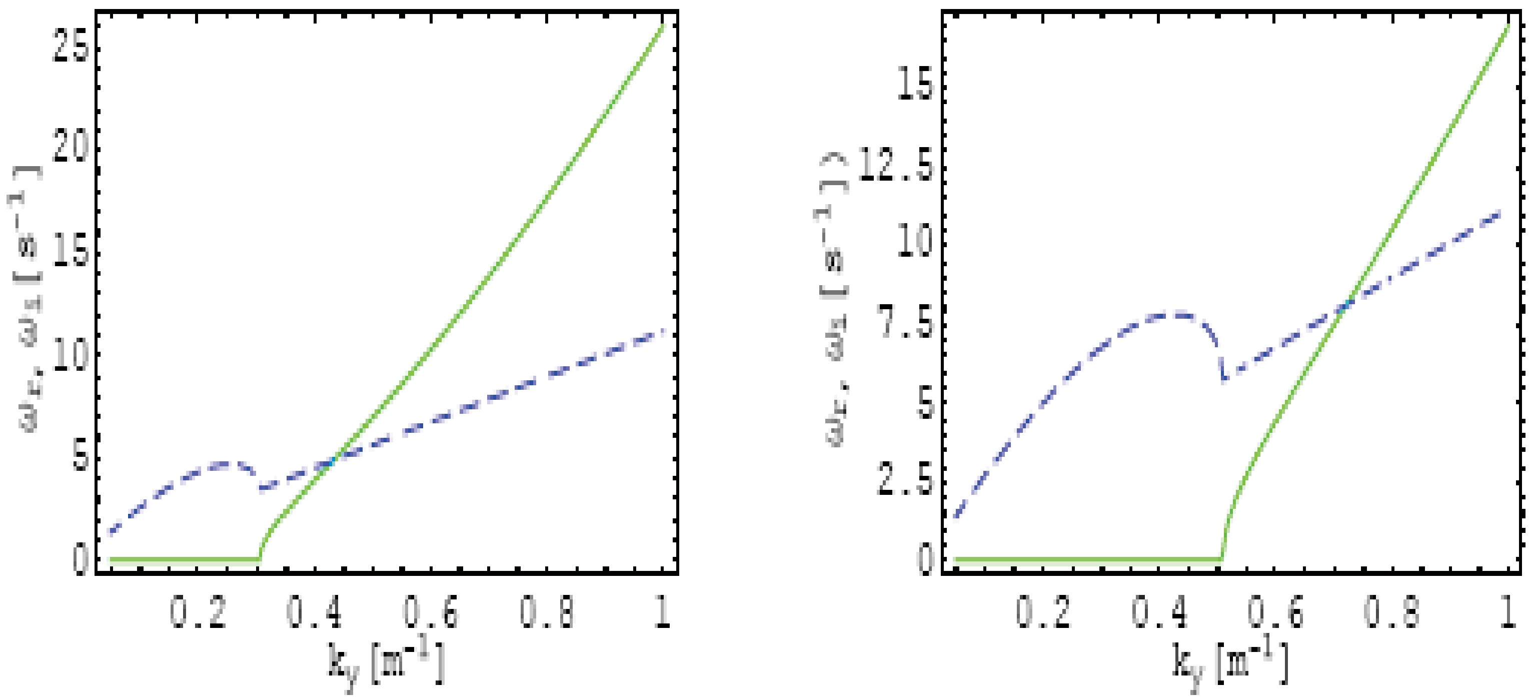



Figure 6.2 (a & b): $\omega_r$(dashed curves) and $\omega_i$ (solid curves)) for (a) $\kappa_\nu = k_y/60$ and (b) $\kappa_\nu = k_y/100$, taking $v_0 = 10kms^{-1}$, $\kappa_n = 1.9\times10^{-3}m^{-1}$, $n_{b0} = 0$, and $k_z = 10^{-4}k_y$.

# Drift Wave Instability (H-Plasma) Larger Shear Flow:

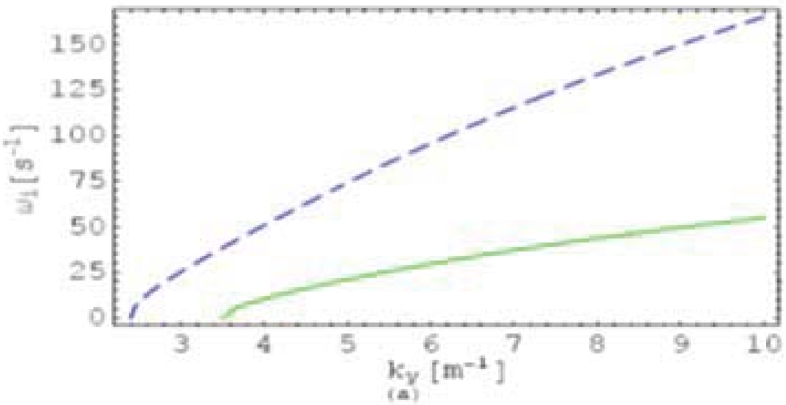
Mixed Modes (drift wave + shear flow) instabilities for larger $\nu_0$. Now $k_y, \omega_r$ and $\omega_i$ become smaller.




(a) (b)

Figure 6.3(a & b): $\omega_r$ (dashed curve), $\omega_i$ (solic curves) for (a) $\kappa_\nu = k_y/60$ and (b) $\kappa_\nu = k_y/100$, for $v_0 = 70kms^{-1}$, $\kappa_n = 1.9 \times 10^{-3}m^{-1}$, $n_{b0} = 0$ and $k_z = 10^{-4}k_y$. Other parameters are same as in fig 6.1 (b).

# **Drift Wave Instability (H-Plasma):** *For different values of $k_z$*



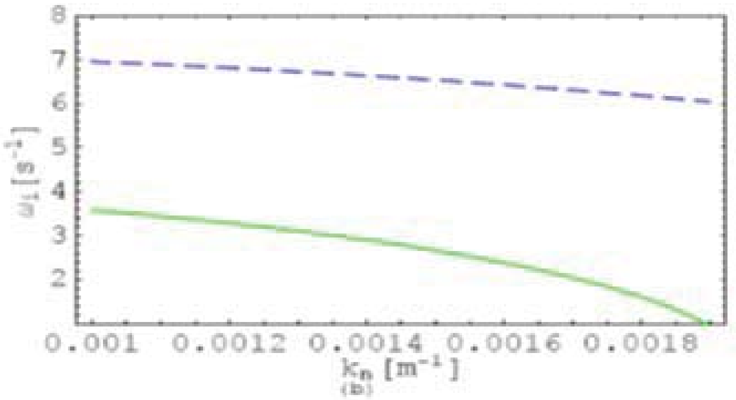
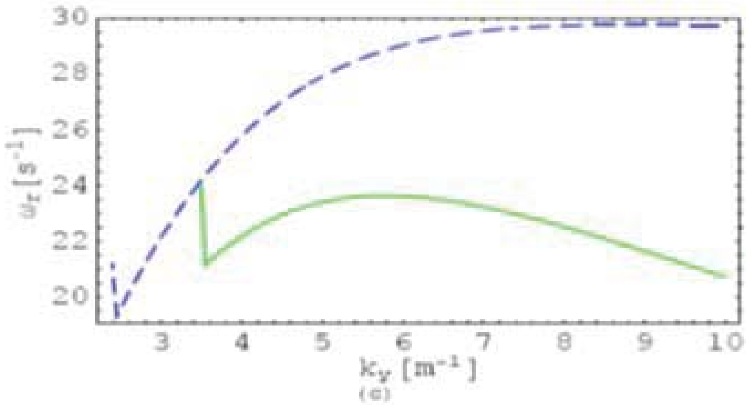




Fig. 6.4(a & b) Growth rates ($\omega_i$) of the perturbations are plotted against the perpendicular component of the wave number ($k_y$) and the inverse density scale length ($\kappa_n$), respectively, for a varying parallel component of the wave number, viz. (a) $k_z = 10^{-5}k_y$ (solid curve) and $k_z = 10^{-4}k_y$ (dashed curve) with fixed values of $v_0 = 10kms^{-1}$, $\kappa_n = 1.9 \times 10^{-3}m^{-1}$, and $\kappa_\nu = k_y/60$, and corresponding to higher streaming velocities (b) $v_0 = 50kms^{-1}$ (solid curve) and $v_0 = 70kms^{-1}$ (dashed curve), for $\kappa_\nu = k_y/60$, $k_y = 0.5m^{-1}$, and $k_z = 10^{-4}k_y$. All other parameters are the same.



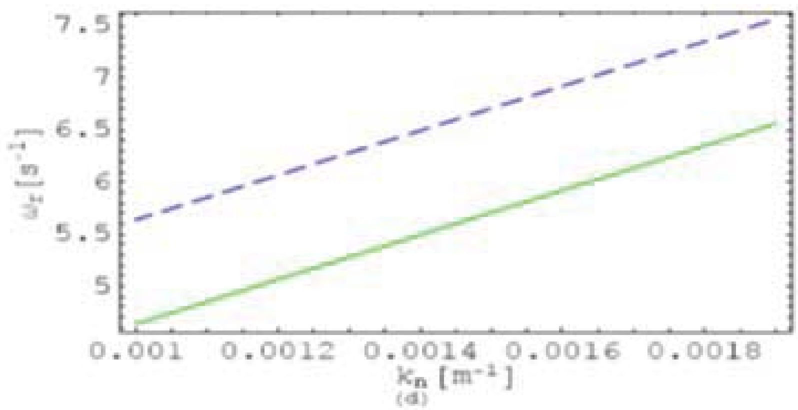




Fig. 6.4(c & d) The variations of the real frequency ($\omega_r$) of the perturbations are also plotted against $k_y$ and $\kappa_n$, respectively, as shown in panels (c) and (d). All the parameters are the same as in Fig. 6.4(a & b)

# Shear Flow Instability and Drift Wave Instability: (Effects of He-presence)

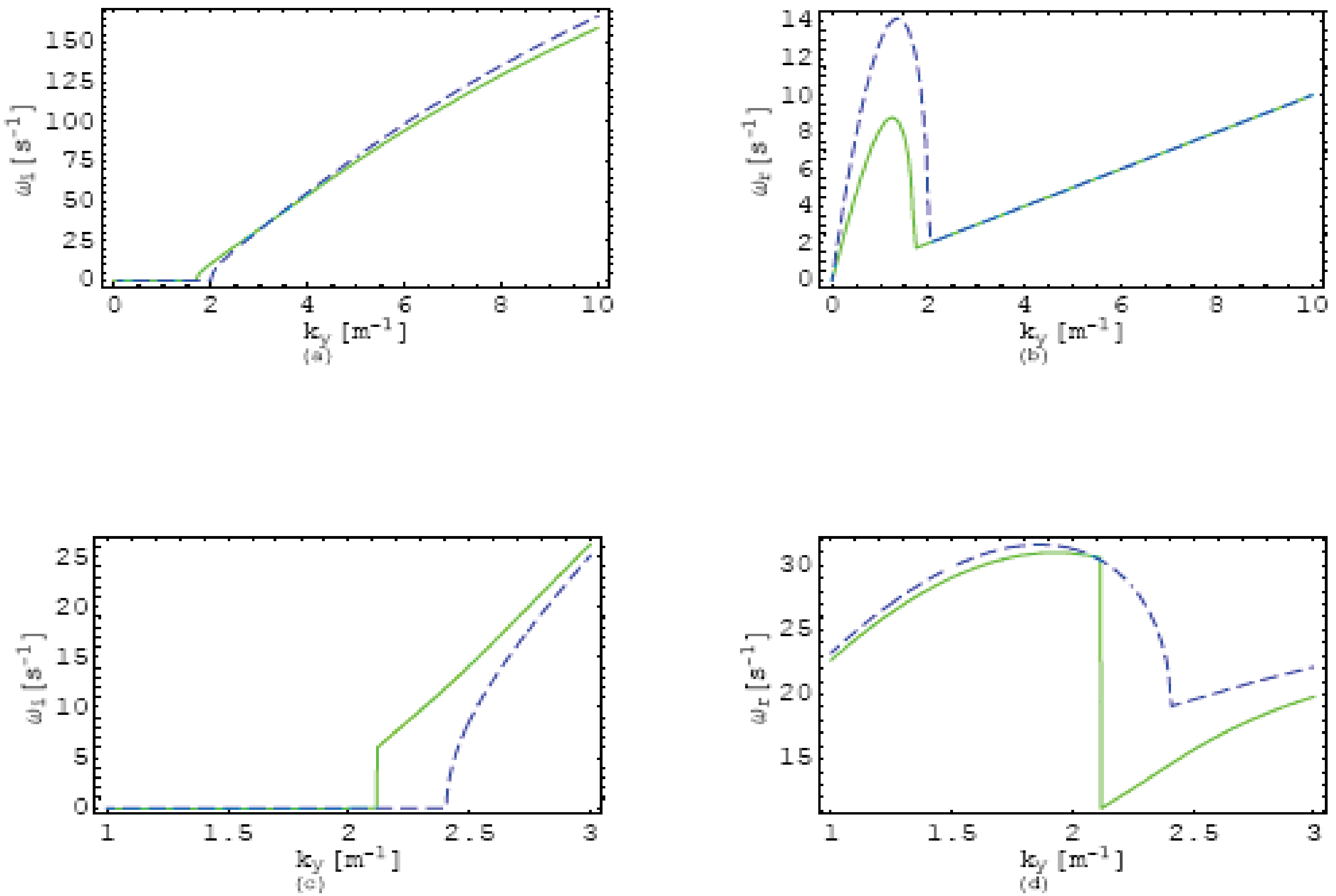



Figure 6.5: ($\omega_i$ and $\omega_r$) in the presence of sheared flow: for $n_{b0} = 0$ (dashed curve) and $n_{b0} = 0.1 n_{e0}$ (solid curve) for $\kappa_n = 0$ (a and b) and for $\kappa_n = 1.9 \times 10^{-3} m^{-1}$ (c and d). All other parameters are the same as used in Fig. 6.1 (b).

## 7. ROLE OF COLLISIONS IN CORONA:-

- Solar Corona is commonly assumed to be collision-less $\nu_{ei} \simeq 36 rad/s$. The reason seems to be that the low frequency waves Alfven, acoustic etc. have been studied in relatively higher frequency regime $\nu_{ei} << \omega$ in this context.

- The drift waves investigated by Vranjes & Poedts (2009 a, 2009 b) have also relatively higher frequency regime $\omega^* \sim \omega_i \sim 10^2 rad/s$. But in the higher frequency regime the required limit $\omega^* << \nu_{te} k_z$ for Boltzmann electrons may not be fulfilled.

- We have assumed Boltzmann electrons and tried to remain in the limit $\omega_a^*, \omega_b^* << \nu_{te} k_z$ in ideal plasma.

- Fig. 6.2(a) shows that for

  i. $k_y < 2$ (drift wave is stable)

  ii. $2 < k_y < 2.5$ (drift wave is unstable)

  iii. $2.5 < k_y$ ($\omega_r << \omega_i$, so shear flow-driven purely growing instability dominates)

## Note:

Let $k_y = 2.2m^{-1}$ (case ii). Then for $\kappa_n = 1.9 \times 10^{-3}m^{-1}$, we find $\omega_a^* = D_e\kappa_n k_y = 36rad/s$ so $\omega_a^* \simeq \nu_{ei}$.

Therefore, dissipation can play an important role and we should consider dissipation in this frequency regime. Let us investigate drift dissipative instability (DDI). Shear flow effects are not taken into account ($\mathbf{v}_0 = 0$). For (DDI) we require

$$\omega_a^* << \nu_{ei} \tag{7.1}$$

If it holds, then

$$\frac{n_{e1}}{n_{e0}} \simeq \frac{e\varphi}{T_e}\left\{1 - \iota\frac{\nu_{ei}}{\nu_{te}^2 k_z^2}(\omega_a^* - \omega)\right\} \tag{7.2}$$

The quasi-neutrality yields linear dispersion relation for DDI $\omega_d = \omega_{rd} + \iota\omega_{id}$ (Weiland 2000),

$$\omega_{rd} \simeq \frac{\omega_a^*}{(1 + \rho_{as}^2 k_y^2)} \tag{7.3}$$

$$\omega_{id} \simeq \left(\frac{\omega_r^2}{\nu_{te}^2 k_z^2}\right)\nu_{ei}\rho_a^2 k_y^2 \tag{7.4}$$

Fig. 6.2(a) indicates that for small $k_y$, the drift wave is stable and shear flow does not have an effect on it.
Therefore, we expect that for longer wavelengths ($k_y << 2m^{-1}$), the DDI should take place in corona.

## Example:

Let us choose $k_y = 0.1m^{-1}$, in Fig. 6.2 while the other parameters are the same i.e. $\kappa_n = 1.9 \times 10^{-3}m^{-1}$, $k_z = 10^{-4}k_y$, $B_0 = 10^{-2}T$ etc. Then we find, $\omega_a^* \simeq 1.63rad/s$; $\nu_{te}k_z \simeq 36$. Thus $\omega_a^* << \nu_{ei} << \Omega_i$ holds along with $\omega_a^* << \nu_{te}^2 k_z^2/\nu_{ei}$. The basic conditions for the existence of drift dissipative instability are fulfilled in solar corona.

## Conclusion:

Electrostatic fields of extremely low frequency ($\omega_a^* \simeq 1Hz$) and relatively longer wavelengths ($\lambda_y \simeq 60m$) can exist in solar corona due to drift dissipative instability even if shear flow is ignored. These fields also contribute to particle acceleration. The heating may take place due to dissipation as well.

# 8. SUMMARY:-

A physical model for the electrostatic wave heating of solar corona has been presented.

## Important Points:

1. Most of the previous fluid models of wave heating are based on MHD.

2. Vranjes and Poedts have considered coronal heating by drift waves using kinetic theory which predicts that the electrostatic drift waves are unstable. These unstable drift waves transfer energy to particles through,
   **i)** Landau damping (in the direction parallel to $\mathbf{B}_0$)
   **ii)** Stochastic heating (in the direction perpendicular to $\mathbf{B}_0$), $\mathbf{B}_0 = B_0\hat{\mathbf{z}}$ ; $\nabla n_{j0} = -\hat{\mathbf{x}}\left|\frac{dn_0}{dx}\right|$.
   For perpendicular wavelength $(\lambda_y) \simeq 0.5m$ & (parallel wavelength) $\lambda_z = 20km$, one estimates growth time of drift wave $\tau_g \simeq 0.02s$ and magnitude of perturbed electrostatic potential $|\varphi_1| \simeq 68$ volts assuming $\left|\frac{e\varphi_1}{T_e}\right| \simeq 10^{-2}$.

3. The drift wave is stable in collision-less plasma within the fluid theory frame work which we have used. But in the presence of sheared flows these waves can become unstable.

4. Sheared flows $\mathbf{v}_0(x)$ are omnipresent in collision-less rarefied corona with $n \sim 10^9 cm^{-3} = 10^{15} m^{-3}$.

**Suggestion: The flow energy generates electric fields through electrostatic perturbations which accelerate the charged particles throughout the corona.**

Fluid theory used by us predicts that sheared flows can produce short scale electrostatic fields in the corona through following mechanisms,

**A**. giving rise to purely growing sheared flow-driven instability with $\omega = \pm i\omega_i$ for $\nabla n_{j0} = 0$ and $\nabla v_0 \neq 0$.

**B**. giving rise to unstable electrostatic drift waves ($\omega = \omega_r \pm i\omega_i$) of different wavelengths depending upon gradient scale lengths for $\nabla n_{j0} \neq 0$ and $\nabla v_0 \neq 0$.

**C**. It is pointed out that in 2-ion coronal plasma the sheared flow instabilities for hydrogen ions (a) and helium ions (b) couple together and develop a real part of frequencies as shown in Fig. 6.5(a,b) for $\nabla n_{j0} = 0$.

5. Dissipation also plays a role in producing very low frequency (of the order of 1Hz) and relatively longer wavelength (of the order of 60m) drift waves in corona.
Following condition for DDI remain valid

$$\omega_a^* << \nu_{ei} << \Omega_i$$

$$\omega_a^* << \nu_{te}^2 k_z^2 / \nu_{ei}$$

6. The electrostatic fields discussed here will be observed in solar corona when the future probes will be able to detect such short scale phenomena.

## D. Electric Fields:

As an example,
for $\mathbf{B}_0 = B_0\hat{\mathbf{z}}$, $\nabla n_{j0} = 0$ and $\lambda_\perp \simeq 10cm$, growth time $\tau_g \simeq 0.03s$ and $|\varphi_1| \simeq 68$ volts if $\left|\frac{e\varphi_1}{T_e}\right| \simeq 10^{-2}$ is assumed at $t = 0$.
Thus sheared flows also give rise to electrostatic fields even if density is homogeneous.
We conclude that short scale (wavelengths of a few meters) electric fields are created due to localized sheared flows in the corona. These locally perturbed unstable E-fields accelerate the particles and hence heating takes place.

**Note:**

The DDI can couple with ion acoustic wave if parallel in dynamics is included. Since ions are hot, therefore kinetic models to investigate electrostatic instabilities are more useful.

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# Thank You

where

$$L_4 = \Lambda^2 \alpha_a^2 \alpha_b^2 + \frac{n_{a0}}{n_{e0}}(\alpha_b^2 \rho_{as}^2 k_y^2) + \frac{n_{b0}}{n_{e0}}(\alpha_a^2 \rho_{bs}^2 k_y^2)$$

$$L_3 = -\left\{\frac{n_{a0}}{n_{e0}}\alpha_b^2 \omega_a^* + \frac{n_{b0}}{n_{e0}}\alpha_a^2 \omega_b^*\right\}$$

$$L_2 = -\Lambda^2(\alpha_a^2 \nu_{bT}^2 k_z^2 + \alpha_b^2 \nu_{aT}^2 k_z^2) + \frac{n_{a0}}{n_{e0}}(\alpha_b^2 g_a c_{sa}^2 k_z^2$$

$$-\rho_{as}^2 k_y^2 \nu_{bT}^2 k_z^2) + \frac{n_{b0}}{n_{e0}}(\alpha_a^2 g_b c_{bs}^2 k_z^2 - \rho_{bs}^2 k_y^2 \nu_{aT}^2 k_z^2)$$

$$L_1 = \frac{n_{a0}}{n_{e0}}(\nu_{bT}^2 k_z^2 \omega_a^*) + \frac{n_{b0}}{n_{e0}}(\nu_{aT}^2 k_z^2 \omega_b^*)$$

$$L_0 = \Lambda^2 \nu_{aT}^2 k_z^2 \nu_{bT}^2 k_z^2 - \frac{n_{a0}}{n_{e0}} g_a \nu_{bT}^2 k_z^2 c_{as}^2 k_z^2 - \frac{n_{b0}}{n_{e0}} g_b \nu_{aT}^2 k_z^2 c_{bs}^2 k_z^2$$

Here $g_j = \left(\frac{k_y}{k_z}A_j - 1\right)$, $A_j = \frac{1}{\Omega_j}\frac{dv_0}{dx}$, $\alpha_j^2 = (1 + \rho_{jT}^2 k_y^2)$, $\lambda_{De}^2 = \frac{\epsilon_0 T_e}{n_{e0} e^2}$, and $\Lambda^2 = (1 + \lambda_{De}^2 k^2)$.

Here we have defined $\nu_{Tj}^2 = \frac{T_{j0}}{m_j}$, $\Omega_j = \frac{q_j B_0}{m_j}$, $c_{js}^2 = \frac{T_e}{m_j}$, $\Omega_\omega = (\omega - \omega_0)$, $\omega_0 = v_0 k_z$, $\omega_j^* = D_e \kappa_{jn} \kappa_y$, $\kappa_{jn} = \left|\frac{1}{n_{j0}}\frac{dn_{j0}}{dx}\right|$, and $\Phi = \frac{e\varphi}{T_c}$.

The wave-particle resonances impede the free motion of electrons along $\mathbf{B}_0$ which causes drift instability for $\omega < \omega_e^*$ (Universal instability). On the other hand ions will cause damping and will get energy from the wave. For $k_z\nu_{ti} << \omega << k_z v_{te}, \omega << \Omega_i$

$$1 << \left|\frac{k_y}{k_z}\right| \left(\frac{T_e}{T_i}\right)^{\frac{1}{2}} \frac{\rho_i}{L_n}$$

$$\omega_r = -\frac{\omega_i^* \Lambda_0(b_i)}{1 - \Lambda_0(b_i) + T_i/T_e + k_y^2 \lambda_{Di}^2}$$

$$\omega_i \simeq \left(\frac{\pi}{2}\right)^{\frac{1}{2}} \frac{\omega_r^2}{\omega_i^* \Lambda_0(b_i)} \left[\frac{T_i}{T_e} \frac{(\omega_r - \omega_e^*)}{|k_z|\nu_{te}} e^{\frac{-\omega_r^2}{k_z^2 \nu_{te}^2}} + \frac{\omega_r - \omega_i^*}{|k_z|\nu_{ti}} e^{\frac{-\omega_r^2}{k_z^2 \nu_{ti}^2}}\right]$$

$\Lambda_0(b_i) = I_0(b_i)e^{-b_i}$, $b_i = k_y^2\rho_i^2$, $\rho_i = \nu_{ti}/\Omega_i$, $\lambda_{Di} = v_{ti}/\omega_{ii}$, $\omega_i^* = -\omega_e^* \frac{T_e}{T_i}$, $\omega_e^* = k_y v_{D0}$, $\omega_e^* = \frac{T_e}{eB_0} \nabla ln n_0 \times \hat{\mathbf{z}}.\hat{\mathbf{k}}$ and $I_0$ is modified Bessel function of the first kind and zero order. One may express $\omega_r$ as

$$\omega = \omega_e^* \left[1 - \frac{1}{2} k_y^2 \rho_i^2 \left(1 + \frac{T_e}{T_i}\right)\right]$$

which shows that due to ion Larmor radius effect ($k_y^2\rho_i^2 \neq 0$), $\omega < \omega_e^*$. Therefore, $\omega_i \simeq |r_{el}| - |r_{ion}|$ where $|r_{el|}$ causes growth of the wave for $|r_{ion}| < |r_{el}|$.

Collision-less part of stress tensor cancels out the contribution of diamagnetic drift in the polarization drift term $(\partial_t + \mathbf{v}_{D0}.\nabla + ....)\mathbf{v}_{i\perp}$. That is [Weiland 2000],

$$\nabla.(n\mathbf{v}_\pi) + \nabla.\left\{\frac{n}{\Omega_i}(\mathbf{v}_{D0}.\nabla)(\hat{\mathbf{z}} \times \mathbf{v}_i)\right\} = 0$$

in ion continuity equation.