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SPRING COLLEGE ON PLASMA PHYSICS

(25 May - 19 June 1987)

SIMULATION AND THEORY OF SPACE PLASMA HEATING AND TRANSPORT IN DRIVEN SYSTEMS

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Simulation and Theory of Space Plasma Heating and Transport in Driven Systems

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Lecture I: Heating & Transport of Ionospheric Ions

Outline

(1) Motivation and Scientific Objectives

(2) Summary of Observations

(3) Theoretical Approaches to Ionospheric Ion Heating

(4) Kinetic Alfven Wave Heating model

(5) Simulation Configuration & Model

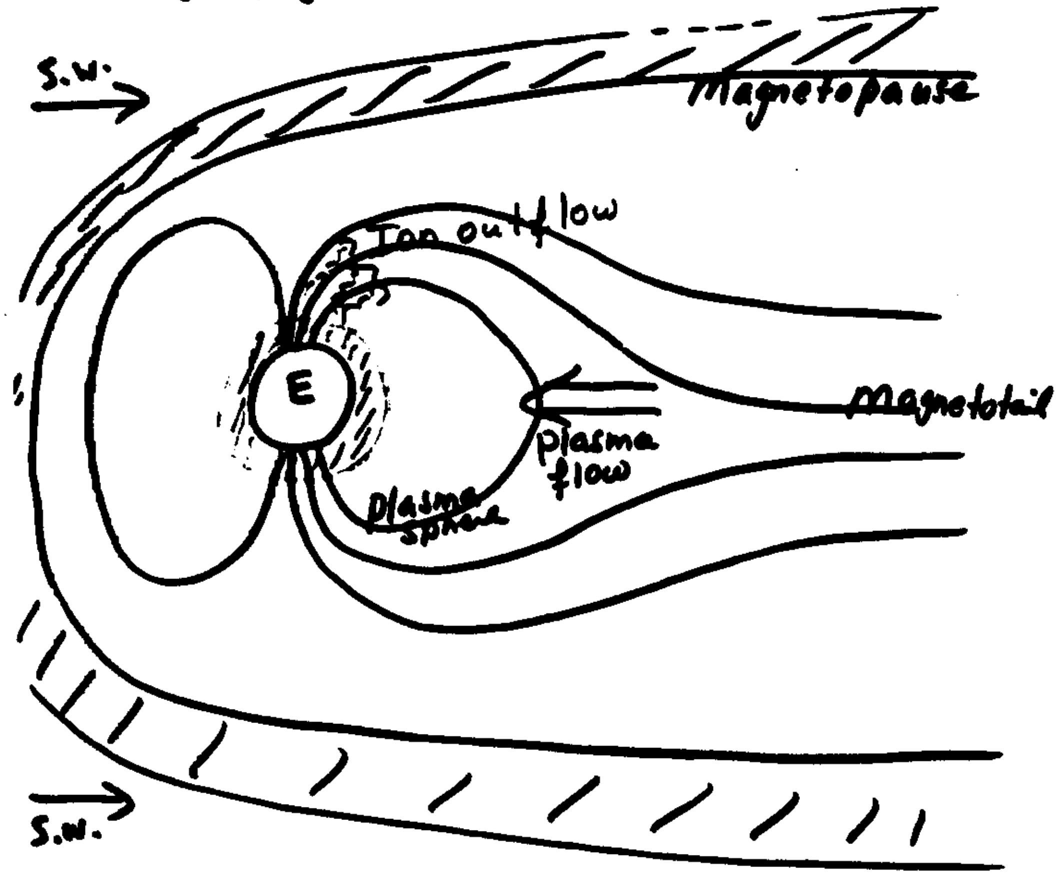
(6) Simulation Results & Interpretation

(7) Conclusions and Future Efforts

(1) Motivation and Scientific Objectives

- understanding of heavy ions (of ionospheric origin) and role in magnetosphere dynamics and stability.
- seek to obtain ion compositions, spatial abundances, energy and pitch angle characteristics as well as correlations with wave measurements.
- main objective is to build a self-consistent picture of heavy ion heating and transport around the earth. (One of few places in the magnetosphere we have gotten this far)

- solar wind was once thought to dominate supply of plasma in the earth's magnetosphere but it is now believed earth's ionosphere is a signifigant contributor.



Magnetospheric Cavity

- **main considerations**

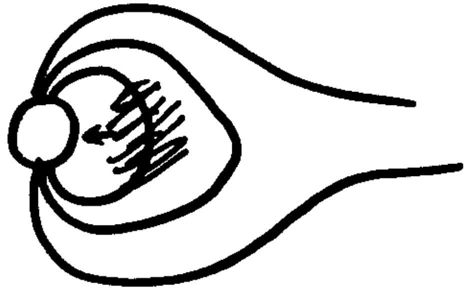
→ **Sources of ionospheric plasma in magnetosphere**

- light ion outflow from polar cap
- light & heavy ion flow from dayside cusp
- upward acceleration of ionospheric ions over latitudinally wide regions, nearly always located within (high lat. extension) plasma sheet.

→ * **Mechanisms for ionospheric outflow into magnetosphere**

→ **Consequences of ionospheric plasma in magnetosphere**

- deals with interactions between magnetosphere particles and fields.
- generation of waves and subsequent 'back reaction' on particles. Production of [illegible] conics and e.s. and e.m. noise [illegible]
- relation of waves in plasmasphere refilling.



- During storms, plasmasphere severely depletes itself to very low L-shells. Then the plasmasphere refills itself. [illegible] streaming from ionosphere may be result of an increase in outflow of ionospheric plasma to fill depleted plasmasphere. Does refilling relate to conic formation?

2) Summary of Observations

- **Sounding Rockets** (100–800 km)
  - Bering et. al., 1975
  - Kelley et. al., 1975
  - Yau, 1983
  - Kellog, 1984
  - → • Heating of O^+ and not H^+, He^+ • auroral e^- prec. at 300–350 km.

- **ISIS-1,2** (1000–3500 km)
  - Klumpar et. al., 1979
  - Ungstrup et. al., 1979
  - → • 900 eV ions • pitch angle • ion events in discrete aurora with e^- precip.

- **S3-3** (2000–6000 km)
  - Shelley et. al., 1976; Ghielmetti et. al., 1976 → • energetic ions
  - Kintner, 1979
  - Mozer, 1981
  - Gorney, 1981 → • Ion conics

- **DE-1** (~1 R_E, polar orbiting)
  - Winningham + Burch, 1984 → • O^+ dominated conics • $T_e \sim 1$–2 eV
  - Gurnett et. al., 1984 → • Banded low frequency noise (50–200 Hz) $\omega \lesssim \Omega_{O^+}$

- **Geos, ATS-6 (Equatorial)**
  - Young et. al., 1981
  - Mauk et. al., 1981
  - Roux et. al., 1982
  - Fraser, 1982
  - → He^+, O^+ Heating

O^+ velocity Space

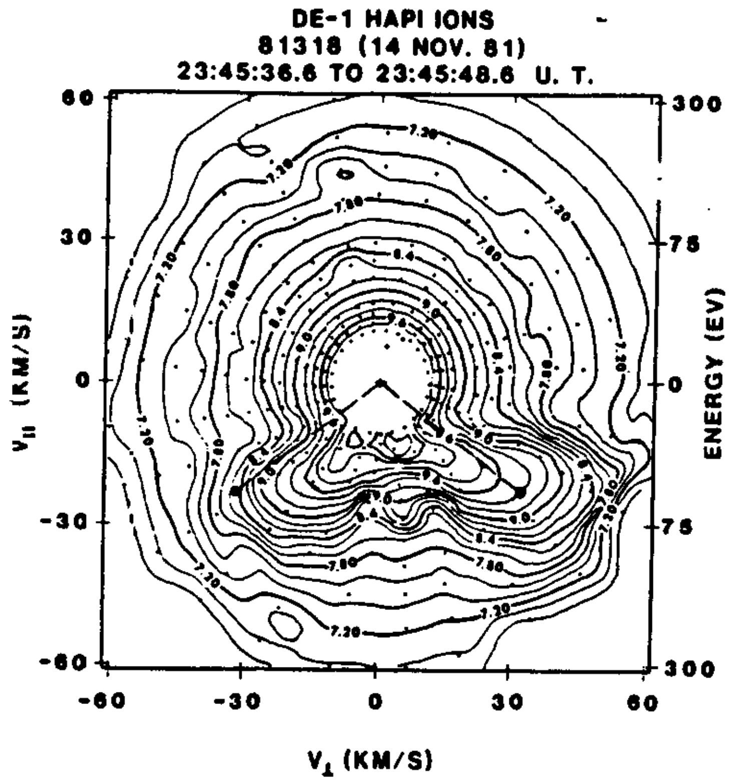
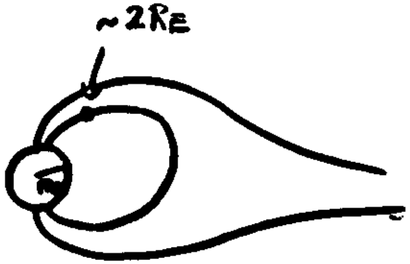


FIG. 7 Contours of a typical oxygen-dominated ion conic distribution function observed in the central plasma sheet ($l = 2.0\ R_E$, ILAT ≈ 60°). Heavy solid dots are results obtained from a mean-particle calculation for $\alpha = 2.2$, $\Sigma_o = (1/8)(2.2 \cdot 10^{-6} V^2/m^2\ Hz)$, $f_o = \Omega_i\,(1.0R_E)/2\pi = \omega_o/2\pi = 45\ Hz$, and T (initial energy) = 1/3 eV.

(Chang et. al., 1986)



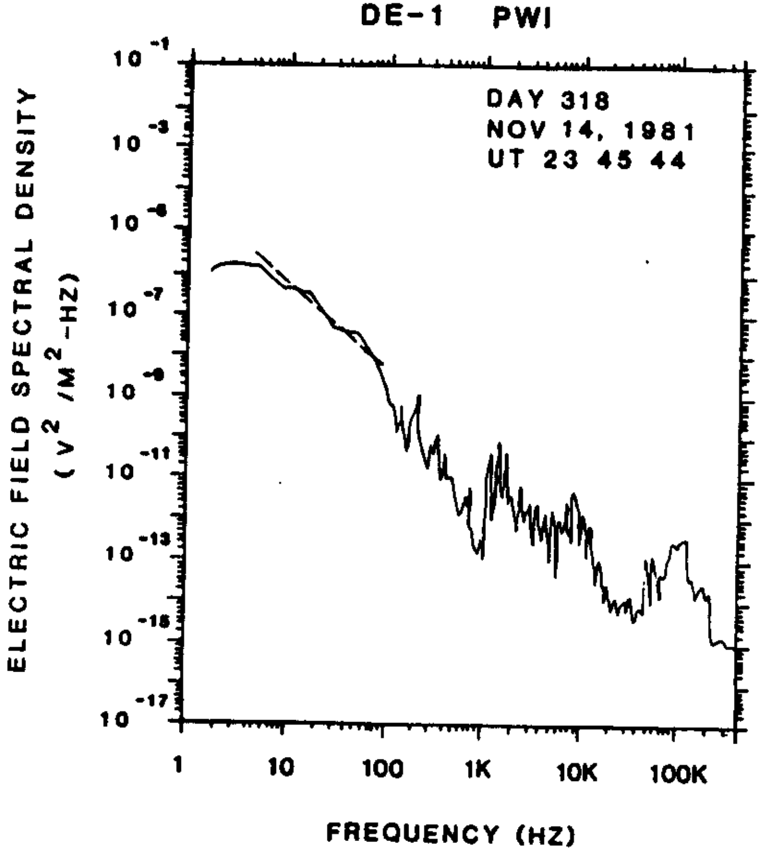
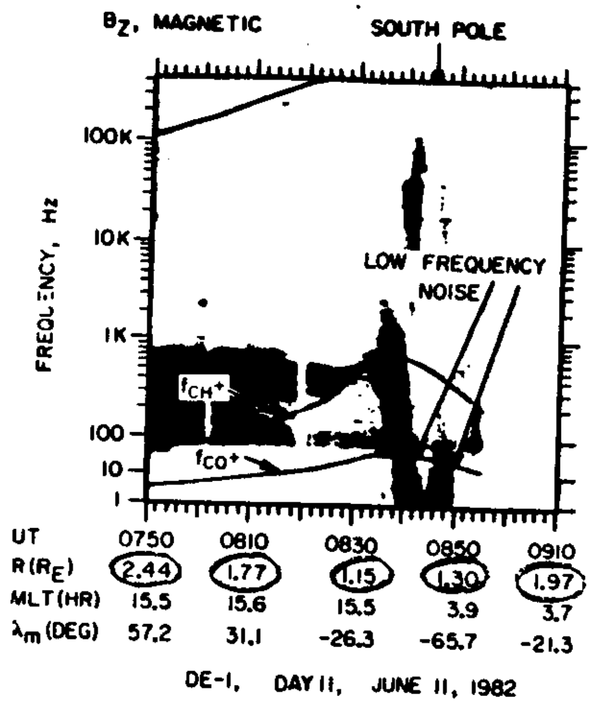


FIG. 2 Typical electric field spectral density in the central plasma sheet ($l = 2.0\ R_E$, ILAT = 60 °). Dashed line represents a power law fit of the low frequency portion of the spectrum with $\Sigma = \Sigma_o\ (\omega_o/\omega)^{\alpha}$, $\alpha = 2.2$, $\Sigma_o = 2.2 \cdot 10^{-6} V^2/m^2\ Hz$, and $f_o = \Omega_i\ (1.0R_E)/2\pi = \omega_o/2\pi = 45\ Hz$,



(3) Theoretical Approaches to Heavy Ion Heating

- What is the low altitude (< 8000 km) acceleration mechanism energizing ionospheric ions?

- Proposed source **mechanisms*** (electrostatic)

  (i) current-driven e^- model ($V_{De} \geq V_{Te}$)

  - Drummond, Rosenbluth, 1962
  - Kindel, Kennel, 1971
  - Dakin et. al., 1976
  - Pritchett et. al., 1981

    → [illegible]

  - Dusenberry + Lyons, 1981
  - Okuda et. al., 1981
  - Ashour-Abdalla, Okuda, 1984
  - Lysak et al, 1981
  - Papadopoulous, 1980
  - Singh, 1982

    → Nonlinear and Simulation Studies

  (ii) Ion Beams ($V_{bi} \geq V_{Ti}$)

  - Weibel, 1970
  - Perkins, 1976
  - Yamada et. al., 1977
  - Kaufman, Kintner, 1982, '84

    → Linear Theory

  - Miura, Okuda, Ashour-Abdalla → Simulation Study

  (iii) Lower Hybid Waves ($V_{De} > V_{Te}$)

  - Chang, Coppi, 1981
  - Retterer, 1984
  - Crew, Chang, 1985

    → Linear and Quasilinear

  - Okuda et. al., 1985 → Simulation

  (iv) Nonuniform E-fields (Inhomogeneous Current)

  - Ganguli et. al., 1982, 84
  - Pritchett, 1985

    → [illegible]

- Proposed source mechanisms (electromagnetic)

  - Ion Anisotropy

    - Gendrin, Roux, 1980
    - Roux, 1982
    - Gomberoff, Cuperman, 1982

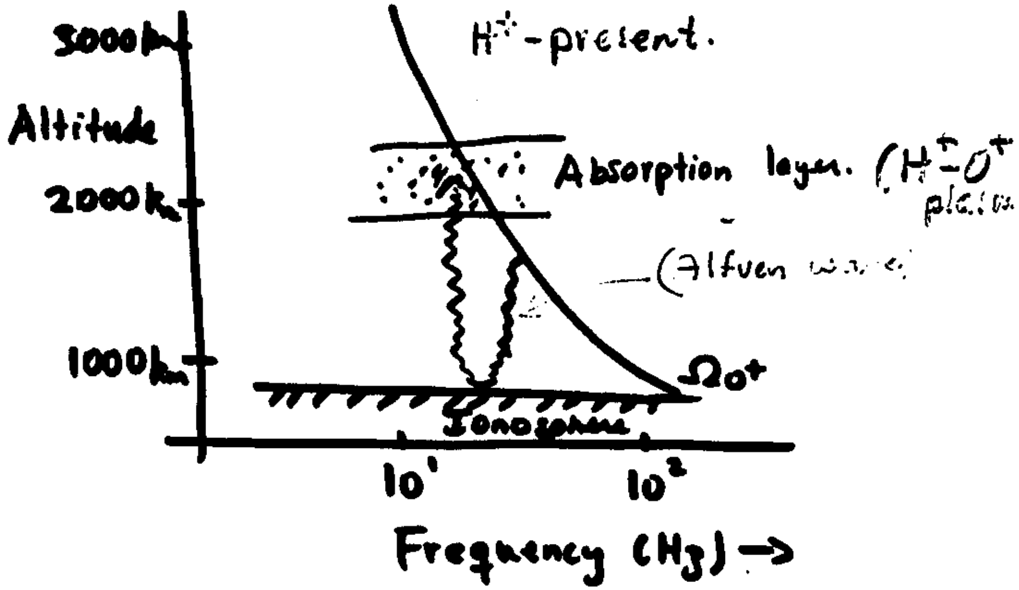
      → Linear and Quasilinear

    - Tanaka, 1985
    - Omura, Gendrin et. al., 1985

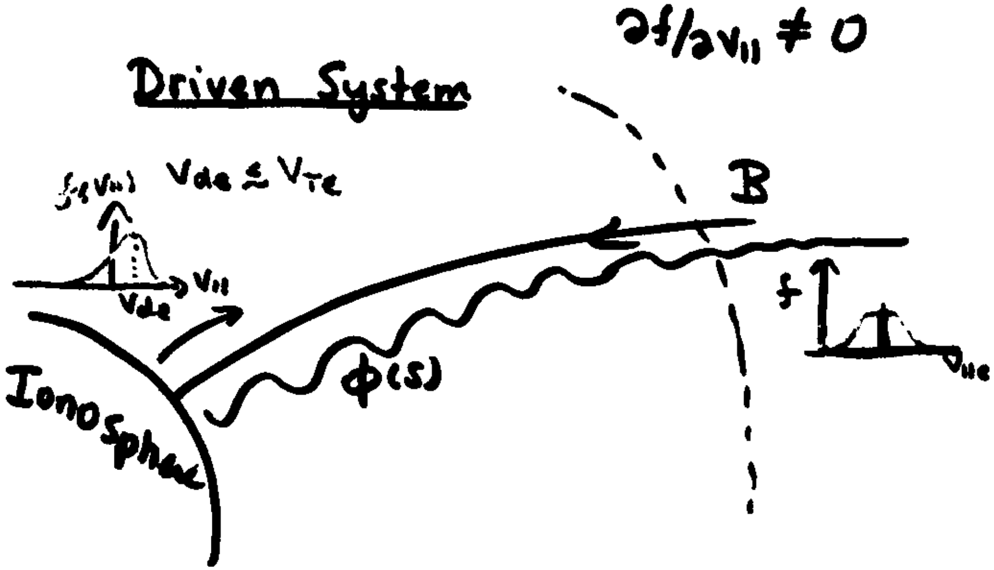
      → Simulation

Motivation

- consider mechanism for ionospheric plasma outflow into magnetosphere.
- observation of conical ion distributions and cyclotron waves suggests wave particle interactions could play a role in ionospheric plasma transport.
- motivated by observations (principally DE-1) we consider generation of Alfven waves by field-aligned currents and subsequent effects on heavy ion distributions.



Driven System



4) Linear Theory (Kinetic Alfven Wave Heating)

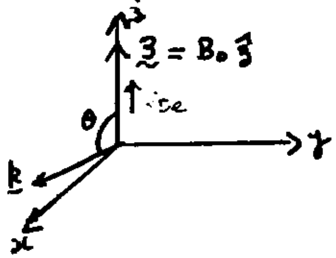
- using parameters and properties of the multi-ion (H^+-O^+) plasma in auroral region have shown shear Alfven waves and electrostatic ion cyclotron waves can persist and impart energy and momentum to ionospheric ions.

- linear stability analysis used to obtain
  - ⟶ dispersive properties of waves
  - ⟶ regime free energy source gives unstable waves
  - ⟶ conditions under which waves become marginally stable (e.g. temperature anisotropy)

(4) Shear Alfven Wave model

- Positive features
  - (i) Resonant with O^+ for wide parameter range.
  - (ii) $\omega \lesssim \Omega_{O}^{+} \Rightarrow$ instability not strongly sensitive to $T_{\perp O^+} / T_{\parallel O^+}$.
  - (iii) $V_{De} < V_{Te}$ for excitation ⟹ low current threshold.

- Equilibrium



Electrons (streaming maxwellian)

$$f_e = \frac{1}{(2\pi)^{3/2} V_{Te}^3} e^{-V_\perp^2/2V_{Te}^2} e^{-\frac{(V_\parallel - V_{De})^2}{2V_{Te}^2}}$$

Ions (bi-maxwellian)

$$f_j = \frac{1}{(2\pi)^{3/2} V_{Tj\parallel} V_{Tj\perp}^2} e^{-V_\perp^2/2V_{Tj\perp}^2} e^{-V_\parallel^2/2V_{Tj\parallel}^2}$$

- Dispersion Characteristics

$$\Lambda_{ij}(\omega, \underset{\sim}{k}) E_j(\omega, \underset{\sim}{k}) = 0$$

$$\Lambda_{ij} = \begin{pmatrix} \epsilon_{xx} - n^2\cos^2\theta & \epsilon_{xy} & \epsilon_{xz} + n^2 \sin\theta\cos\theta \\ -\epsilon_{xy} & \epsilon_{yy} - n & \epsilon_{yz} \\ \epsilon_{xz} + n^2 \cos\theta\sin\theta & -\epsilon_{yz} & \epsilon_{zz} - n^2 \sin\theta \end{pmatrix}$$

- Dispersion characteristics (H^+–O^+ plasma)

  $V_{T\perp O} = V_{T\parallel O} = V_{TO}$

  $k_\perp \rho_{O^+} < 1$

  $V_{TO} < V_{AO} < V_{Te}$

  $k_\perp > k_\parallel$ (nearly $\perp$ propagation)

<u>$E_\parallel = 0$</u>

$$\omega^2 \simeq k_\parallel^2 V_{AO}^2 \left(1 - \omega^2/\Omega_O^2\right)$$

<u>$E_\parallel \neq 0$</u>

Shear Alfven ($\omega < \Omega_{O^+}$)

$$\omega_r^2 \simeq \frac{k_\parallel^2 V_{AO}^2 \left(1 - \omega_r^2/\Omega_O^2\right)}{\left[1 + k_\perp^2 \rho_O^2 \left(\frac{3\Omega_O^2 + \omega^2}{4\Omega_O^2} + \frac{V_{Te}^2}{V_{TO}^2} \frac{m_e}{m_O} \frac{n_O}{n_e} \frac{\Omega_O^2}{\Omega_O^2 - \omega_r^2}\right) + \frac{n_H}{n_O} \frac{m_H}{m_O} \frac{\Omega_O^2 - \omega_r^2}{\Omega_O^2}\right]}$$

ES ICW ($\omega \gtrsim \Omega_{O^+}$)

$$\omega_r^2 \simeq \Omega_O^2 \left[1 + (1 - k_\perp^2 \rho_O^2)\left(\frac{k^2 V_{Te}^2}{\Omega_O^2} \frac{m_e}{m_O} \frac{n_O}{n_e} - \frac{\Omega_O^2}{k_\parallel^2 V_{AO}^2}\right)\left(1 + \frac{n_H}{n_e} \frac{m_H}{m_O} \frac{T_e}{T_O} k_\perp^2 \rho_O^2\right)^{-1}\right]$$

Shear Alfven Wave Dispersion
(H^+-O^+ Plasma)

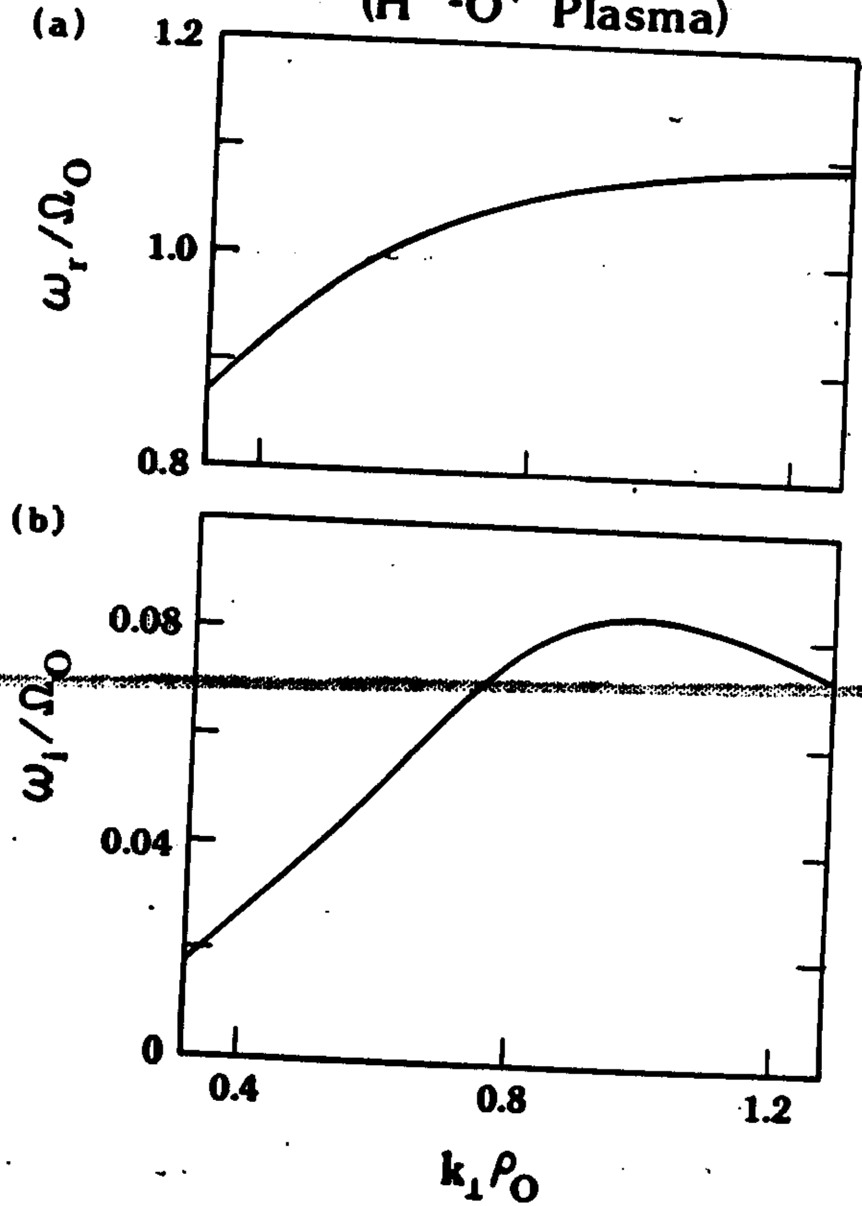
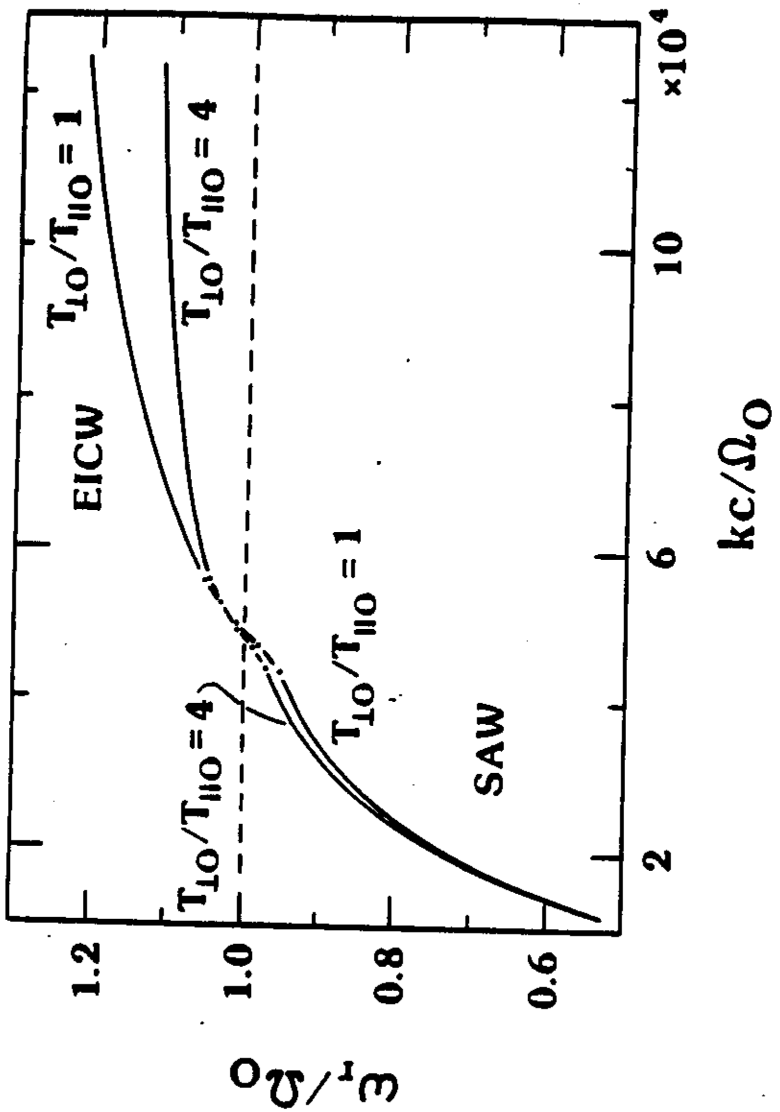
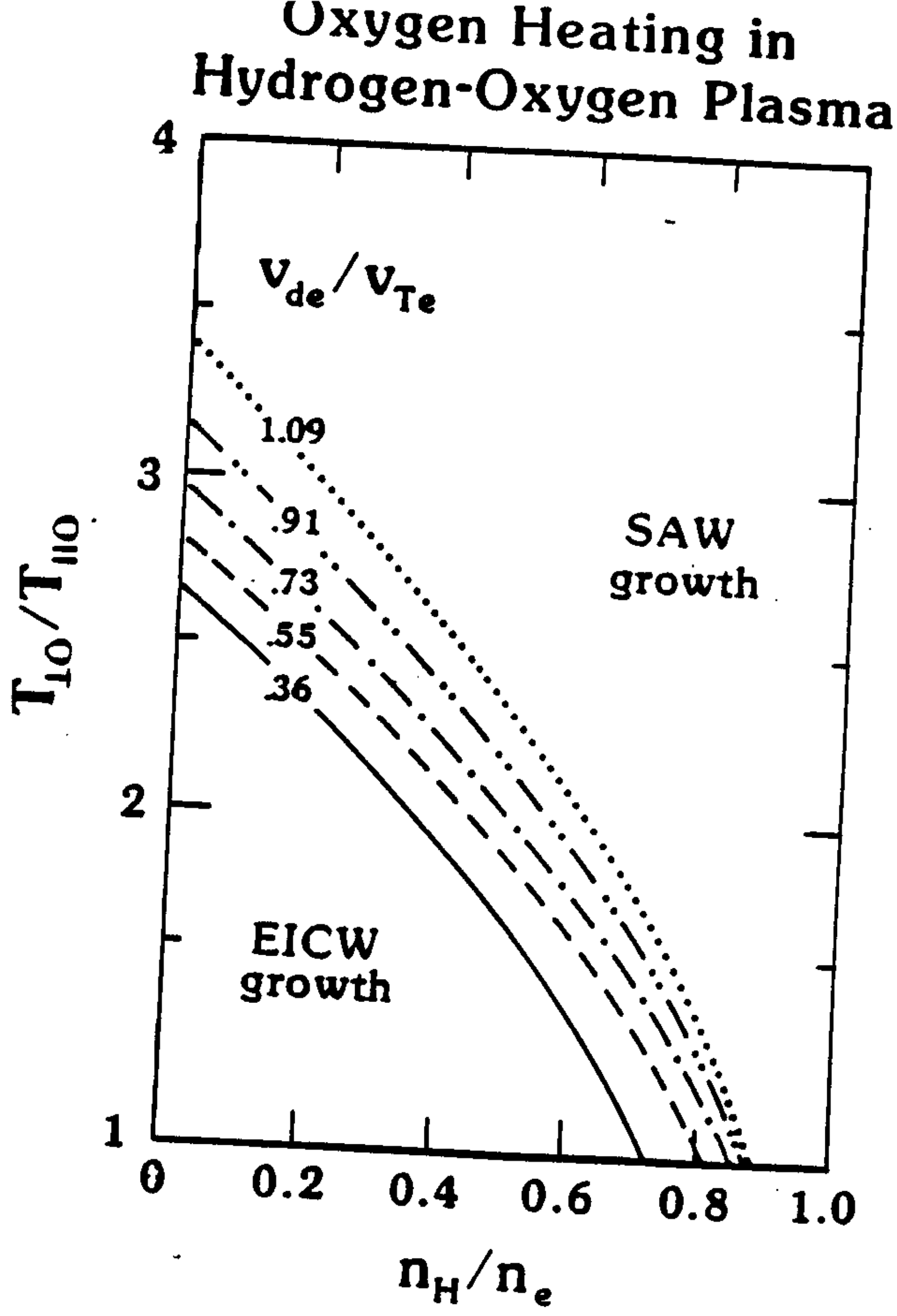


Figure 1



EICW
SAW
T⊥O/T∥O = 1
T⊥O/T∥O = 4
T⊥O/T∥O = 1
T⊥O/T∥O = 4
kc/ΩO
×10⁴
ωr/ΩO



Oxygen Heating in
Hydrogen-Oxygen Plasma
Vde/VTe
1.09
.91
.73
.55
.36
SAW
growth
EICW
growth
T⊥O/T∥O
nH/ne

Figure 2

(5) Simulation model and Configuration

- Physical effects needed in simulation model to model dynamics of shear Alfven wave

  (i) parallel e^- Landau resonance ($\omega/k_\parallel \lesssim V_{Te}$)

  (ii) $T_i \neq 0$

  (iii) Electrostatic (Poisson Eq.) + Electromagnetic (Amperes Eq.) Fields.

  (iv) Maintenance of source (e^-) distribution (Prevent quasilinear effects)

- Particle dynamics

Electrons (drift-kinetic)

$$\omega < \omega_{ce}, \quad k_\perp \rho_e < 1$$

$$\begin{cases} m_e \, dv_\parallel/dt = -|e| E_\parallel \\ \underset{\sim}{V}_{\perp e} = c \, \underset{\sim}{E}_\perp \times \underset{\sim}{B} / B^2 \end{cases}$$

Ions (Exact)

$$\left\{ m_i \, d\underset{\sim}{V}_i/dt = |e| \left(\underset{\sim}{E} + \underset{\sim}{V} \times \underset{\sim}{B}/c \right) \right.$$

- Fields (low β)

$$\underset{\sim}{E} = \underset{\sim}{E}^L + \underset{\sim}{E}^T$$

$$\underset{\sim}{\nabla} \times \underset{\sim}{B} = \frac{4\pi}{c} \underset{\sim}{J} + \cancel{\frac{1}{c} \frac{\partial \underset{\sim}{E}^T}{\partial t}} \quad (\omega < ck)$$

- Darwin approx. to Ampere's law
- Field equations

$$\begin{cases} \underset{\sim}{\nabla} \cdot \underset{\sim}{E}^L = 4\pi\rho \\ \nabla^2 \underset{\sim}{E}^T = \frac{4\pi}{c^2} \frac{\partial \underset{\sim}{J}^T}{\partial t} = \frac{4\pi}{c^2} \frac{\partial}{\partial t} \left(\sum_i q_i \underset{\sim}{V}_i \, \delta(\underset{\sim}{x} - \underset{\sim}{x}_i) \right) \\ \underset{\sim}{\nabla} \times \underset{\sim}{B}^T = \frac{4\pi}{c} \underset{\sim}{J}^T \end{cases}$$

$$B^T_{x,y} \gg B^T_z$$

(neglect compressional effects)

Simulation Configuration

(H^+-O^+ plasma)

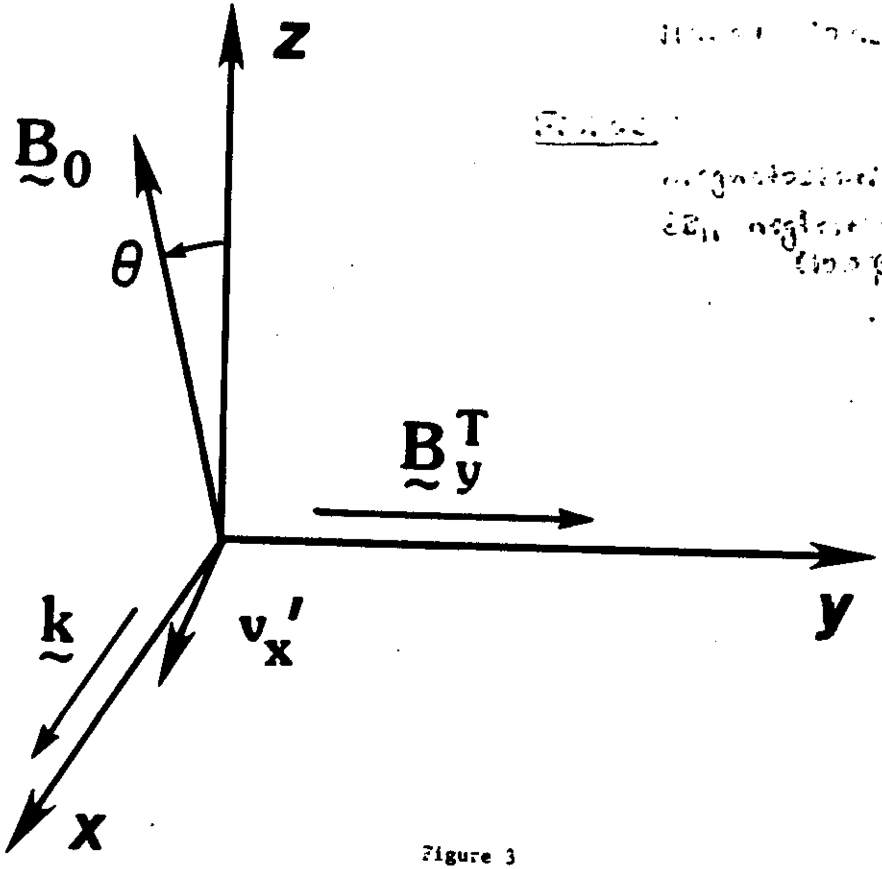


Figure 3

PARALLEL DISTRIBUTION FUNCTIONS

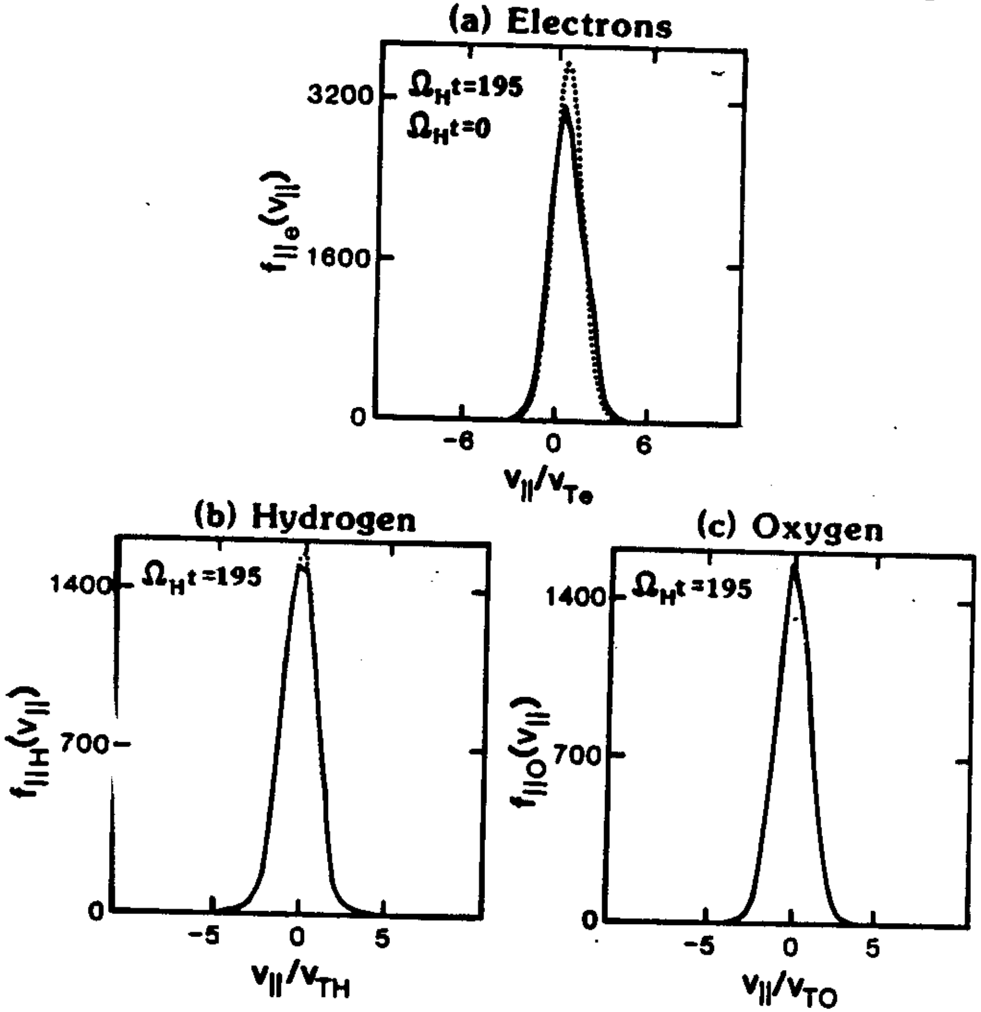


Figure 9

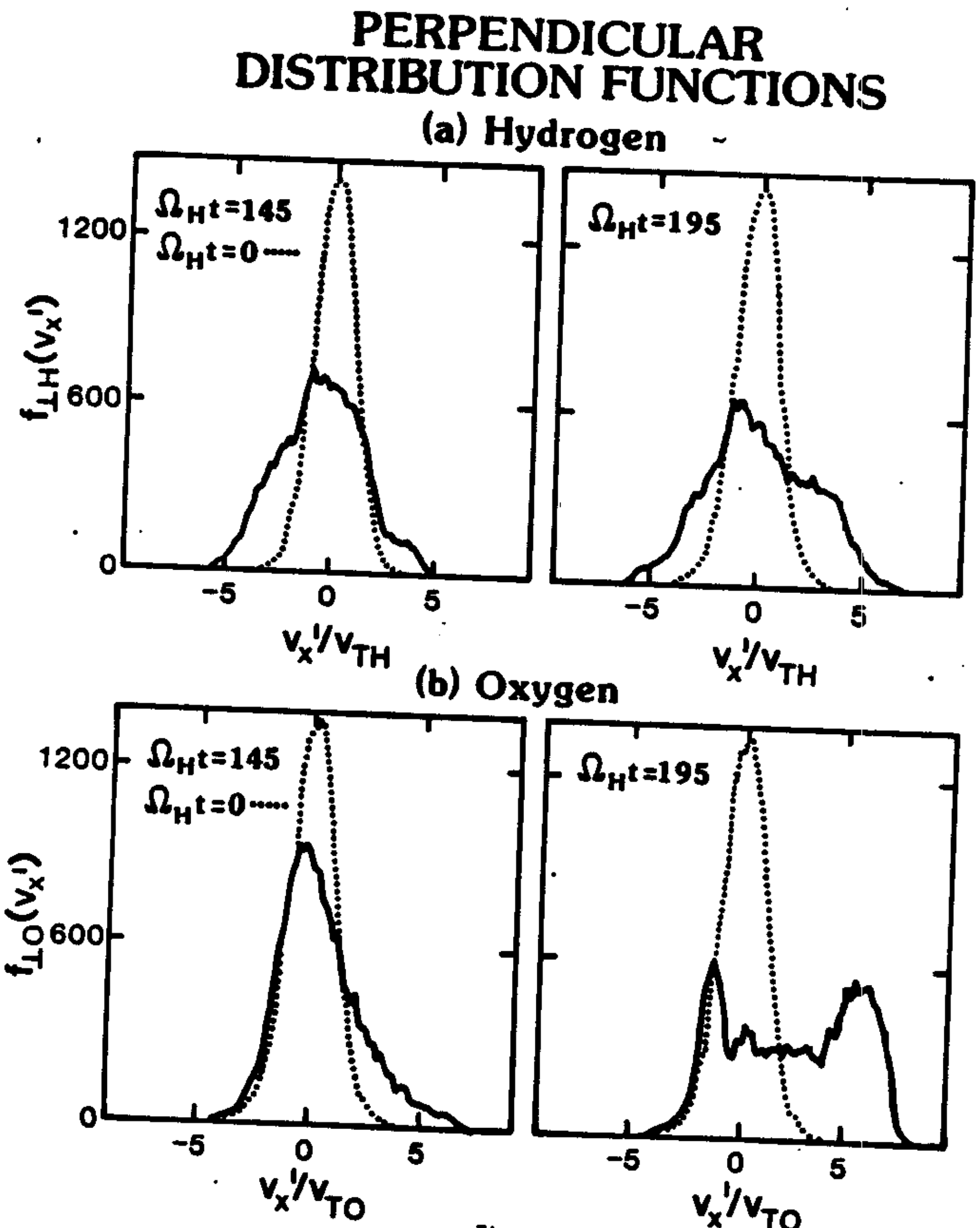


Figure 6

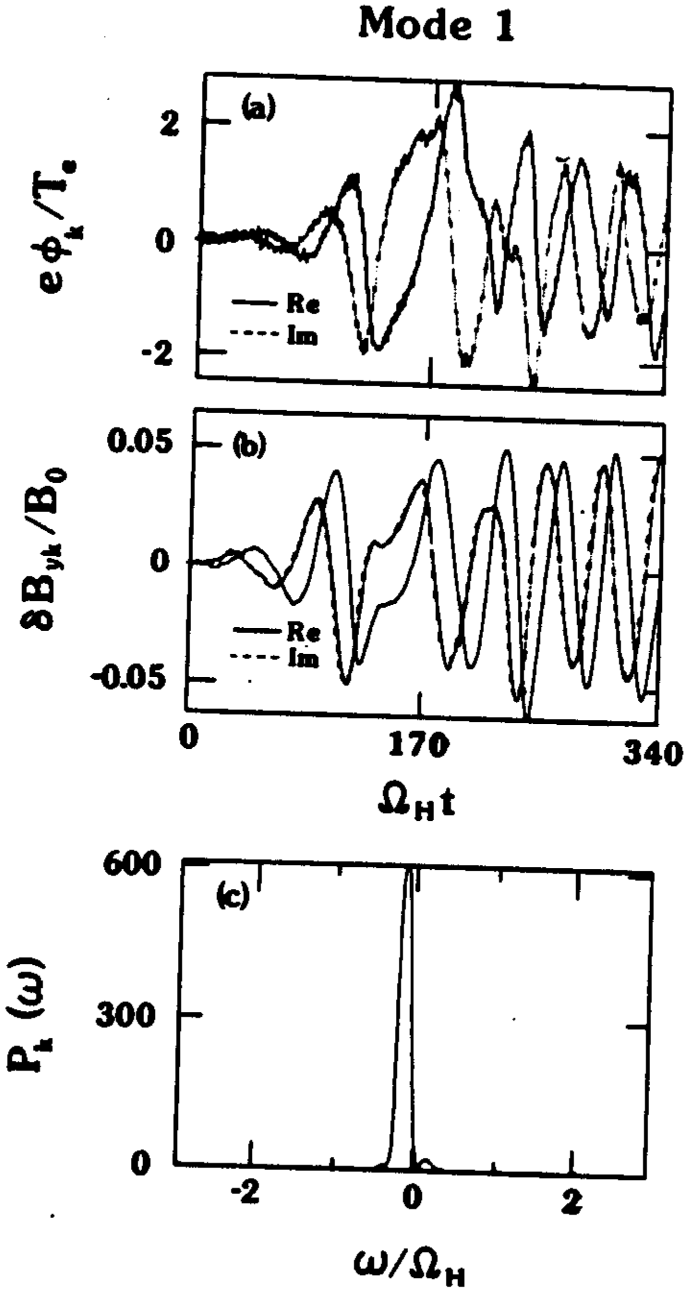


Figure 5

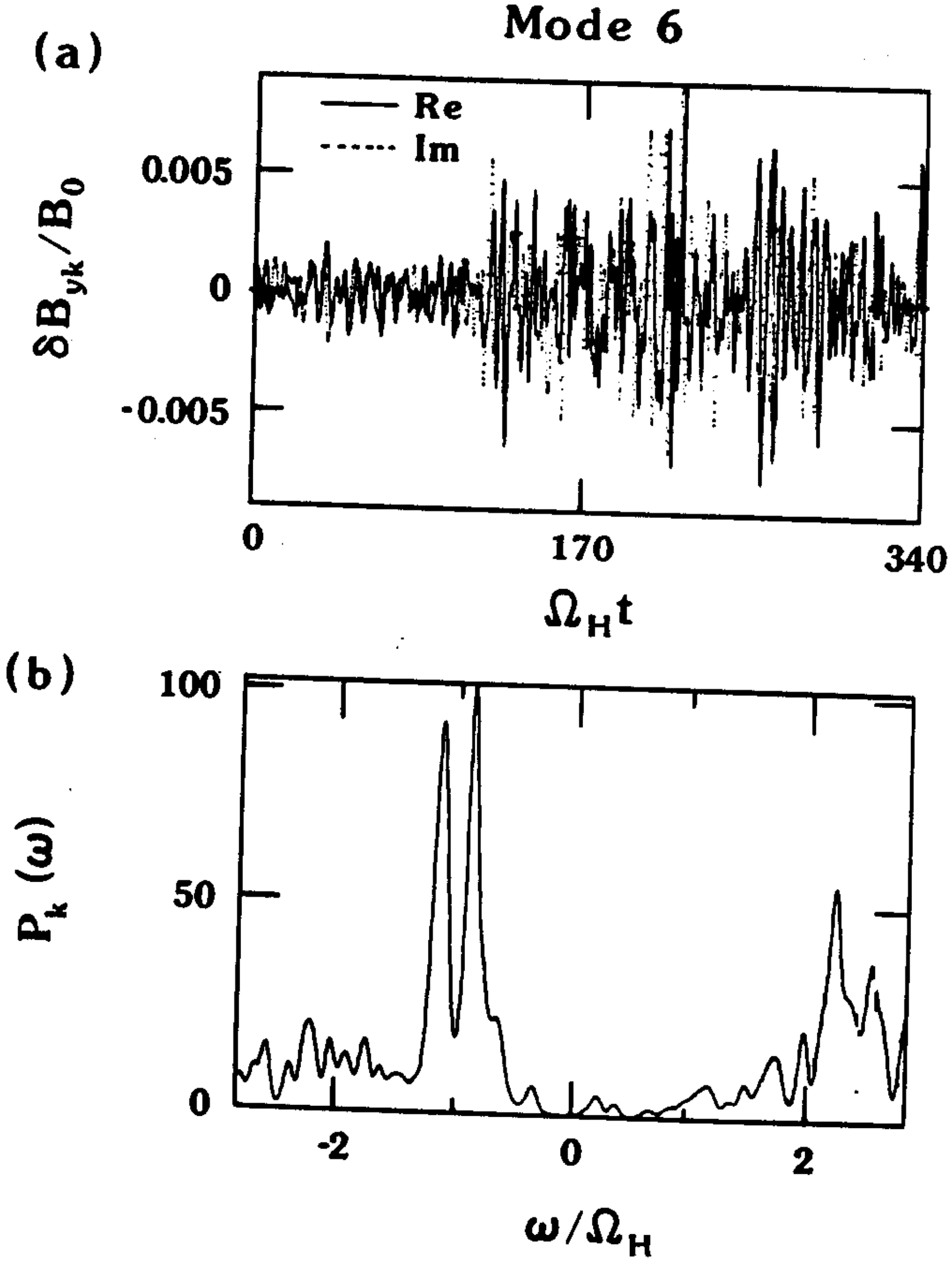


Figure 6

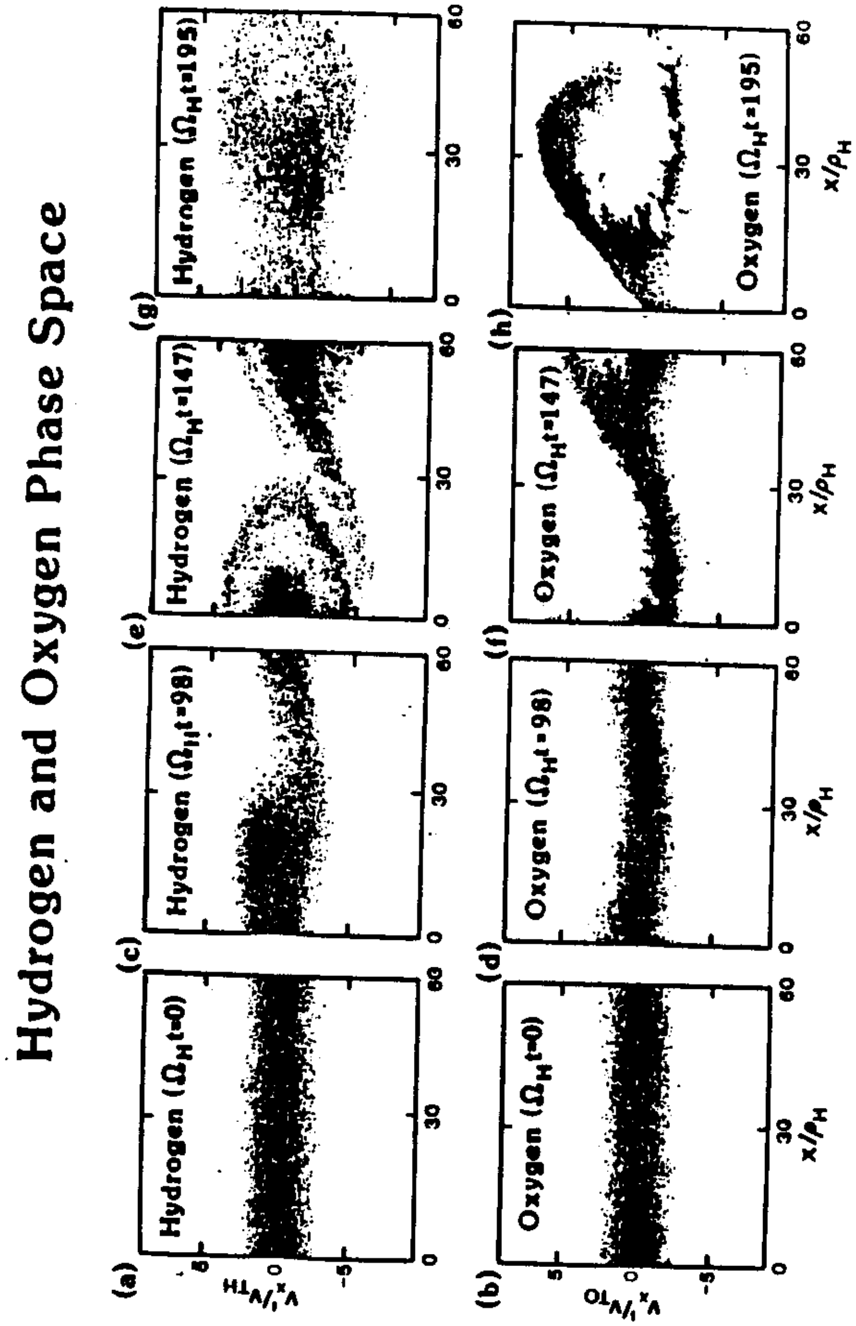


Figure 7

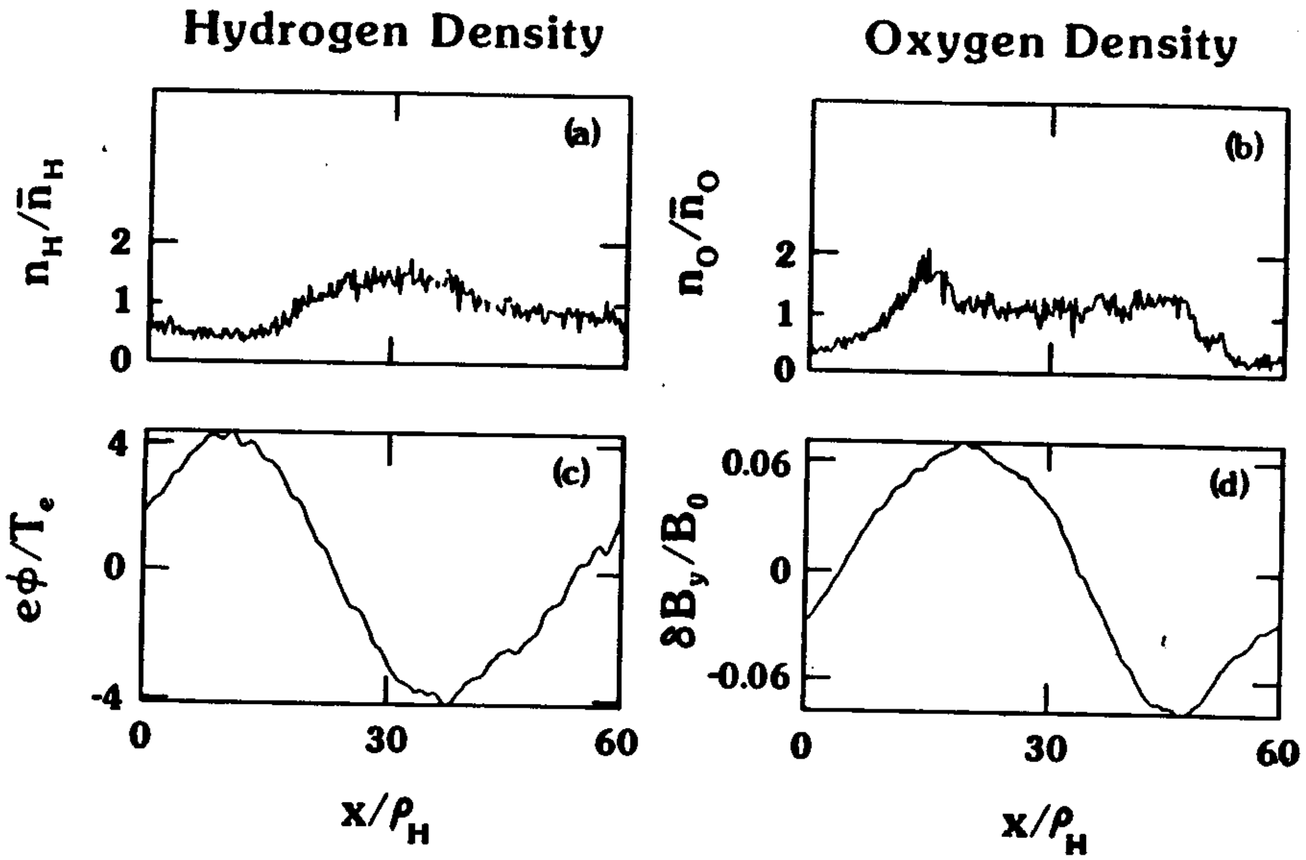


Figure 4

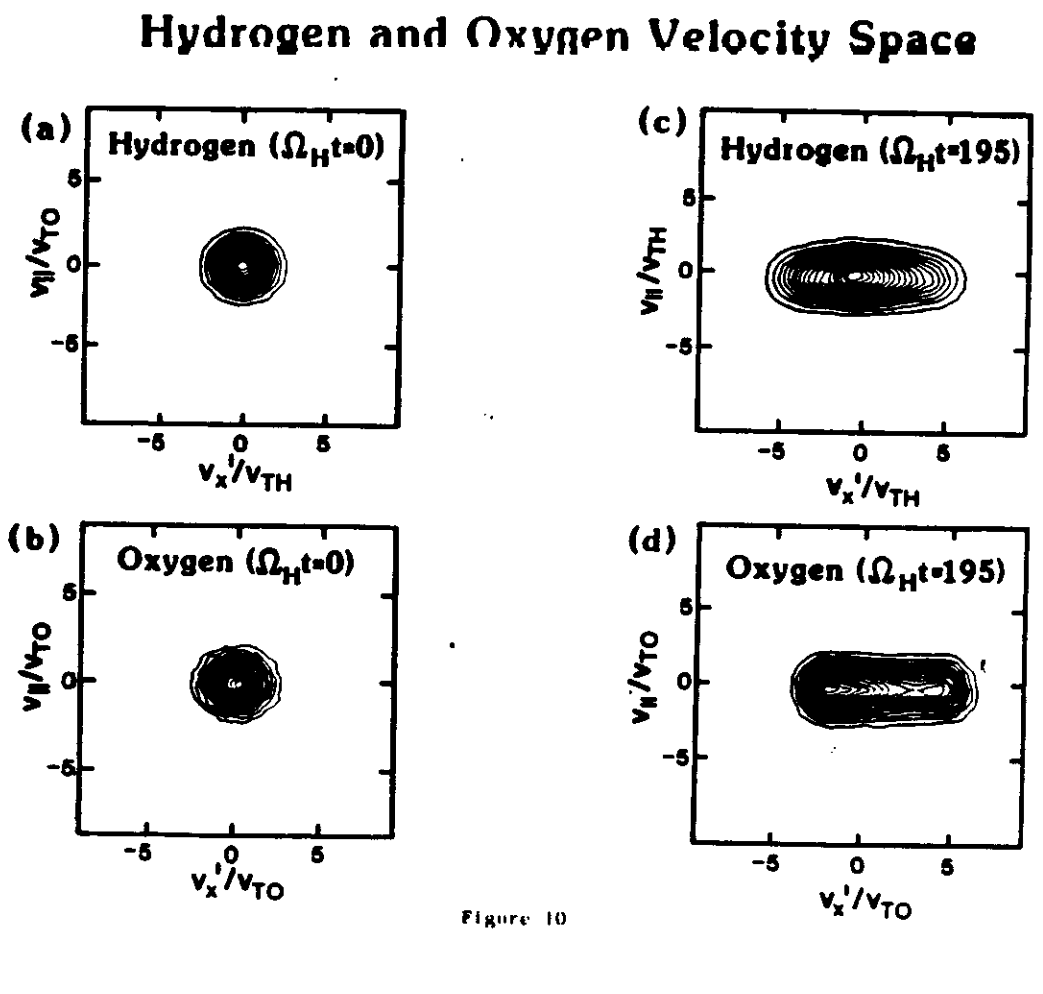


Figure 10

PERPENDICULAR ION TEMPERATURES

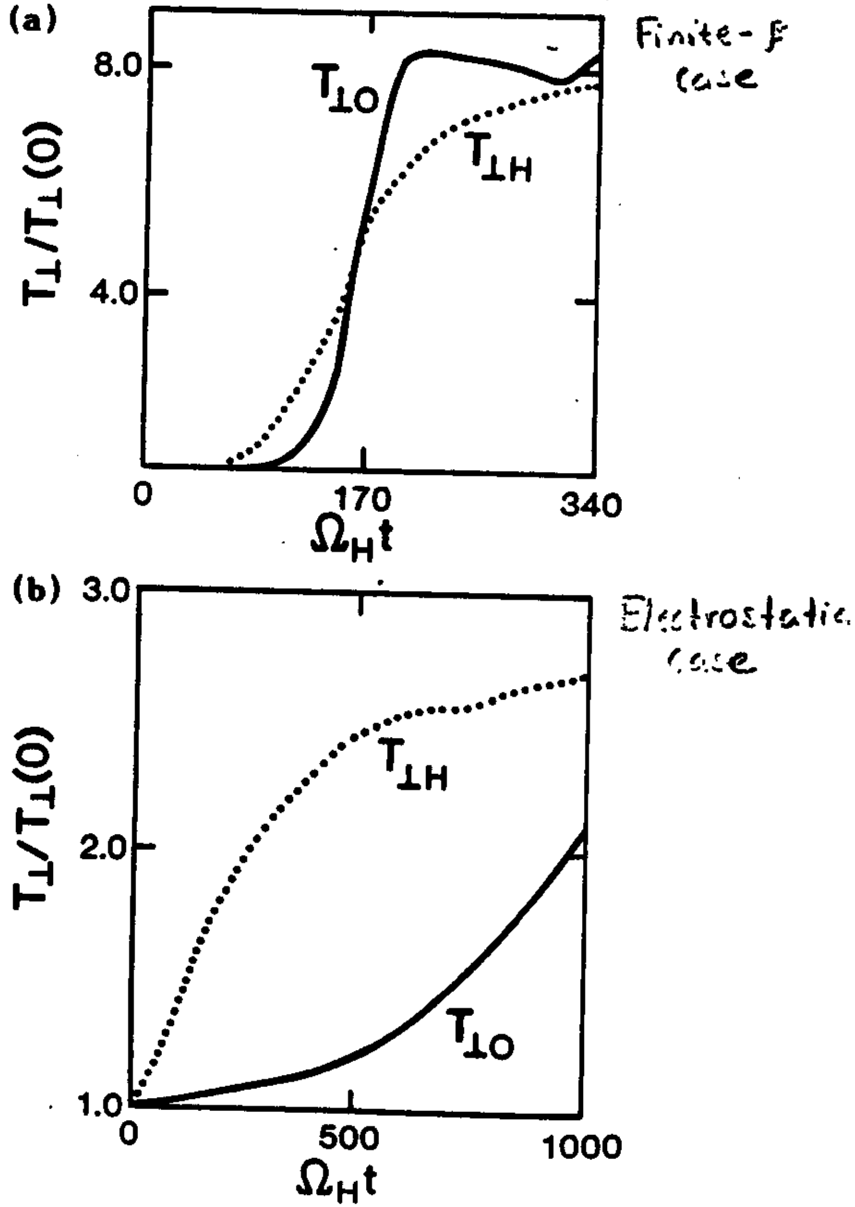


Figure 11

→ Electrostatic Only

[illegible] ⇒ Amp. of [illegible] and Spectrum [illegible]

[illegible]

The [illegible] equation

$$\frac{\partial \langle f \rangle}{\partial t} = \frac{\partial}{\partial \underline{v}} \cdot D \cdot \frac{\partial \langle f \rangle}{\partial \underline{v}}$$

$D \sim |\hat{E}|^2$

$$\rightarrow \frac{\partial \langle f \rangle}{\partial t} = \frac{1}{v_\perp} \frac{\partial}{\partial v_\perp} D_\perp (v_\perp, t)\, v_\perp \frac{\partial \langle f \rangle}{\partial v_\perp}$$

For [illegible] ⇒ Self-similar form

$D_\perp = D_1 v_\perp^{-p}$

$\langle f \rangle \sim e^{-(\ldots)^{p+2}}$ (flat top form)

Can derive an equation for ⊥ - temp.

$$\frac{d}{dt}\left[\frac{T_\perp}{T_{\perp 0}}\right]^{(p+2)/2} = (p+2)^2 D_0(t)$$

[illegible]

$$D \propto ...$$

$$\rightarrow f \propto e^{-(v_\perp/v_0)^5} \quad \text{and} \quad T \propto t^{0.4}$$

... wave amp.

→ Electromagnetic (Finite-β)

$\tau_{AC} \sim \tau_{tr}$ Trapping Dominant

- narrow spectrum, large amplitude waves.
- $\omega_{tr} \sim k \left(\frac{e\phi}{m_i} J_N(k_\perp \rho) \right)^{1/2} \sim \gamma_L$

$$\left(\frac{e\phi_k}{T_e} \right)^{sat.} \sim \left(\frac{\gamma}{\Omega_{i}} \right)^2 \frac{1}{(k_\perp \rho_0)^2}$$

(7) Conclusions

- Current-driven shear-Alfven wave a candidate to explain perpendicular O^+ heating. Computer Simulations demonstrate the efficiency of the heating process.
- Details of heating process should be compared with observations when fields and particle distributions known. Low energy cutoffs and wave Doppler shifts make make this difficult.
- Results depend <u>on mass</u>
  ⇒ selective acceleration possible.
- Interplay between observation, theory and computer simulation needed to gain understanding of plasma dynamics in magnetosphere

- Summary of Simulation Results

  - O^+ heating from shear Alfven waves (e^- current-driven) via gyroresonance absorption.

  - Saturation due to trapping of O^+ in obliquely propagating, large amplitude shear-Alfven wave.

  - secondary H^+ heating due to light ions trapped in potential set up by O^+ ions.