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The Role of Lower Hybrid Waves in Space Plasmas

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Conference on Sun-Earth Connections: Multiscale Coupling in Sun-Earth Processes, Feb. 2004.

Summary of Talk

Introduction

- Role of Waves in the Space
- Generation of waves – nonlinear propagation
- Acceleration of Particles
- Radiation – AKR

Waves

Lower Hybrid +
Kinetic Alfven
Ion Acoustic

} ⟹ Nonlinear Structures
e.g. CAVITONS

Particles

Electron, Ion: Beams
Electron, Ion: Beams

⟹ Instabilities

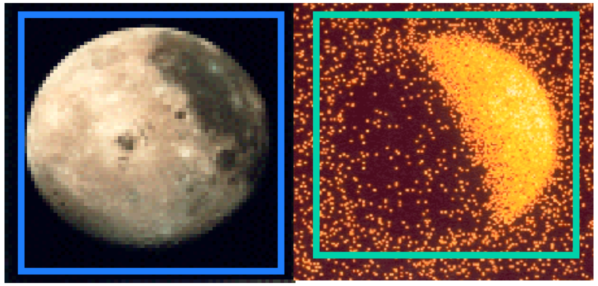
e.g. CYCLOTRON MASER

Introduction

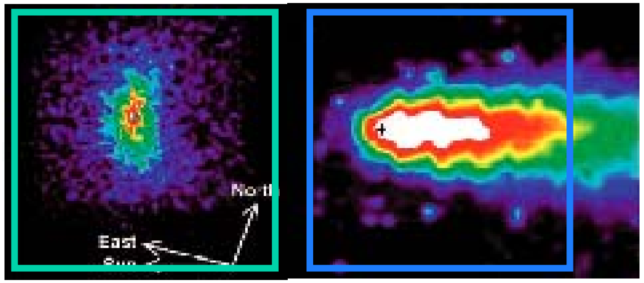
- **Interactions between the solar wind and comets and non-magnetised planets lead to the production of energetic electrons and ions which are responsible for:-**
  - X-ray Emission from Comets – Chandra and XMM spectra
  - X-rays from Planets
    - Venus
    - Earth
    - [Mars] ⇐ **Now detected in X-rays!**
    - Jupiter
      - Io torus and several Jovian moons
    - [Saturn
      - Titan] ⇐ **Future planned targets!**
- **Similar processes may also be occurring elsewhere:-**
  - Helix Nebula – Cometary Knots
  - High Velocity Clouds
  - Supernova Shock Front/Cloud Interaction
- **Theory and Modelling**
  - Energetic electron generation by lower-hybrid plasma wave turbulence
  - Comet X-ray spectral fits
  - Io torus model

Sources – Optical & X-ray Images

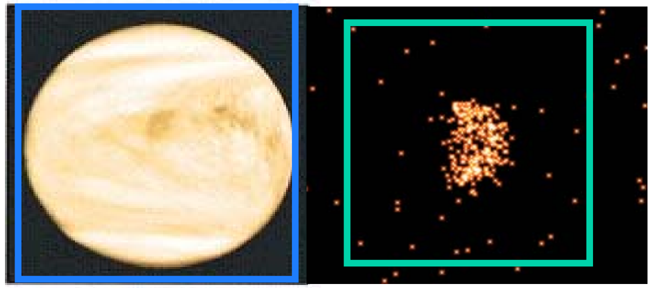
MOON



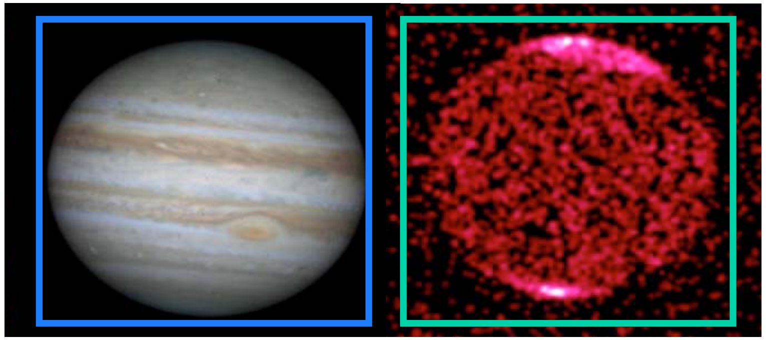
COMET C/LINEAR



VENUS

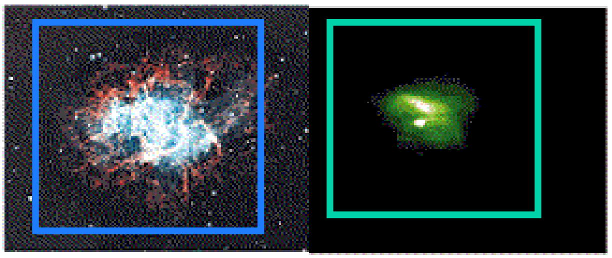


JUPITER



SUN

CRAB NEBULA (SNR)



SKY (HVCs)

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Role of Waves

Introduction:

- Large Amplitude Waves - collisionless energy and momentum transport.
  - Formation of coherent nonlinear structures.
- Kinetic Alfven waves and ion cyclotron waves
  - Accelerate ions parallel to the magnetic field
  - Ponderomotive force also creates density striation structures
    - **Kinetic Alfven wave Solitons – SKAWs**
- Lower-Hybrid
  - Accelerates electrons parallel to the magnetic field
  - Accelerates ions perpendicular to the magnetic field
  - Formation of cavitons
- Langmuir Waves – consequences of electron beams
- Ion (electron) acoustics
- Whistlers + LH present at reconnection sites
- Anisotropic electron beam distributions $\Rightarrow$ AKR (Auroral Kilometric Radiation)

Lower-Hybrid Waves in Space Plasmas

- Auroral region
  - Precipitating electrons, perpendicular ion heating (Chang & Coppi, 1981).
  - Ion horseshoe distributions – electron acceleration.
  - Cavitons (Shapiro et al., 1995).
- Magnetopause
  - L-H turbulence – cross field e^- transport, diffusion close to Bohm.
  - Anomalous resistivity – reconnection (Sotnikov et al., 1980; Bingham et al., 2004).
- Bow Shock
  - Electron energization (Vaisling et al., 1982).
- Magnetotail
  - Anomalous resistivity, LHDI (Huba et al., 1993; Yoon et al., 2002).
  - Current disruption (Lui et al., 1999).

Lower-Hybrid Waves in Space Plasmas (cont.)

- Mars, Venus (Mantle region)
  - Accelerated electrons, heated ions (Sagdeev et al., 1990; Dobe et al., 1999).
- Comets
  - Electron heating (Bingham et al., 1997).
- Critical velocity of ionization
  - Discharge ionization (Alfven, 1954; Galeev et al., 1982).
- Artificial comet release experiments
  - AMPTE comet simulations (Bingham et al., 1991).

Lower-Hybrid Waves in Space Plasmas

$$\omega_{pp} \ll \omega_{LH} \ll \omega_{ce}, \quad \mathbf{k} \perp \mathbf{B_0} \quad \text{with small } k_{\|}$$

- Hence electrons are magnetized, ions are unmagnetized.
- Cerenkov resonance with electrons parallel to the magnetic field:-

$$\frac{\omega}{k_{\|}} = v_{e\|}$$

- Cerenkov resonance with ions perpendicular to magnetic field:-

$$\frac{\omega}{k_{\perp}} = v_{i\perp} \qquad\qquad k_{\|} \ll k_{\perp}$$

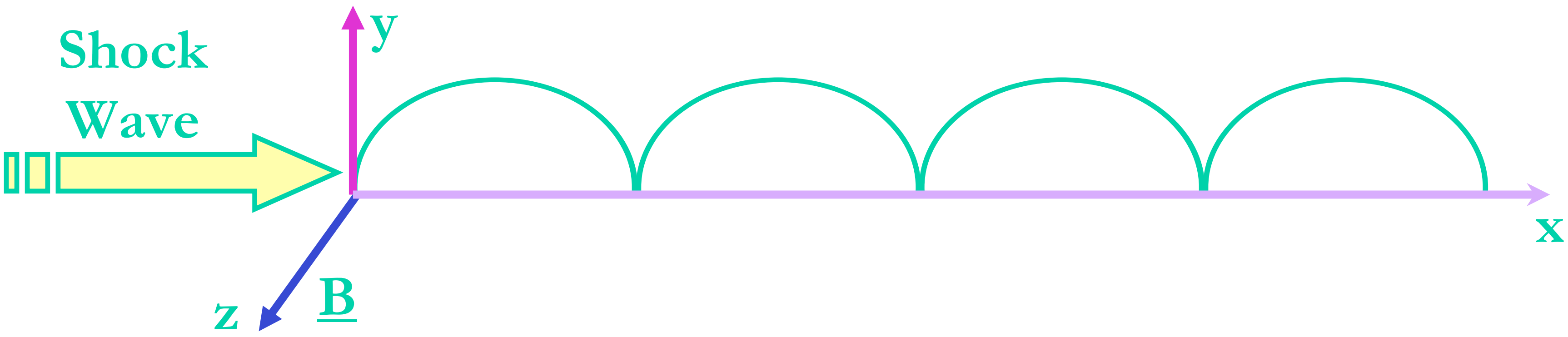
- Simultaneous resonance with fast electrons moving along <u>*B*</u> and slow ions moving across <u>*B*</u>.
- Transfers energy from ions to electrons (or vice versa)

$$\omega = \frac{\left(\omega_{pp}^2 + \omega_{pe}^2 \frac{k_{\|}^2}{k^2}\right)^{\frac{1}{2}}}{\sqrt{\varepsilon_e}} = \frac{\left(\omega_{pp}^2 + \omega_{pe}^2 \frac{k_{\|}^2}{k^2}\right)^{\frac{1}{2}}}{\left(1 + \frac{\omega_{pe}^2}{\omega_{ce}^2}\right)^{\frac{1}{2}}}$$

where $\omega_{pp} = \sqrt{\dfrac{4\pi n_0 e^2}{m_p}}$

Generation of Lower-Hybrid Waves at Shocks

As the plasma flows through the interacting medium, pick-up ions form an anisotropic distribution



These ions move in the crossed E and B fields - following cycloidal paths:-

$$\mathrm{v}_x = u_\perp\left(1 - \cos\omega_{ci}(t - t_0)\right) \qquad \mathrm{v}_y = u_\perp\left(\sin\omega_{ci}(t - t_0)\right)$$

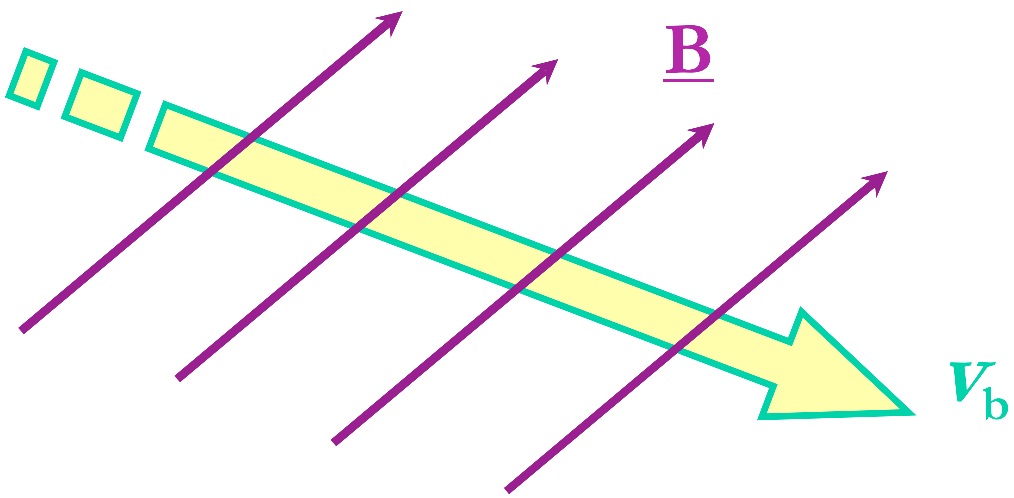
where $u_\perp = E / B$ **is the shock wave velocity ⊥ to the magnetic field B.**

Ion Pick-Up in Comets (also Mars & Venus)

- **If B ⊥ v_{SW} the heavy ions are carried away by the streaming plasma (pick-up)**
- **Energy** $\varepsilon_\perp = \frac{m_i \mathrm{V}_i^2}{2}$

keV $= 20$ **for N, $v_\perp \sim 400$ km/sec**

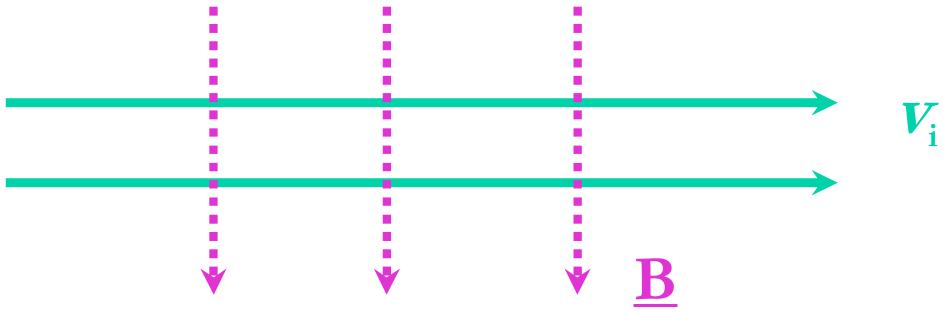
i.e. a beam is formed



The beam is unstable ⇒ modified two stream instability (MTSI) (McBride et al. 1972).

The Modified Two Stream Instability

- A cross-field ion beam generates lower-hybrid waves



Lower-hybrid dispersion relation

$$1 + \frac{k_\perp}{k^2}\frac{\omega_{pe}^2}{\omega_{ce}^2} + \frac{k_z^2}{k^2}\frac{\omega_{pe}^2}{\omega^2} - \frac{\omega_{pi}^2}{\omega^2} = 0$$

$$k_\perp = k_x^2 + k_y^2, \qquad k = k_\perp^2 + k_\parallel^2, \qquad k_\parallel = k_z, \qquad k_\perp >> k_\parallel$$

$$\Rightarrow \quad v_\perp = \frac{\omega}{k_\perp}, \qquad v_\parallel = \frac{\omega}{k_\parallel}$$

$$\therefore \quad v_\perp << v_\parallel$$

- **Dispersion relation changes when an ion beam is present -**

$$1+\frac{k_x^2}{k^2}\frac{\omega_{pe}^2}{\omega_{ce}^2}-\frac{k_z^2}{k^2}\frac{\omega_{pe}^2}{\omega^2}-\frac{\omega_{pi}^2}{(\omega-\underline{k}\cdot\underline{u}_i)^2}=0 \qquad (1)$$

u_i is ⊥ ion beam, $k_z = k_{||}$

(Fluid limit $k\rho_e \ll 1, \quad k\mathrm{v}_i < |\omega-\underline{k}\cdot\underline{u}_i|, \quad k_{\|}\mathrm{v}_e \le \omega$ **)**

For

$$\frac{k_z}{k}\sim\left(\frac{m_e}{m_i}\right)^{1/2}, \qquad \frac{k_x^2}{k^2}\cong 1$$

Then (1) becomes $$1+\frac{\omega_{pe}^2}{\omega_{ce}^2}-\frac{\omega_{pe}^2}{\omega^2}-\frac{\omega_{pi}^2}{(\omega-\underline{k}\cdot\underline{u}_i)^2}=0$$

Let $\omega'=\omega-\frac{1}{2}\underline{k}\cdot\underline{u}_i$ **ω′ is complex** $\omega'=x+iy$

⇒ growth rate $$\gamma=\frac{\frac{1}{2}\omega_{pi}}{\left(1+\omega_{pe}^2/\omega_{ce}^2\right)^{1/2}}\cong\frac{1}{2}\omega_{LH}$$

$$\gamma\cong\frac{1}{2}\omega_{LH}$$

Electron Acceleration by Lower-Hybrid Waves

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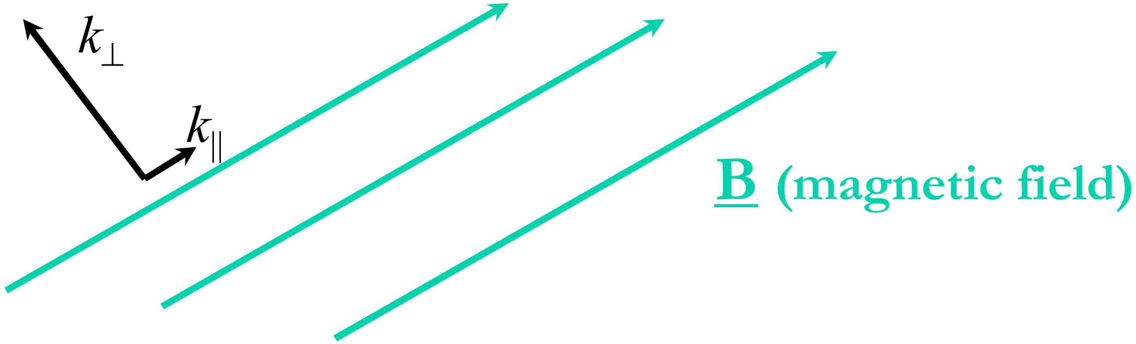

- Parallel component resonates with electrons $\quad \mathrm{v}_e \cong \dfrac{\omega}{k_\parallel}$

- Perpendicular component resonates with ions $\quad \mathrm{v}_i \cong \dfrac{\omega}{k_\perp}$

  - **Note** $\quad \dfrac{k_\perp}{k_\parallel} \sim \left(\dfrac{m_i}{m_e} \right)^{\frac{1}{2}}$

- **Model** **LH waves transfer energy between ions and electrons**

ION BEAM $V_i = V_{i\perp}$	$\Rightarrow$	Lower-Hybrid Waves	$\Rightarrow$	Energetic Electrons $V_e = V_{e\perp}$

Energy Balance at Shocks

- **The free energy is the relative motion between the shock wave and the newly created interaction ions.**
- **Characteristic energy and density of suprathermal electrons obtained using conservation equations between energy flux of ions into wave turbulence and absorption of wave energy by electrons.**
- **In steady state energy flux of pick-up ions equals energy flux carried away by suprathermal electrons.**

Energy flux balance equation:-

$$\alpha\, n_{ci}\, m_{ci}\, u_{SSW}^{3} \cong n_{Te}\, \varepsilon_e \left(\frac{\varepsilon_e}{m_e}\right)^{\frac{1}{2}} \qquad (2)$$

- **Balancing growth rate of lower-hybrid waves γ_i due to interaction pick-up ions with Landau damping rate γ_e on electrons.**

$$\gamma_i + \gamma_e = 0 \quad \Rightarrow \quad \frac{n_{Te}}{\varepsilon_e} \cong \frac{n_{ci}}{m_{ci} u^2} \qquad (3)$$

Example

From 2 and 3 the average energy of the suprathermal electrons is given by

$$\varepsilon_e \cong \alpha^{2/5}\left(m_e / m_{ci}\right)^{1/5} m_{ci} u_{SSW}^2$$

- **For nitrogen ions** $m_{ci}u^2 \approx$ **1 keV**

  Average energy $\varepsilon_e \sim$ **100 eV**

  Density $n_{Te} \approx$ **1 cm^{-3}**

  ⇒ **Powerful source of suprathermal electrons**

  ⇒ **10^{19} erg/sec through X-ray region.**

- **Electron energy spectrum obtained by solving the quasi-linear velocity diffusion equation.**

$$v_\parallel \frac{\partial f_e}{\partial v_\parallel} = \frac{e^2}{m_e^2}\frac{\partial}{\partial v_\parallel}\left\{\frac{\langle |E|^2\rangle}{\Delta k_\parallel \cdot v_\parallel}\cdot\frac{\partial f_e}{\partial v_\parallel}\right\} \quad (4)$$

Note $\Delta k_\parallel v_\parallel = \omega_{LH}$; $\langle |E|^2 \rangle$ **L-H wave field.**

Max. electron energy

$$\varepsilon_{emax} \cong \left[\frac{e^2}{2\pi\, m_e^{1/2}} l \langle E_f^2 \rangle\right]^{2/3} \quad (5)$$

Quasi-Linear Model

- The electron energy spectrum can be obtained by solving the standard quasilinear diffusion equation. Since electrons are magnetised in the lower-hybrid oscillation only field aligned motion is allowed leading to the 1-D stationary case (e.g. Davidson, 1977):

$$v_{\|}\frac{\partial f_e}{\partial z}=\frac{e^2}{2m_e^2}\frac{\partial}{\partial v_{\|}}\left[\int dk_{\|}\left|E_{\|k}\right|^2\delta\left(k_{\|}v_{\|}-\omega_k\right)\frac{\partial f_e}{\partial v_{\|}}\right]$$

Here, $f_e(z,v_{||})$ is the one dimensional electron distribution function, $|E_{||k}|^2$ is the one dimensional electric field spectral density, z is the magnetic field direction and $v_{||}$ denotes the electron velocity parallel to B. Rewriting the electric field spectral density in the electrostatic limit

$$\left|E_{\|k}\right|^2=\left|E_k\right|^2\frac{k_{\|}^2}{k^2}$$

and then integrating over $k_{||}$ with the help of the δ function, leads to the Fokker-Planck equation:

$$v_{\|}\frac{\partial f_e}{\partial z}=\frac{e^2}{m_e^2}\frac{\partial}{\partial v_{\|}}\left[\frac{\left|E_k\right|^2 k_{\|}^2/k^2}{\left|v_{\|}-\partial\omega/\partial k_{\|}\right|_{k_{\|}=\omega_k/v_{\|}}}\frac{\partial f_e}{\partial v_{\|}}\right]$$

- Using $$\omega_k = \omega_{ce}\frac{k_{||}}{k}$$
- And assuming $$\frac{k_{||}}{k} > \sqrt{\frac{m_e}{m_p}} \quad \text{and} \quad \beta \ll 1$$
- We can then write the resonant electron-wave interaction in the form $$\omega_{ce} = kv_{||}$$
- And the denominator as $$\left| v_{||} - \partial\omega \big/ \partial k_{||} \right| \simeq \frac{3}{2} v_{||} \, k_{||}^2 \big/ k^2$$
- Resonance between the electron parallel velocity and the group velocity of the waves then strongly enhances the particle diffusion.
- Using a gaussian wave spectral distribution with $\varepsilon = m_e v_{||}^2/2T_p$ has the field aligned energy of the resonant electrons normalised to the proton temperature

$$|E_k|^2 = \sqrt{\frac{\pi T_p}{m_e}} \frac{1}{\omega_{LH}} \langle E^2 \rangle \frac{\varepsilon}{\Delta} \exp\left[-\frac{(\varepsilon - \varepsilon_e)^2}{\Delta^2} \right]$$

- With some typical scale length R_0, we can normalise the acceleration distance as $\xi = z / R_0$.
- The energy diffusion equation can then be written $\frac{\partial f}{\partial \xi} = \frac{\partial}{\partial \varepsilon} G(\varepsilon) \frac{\partial f}{\partial \varepsilon}$
- The diffusion coefficient $G(\varepsilon)$ is of the form

$$G(\varepsilon) = \frac{1}{4\sqrt{\pi}} \frac{R_0 \omega_{cp}}{\sqrt{T_p / m_p}} \frac{m_p}{m_e} \frac{\omega_{pe}^2}{\omega_{ce}^2} \frac{\langle E^2 \rangle}{n_0 T_p} \frac{\varepsilon}{\Delta} \exp\left[-\frac{(\varepsilon - \varepsilon_e)^2}{\Delta^2} \right]$$

- Assuming a Lorentz shape for the spectral distribution

$$|E_k|^2 = 2 \frac{T_p}{m_e u \omega_{ce}} \frac{1}{\omega_{LH}} \langle E^2 \rangle \frac{\varepsilon^2 \Delta^3}{\left[(\varepsilon - \varepsilon_e)^2 + \Delta^2 \right]^2}$$

- Leads to

$$G(\varepsilon) = \frac{1}{2\pi} \frac{R_0 u}{\omega_{cp}} \frac{m_p}{m_e} \frac{\omega_{pe}^2}{\omega_{ce}^2} \frac{\langle E^2 \rangle}{n_0 T_p} \frac{\varepsilon^2 \Delta^3}{\left[(\varepsilon - \varepsilon_e)^2 + \Delta^2 \right]^2}$$

Solutions of the Fokker-Planck Eq.

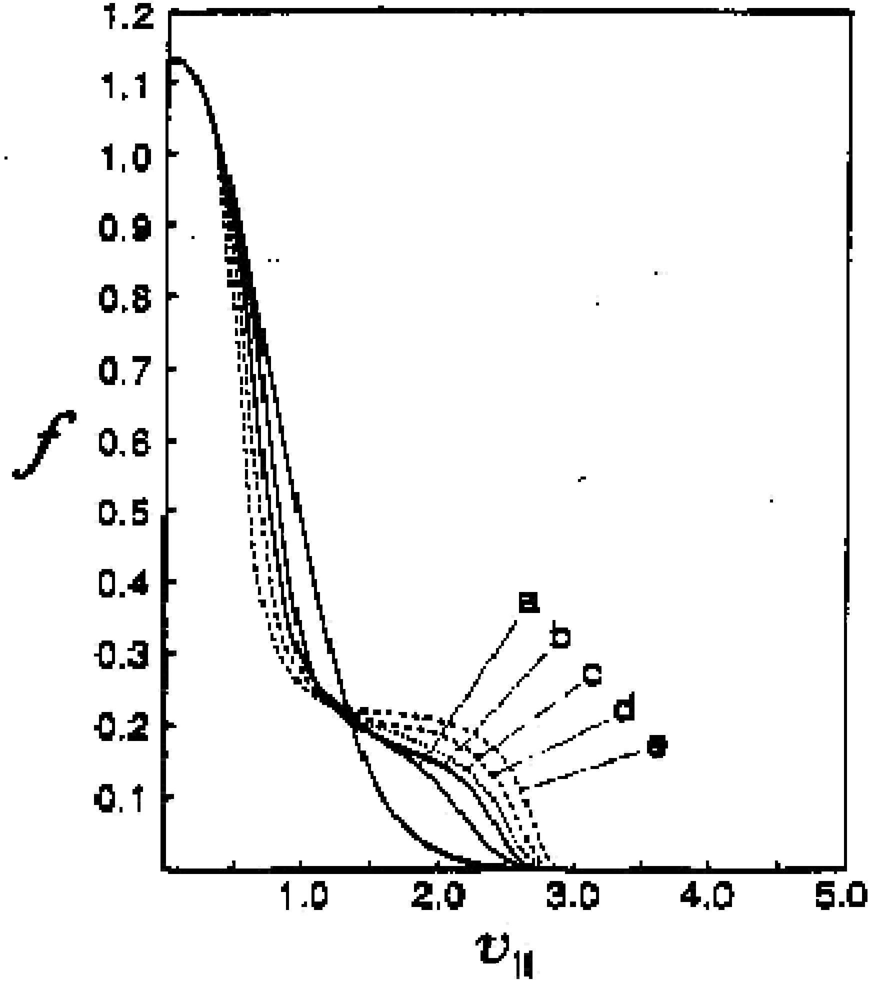

Figure 2. Dependence of computed electron distribution function f on $v_\parallel$, showing wave-driven evolution toward a plateau. The solid thick line represents the initial distribution, while the other lines denote successive time steps. The lower hybrid spectrum is centered at $\omega/k_\parallel = 1.5 v_T$.

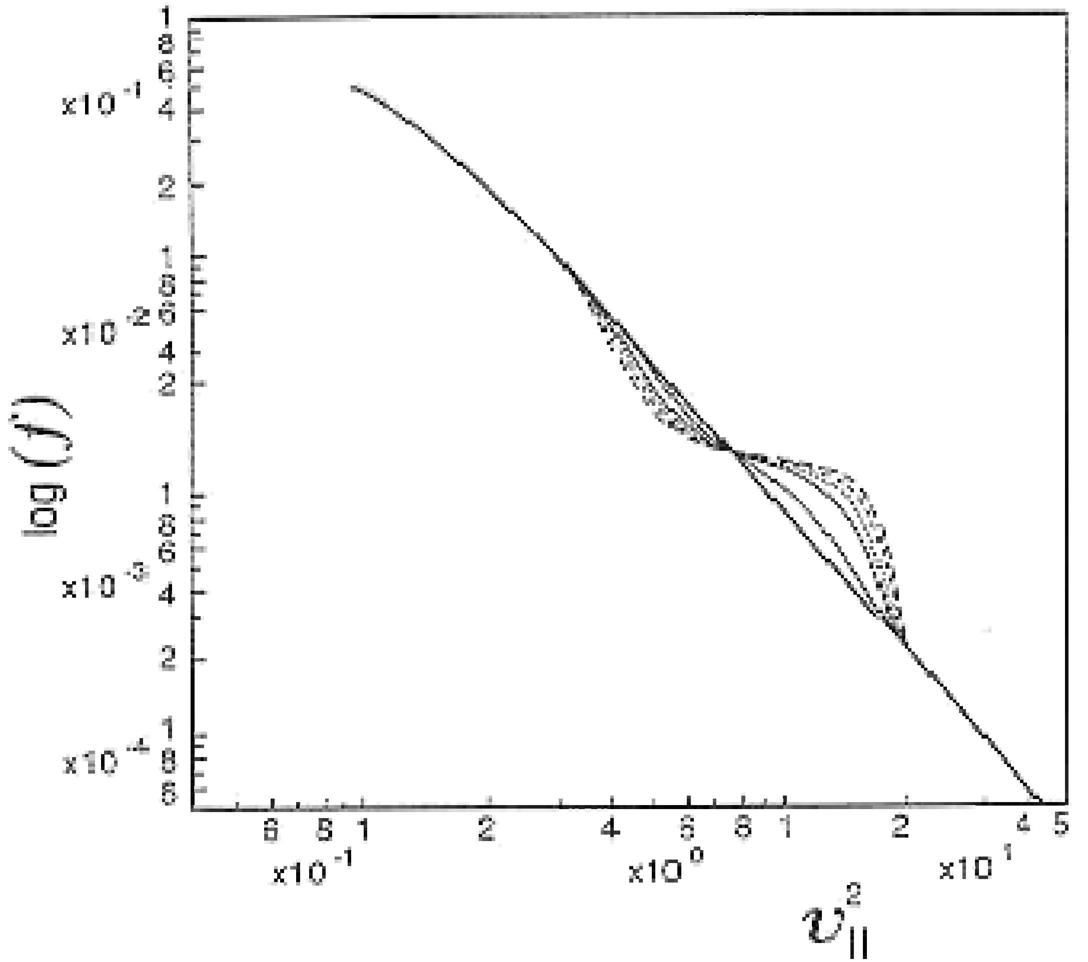

Figure 5. Numerical results for an initially power law distribution function $f(v_\parallel) \sim v_\parallel^{-5.4}$, showing phenomena similar to those occurring for initially Maxwellian distributions.

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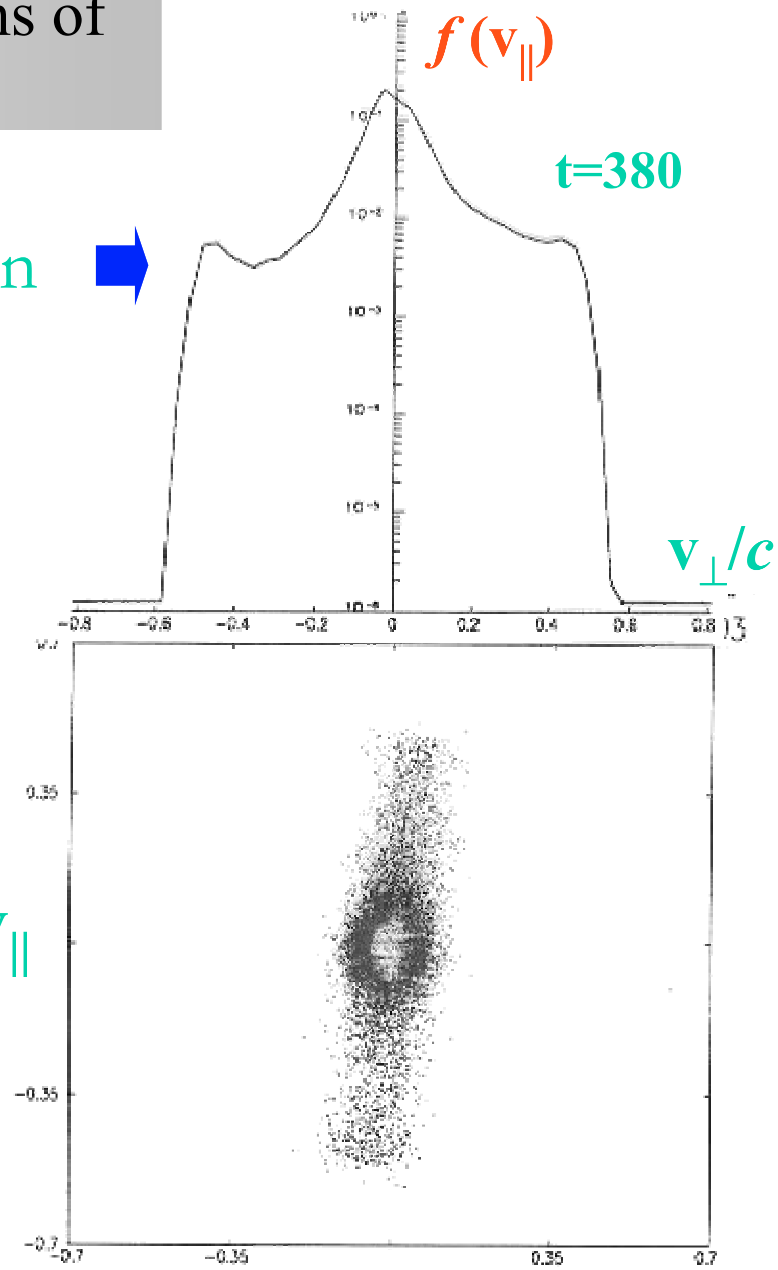
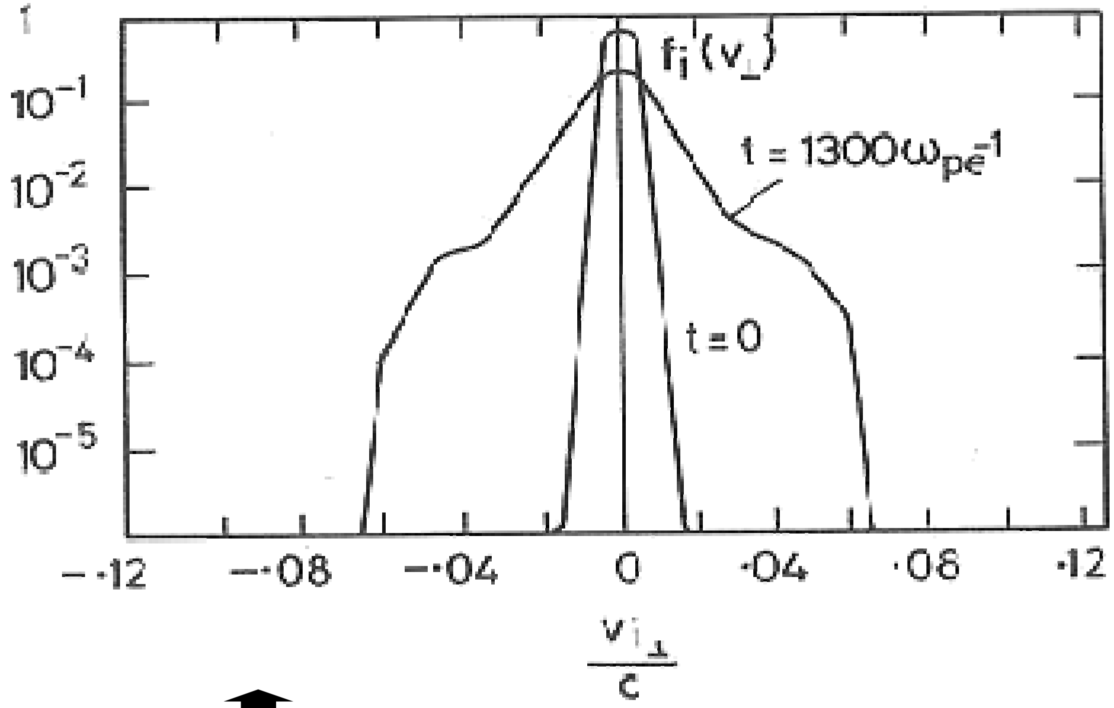
Particle-in-Cell Simulations of Cross Field Ion Flow

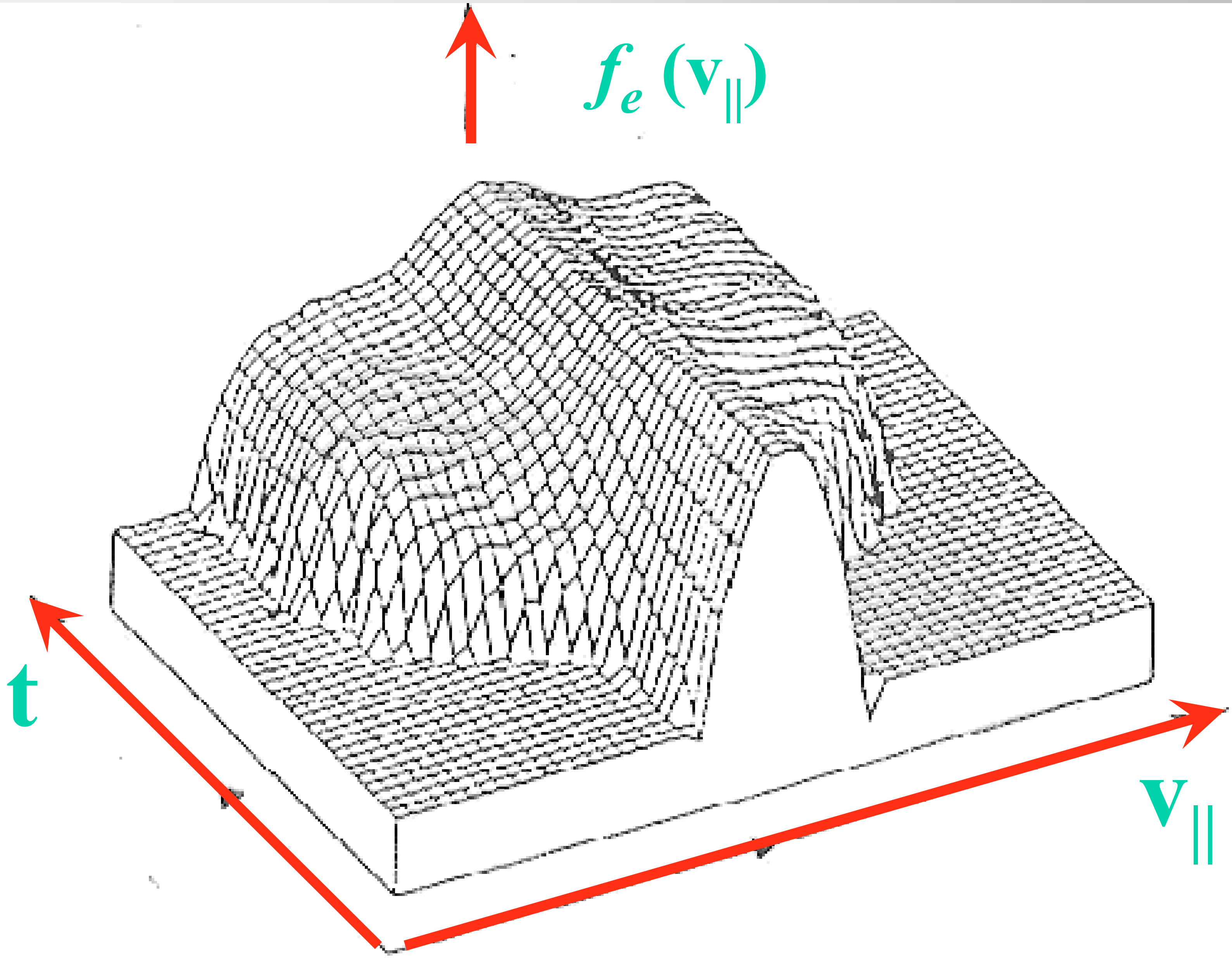
Final electron distribution





Ion energy increased by x30-100

Time evolution of the parallel component of the electron distribution



Test Particle Trajectories & Caviton Formation

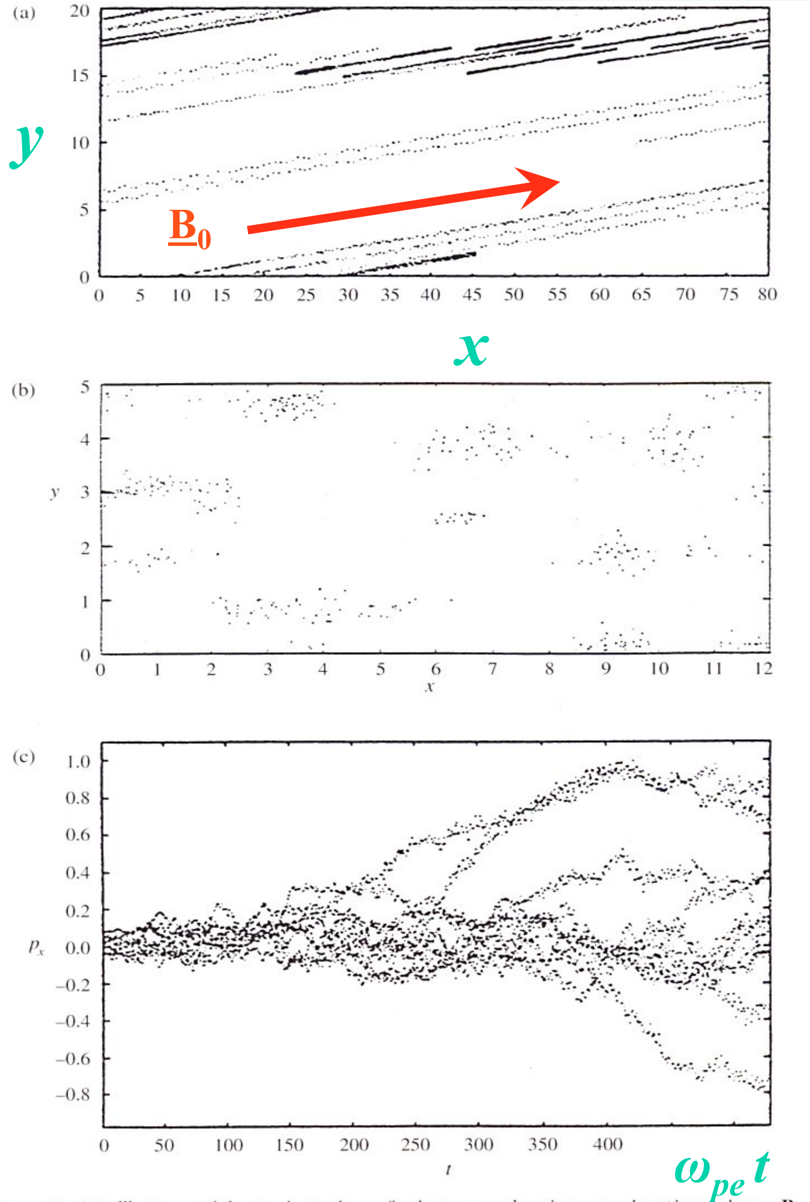


Figure 6. (a) Test particle trajectories of electrons showing acceleration along $\mathbf{B}_0$. (b) Energetic test particle electron positions in the plane perpendicular to acceleration. (c) Time history of test particle parallel momentum.

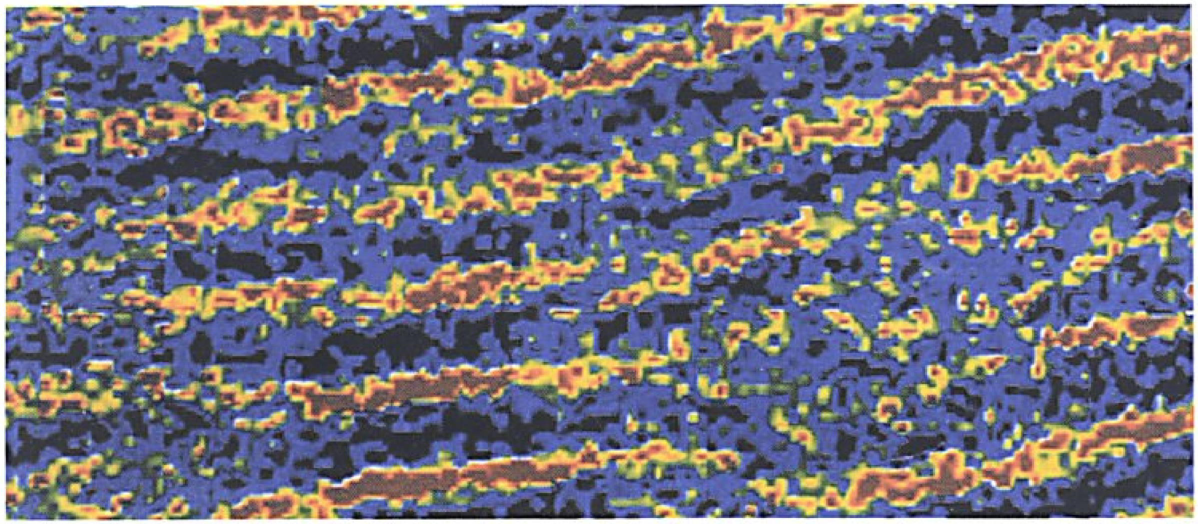


Figure 7. Caviton structures in the magnetic field direction, red indicates a more pronounced caviton density depression and stronger field strength.

Strong Turbulence/Caviton Formation

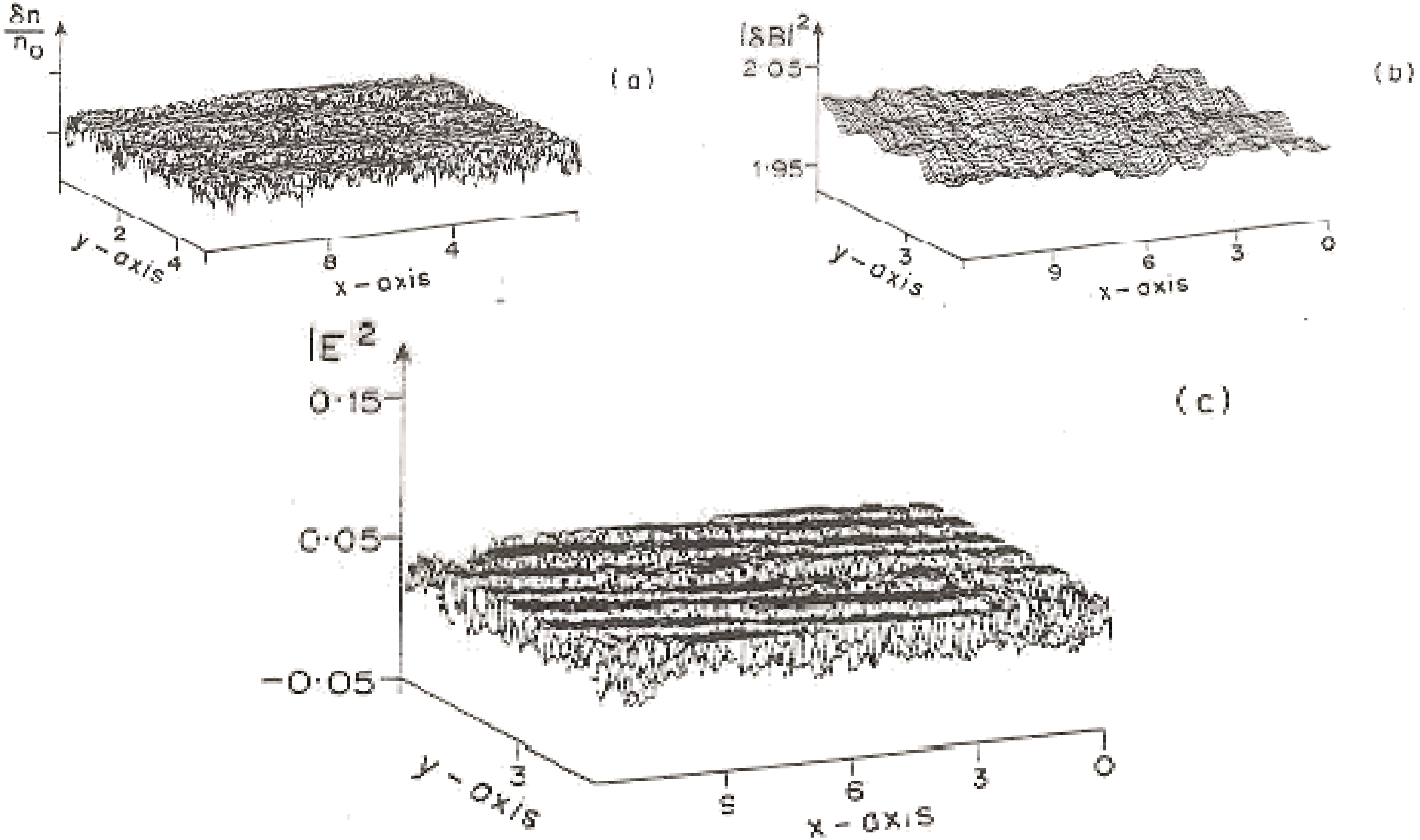
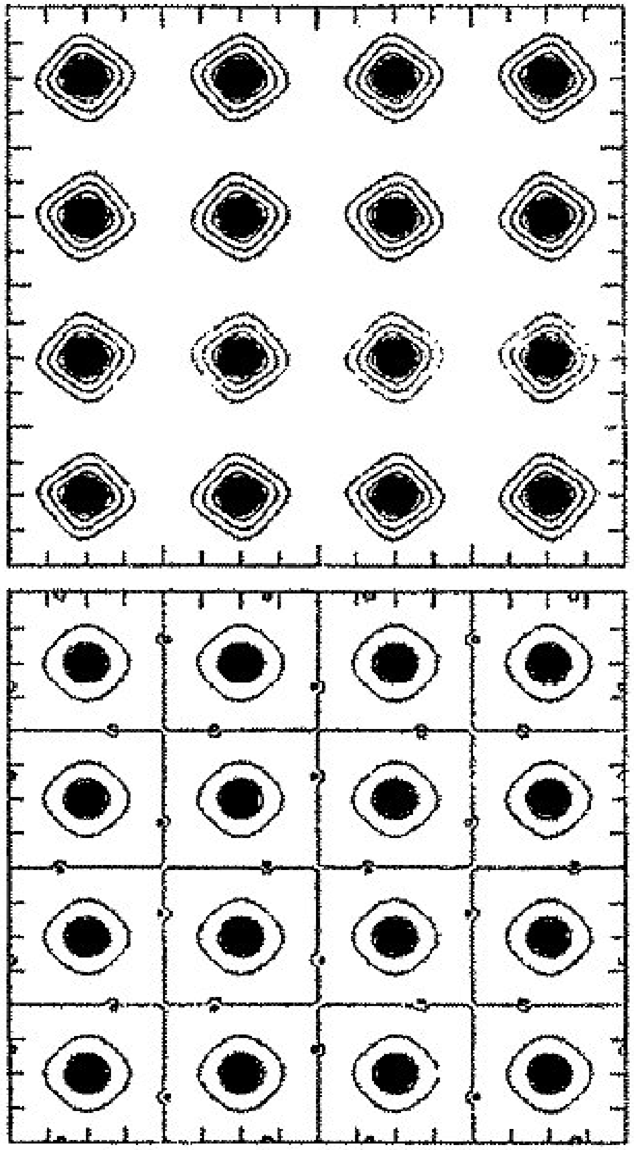
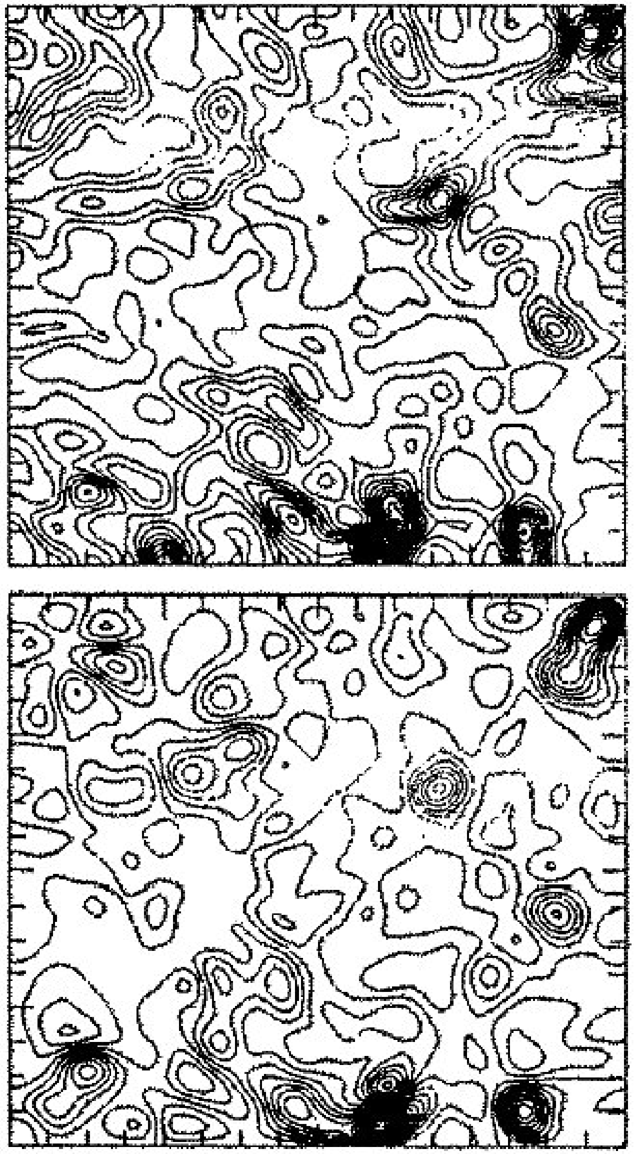


FIG. 6.–Low frequency density (a) and magnetic field (b) cavitons, arising from the high frequency electric field envelope (c). x and y are in units of the plasma skin depth, c/ω_{pe}.

Simulations

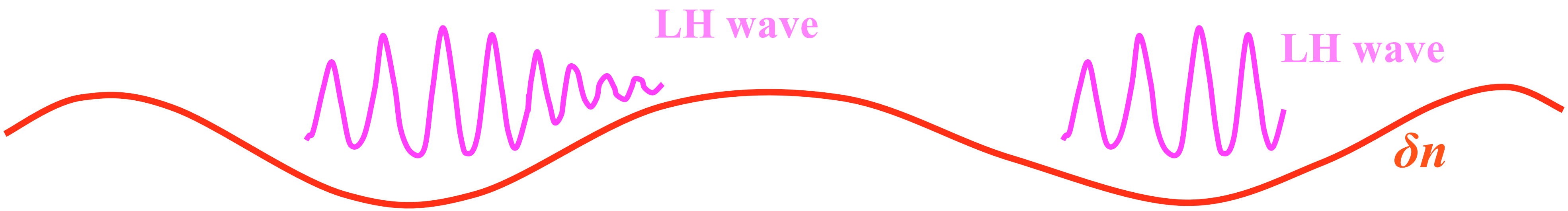


(b)



Lower-Hybrid Dissipative Cavitons

- Lower-hybrid cavitons in the auroral zone.
  - Observations reveal $E \geq 300$mV/m – this is greater than the threshold (~50 mV/m) for Modulational Instability (Kintner et al., 1992; Wahlund et al., 1994).
- The modulational interaction is created by the ponderomotive force exerted by the waves on the plasma particles.
- The ponderomotive force is due to the Reynolds stress $B\left\langle\left(\underline{v}.\nabla\right)\underline{v}\right\rangle$ and creates density modulations.



- Density modulations lead to the formation of unipolar and dipolar cavitons.
- Density modulation $\delta n/n_0$ produces two corrections to the lower-hybrid frequency

Cavitons

- The equation for the slow variation of the lower-hybrid electric potential is

$$-\frac{2i}{\omega_{lh}}\frac{\partial}{\partial t}\nabla^2\varphi - R^2\nabla^4\varphi + \frac{m_i}{m_e}\frac{\partial^2\varphi}{\partial z^2} + \frac{\omega_{pe}^2}{c^2}\varphi =$$

$$\frac{\omega_{lh}}{in_0\omega_{ce}}\frac{m_i}{m_e}(\nabla\varphi\times\nabla\delta n)\cdot\mathbf{e} - \frac{1}{1+\frac{\omega_{pe}^2}{\omega_{ce}^2}}\nabla^2\frac{\delta n}{n_0}\varphi + \frac{2}{i\omega_{lh}}\int\Gamma(\mathbf{r}-\mathbf{r}')\nabla^2\varphi(\mathbf{r}')d\mathbf{r}$$

- The equation for the slow density variation is

$$\frac{\partial^2\delta n}{\partial t^2} - \frac{T}{m_i}\nabla^2\delta n = -\frac{1}{16\pi m}\frac{\omega_{pe}^2}{\omega_{ce}^2}\Delta\left|\nabla\varphi\right|^2 + \frac{i}{16\pi m_i}\frac{\omega_{pe}^2}{\omega\omega_{ce}}\left(\nabla\varphi^*\times\nabla\varphi\right)\cdot\mathbf{e}$$

- Driven by the ponderomotive force of the lower-hybrid wave.
  - 1^{st} term on RHS is the scalar non-linearity
  - 2^{nd} term on RHS is the vector non-linearity
- Similar process can occur for lower-hybrid waves coupled to kinetic Alfven waves. In this case the density perturbation of the Alfven wave is expressed through the vector potential.
- Observed lower-hybrid waves with fields of order 300mV/m can excite Alfven waves with field strength B ~ 1nT.

Lower Hybrid Drift Instability

- **We assume the lower hybrid drift instability is operating in the kinetic regime *($V_{Di} << V_{Ti}$)*. Its maximum growth rate is:**

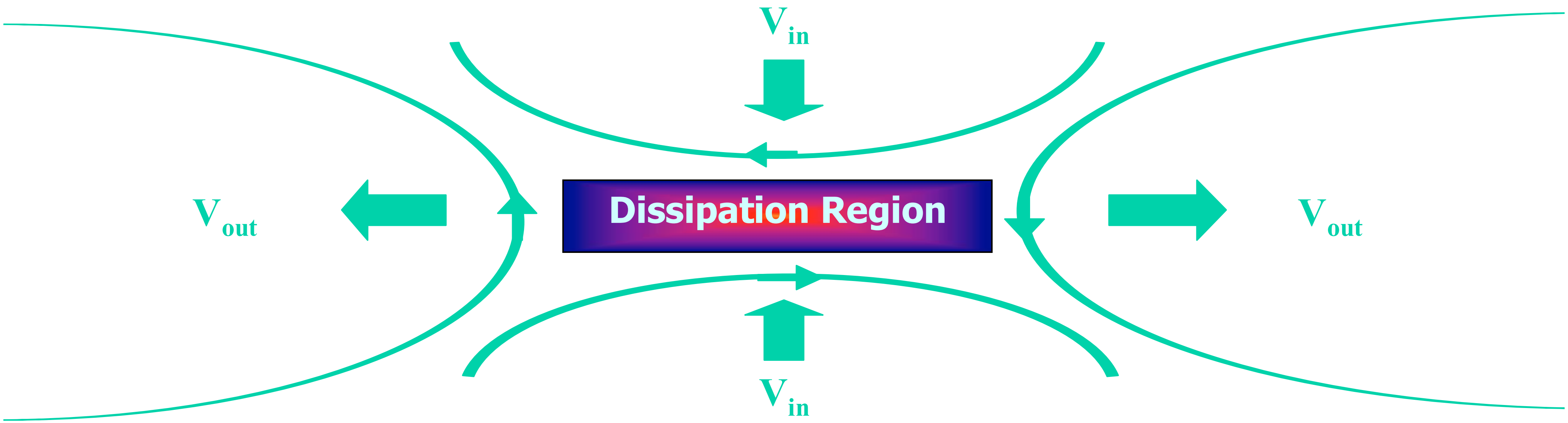
$$\gamma = \frac{\sqrt{2\pi}}{8}\left(\frac{V_{Di}}{V_{Ti}}\right)^2 \omega_{lh}$$

- **with a perpendicular wavenumber of**

$$k_m = \sqrt{2}\,\frac{\omega_{lh}}{V_{Ti}} = \sqrt{2}\left(\frac{m_e}{m_i}\right)^{1/2}\frac{\Omega_{ce}}{V_{Ti}}$$

- **Where** $$\frac{V_{Di}}{V_{Ti}} = \frac{1}{2}\left(\frac{r_{Li}}{\Delta x_\perp}\right)^2$$

- **and** $$\Delta x_\perp^{-1} = \frac{\partial \ln \rho}{\partial x_\perp} \approx \frac{\partial \ln B}{\partial x_\perp}$$



Basic Theory of Magnetic Reconnection

- The Lower Hybrid Drift Instability (LHDI) is an excellent mechanism for producing LHWs and is relatively easy to excite by slow moving MHD flows found at reconnection sites

- **Demanding the waves have time to grow places a constraint on the damping rate, we require**

$$\gamma_D \approx 10 \frac{V_{g\perp}}{\Delta x_\perp}$$

- **The characteristic scale length required to maintain the drift current at marginal stability is given by**

$$\Delta x_\perp \approx \frac{1}{5} \frac{\sqrt{2}\pi}{32} r_{Li} \sqrt{\frac{m_i}{m_e}}$$

- **If we now demand a balance between the Poynting flux of electromagnetic energy flowing into the tail and the rate of Ohmic dissipation, we find the resistivity required**

$$\eta = \frac{4\pi V_{in}\Delta x_{\perp}}{c^2}$$

- **Now** $\eta = 4\pi v_{\perp} / \omega_{pe}^2$ **which implies** $v_{\perp} = \frac{4\pi}{\omega_{pe}^2}\frac{4\pi V_{in}\Delta x_{\perp}}{c^2} = \omega_{pe}\frac{\omega_{pe}}{c}\frac{V_{in}}{c}\Delta x_{\perp}$

- **but** $v_{\perp} = \omega_{pe}\frac{\langle \delta E^2 \rangle}{8\pi nkT}$

- **or**

$$\frac{\langle \delta E^2 \rangle}{8\pi nkT} = \frac{1}{5}\frac{\sqrt{2}\pi}{32}\sqrt{\frac{m_i}{m_e}}\frac{r_{Li}}{\lambda_{pe}}\frac{V_{in}}{c}$$

- **where we have used an earlier result and $\lambda_{pe} = c/\omega_{pe}$ is the plasma skin depth.**

- **Using the same set of parameters as used by Huba, Gladd, and Papadopoulos *(1977)*, that is, B ≈ 2.0×10^{-4} gauss, $n \approx 10$, and $kT_i \approx 10^{-3} m_i c^2$ we find $\Delta x_\perp \approx 0.67 r_{Li}$, $r_{Li} \approx 1.16 \times 10^7$ cm, $V_{Ti} \approx 2.2 \times 10^7$ cm/s, $\lambda_{pe} \approx 1.68 \times 10^6$ cm, and $V_A \approx 1.38 \times 10^7$ cm/s.**
- **Taking $V_{in} \approx 0.1 V_A$ we find**

$$\frac{\left\langle \delta E^2 \right\rangle}{8\pi nkT} \approx 2.13 \times 10^{-4}$$

- **We can compute the energies and fluxes of non-thermal electrons.**

Electron Temperature

- A rough estimate of the change in temperature of the electrons due to the Ohmic heating can be obtained by noting that as the plasma flows through and out of the region of instability electrons will experience Ohmic heating for a time $\Delta t \approx L/V_A$, hence the change in electron temperature during this period is

$$\Delta k_B T \approx \frac{\eta J^2}{n}\frac{L}{V_A}$$

- We find

$$\Delta k_B T \approx \frac{5\cdot 32}{n\sqrt{2\pi}}\sqrt{\frac{m_e}{m_i}}\frac{u}{V_A}\frac{B^2}{4\pi}\frac{L}{r_{Li}}$$

- Using the previous parameters we find

$$\Delta T(ev) \approx 2.9 \times 10^{1} \frac{L}{r_{Li}}$$

- In the magneto-tail $r_{Li} \approx 1.16 \times 10^{7}$ cm, $V_A \approx 1.38 \times 10^{7}$ cm/s and $\Delta x_{\|} \approx V_A \Delta t \approx 1000 - 6000$ km and using

$$\Delta T(ev) \approx 2.9 \times 10^{1} \frac{L}{r_{Li}}$$

- results in electron temperatures of order a few hundred or more eV

Ion Temperature

- **The LHDI leads to strong ion heating perpendicular to the magnetic field. Equipartition of energy indicates that 2/3 of the available free energy ends up in ion heating and 1/3 ends up in heating the electrons parallel to the magnetic field. The simple calculation below confirms this argument. To estimate the ion temperature we utilize the fact that the ratio of ion and electron drifts is given by**

$$\frac{V_{Di}}{V_{De}} = \frac{T_i}{T_e}$$

- **together with Ampere's equation yields**

$$T_i = T_e \left(1 + 2 \frac{V_A}{u} \frac{\Delta x_\perp}{\Delta x_\parallel} \right)$$

The LHD instability can generate relatively large amplitude lower hybrid waves in current sheets.

These LH waves are shown to be capable of accelerating electrons and heating ions in the current sheet during reconnection.

The process describes the micro-physics of particle heating and generation during reconnection. The mechanism is important in the magnetosphere and other space environments where reconnection is invoked to explain particle heating and acceleration.

Wave Kinetic Approach to Drift Mode Turbulence

- **Wave kinetics: a novel approach to the interaction of waves with plasmas, leading to a new description of turbulence in plasmas and atmospheres [1-5].**
- **A monochromatic wave is described as a compact distribution of quasi-particles.**
- **Broadband turbulence is described as a gas of quasi-particles (photons, plasmons, driftons, etc.)**

[1] R. Trines *et al.*, in preparation (2004).
[2] J. T. Mendonça, R. Bingham, P. K. Shukla, Phys. Rev. E 68, 0164406 (2003).
[3] L.O. Silva *et al.*, *IEEE Trans. Plas. Sci.* **28**, 1202 (2000).
[4] R. Bingham *et al.*, Phys. Rev. Lett. **78**, 247 (1997).
[5] R. Bingham *et al.*, Physics Letters A **220**, 107 (1996).

Applications

- Lower-hybrid drift modes at the magnetopause
- Strong plasma turbulence – Langmuir wave collapse
- Zonal flows in a “drifton gas” – anomalous transport driven by density/temperature gradients
- Turbulence in planetary, stellar atmospheres – Rossby waves
- Intense laser-plasma interactions, e.g. plasma accelerators
- Plasma waves driven by neutrino bursts
- The list goes on

Liouville Theory

We define the quasiparticle density as the wave energy density divided by the quasiparticle energy:

$$N(\vec{k},\vec{r},t) = W(\vec{k},\vec{r},t)/\omega(k)$$

The number of quasiparticles is conserved:

$$\frac{d}{dt}\int N(\vec{k},\vec{r},t)\,d\vec{r}\,d\vec{k} = 0$$

Then we can apply Liouville's theorem:

$$\frac{d}{dt}N(\vec{k},\vec{r},t) = \left(\frac{\partial}{\partial t} + \vec{v}\frac{\partial}{\partial \vec{r}} + \vec{F}\frac{\partial}{\partial \vec{k}}\right)N(\vec{k},\vec{r},t) = 0$$

where $\vec{v} = d\vec{x}/dt = \partial\omega/\partial\vec{k}$ **and** $\vec{F} = d\vec{k}/dt = -\partial\omega/d\vec{x}$
are obtained from the q.p. dispersion relation

Application: Drift Waves

Lower hybrid drift modes…

- **control plasma transport at the magnetopause,**
- **provide anomalous resistivity necessary for reconnection at tangential discontinuities,**
- **control the transport determining the thickness of the magnetopause boundary layer.**

We aim to study them through the quasi-particle method.

Condensed Theory of Drift Waves

- **We use the model for 2-D drift waves by Smolyakov, Diamond, and Shevchenko [6]**

- **Fluid model for the plasma (el. static potential Φ(r)):**

$$\frac{\partial \Phi}{\partial t} = \int \frac{k_r k_\vartheta}{\left(1 + k_r^2 + k_\vartheta^2\right)^2} N_k d^2 k$$

- **Particle model for the "driftons":**
  - **Drifton number conservation;**
  - **Hamiltonian:** $\omega_i = k_\vartheta \frac{\partial \Phi}{\partial r} + \frac{k_\vartheta V_*}{\left(1 + k_r^2 + k_\vartheta^2\right)}, \qquad V_* = -\frac{1}{n_0}\frac{\partial n_0}{\partial r}$
  - **Equations of motion: from the Hamiltonian**

[6] A.I. Smolyakov, P.H. Diamond, and V.I. Shevchenko, Phys. Plasmas **7**, 1349 (2000).

Simulations

- Two spatial dimensions, cylindrical geometry,
- Homogeneous, broadband drifton distribution,
- A 2-D Gaussian plasma density distribution around the origin.

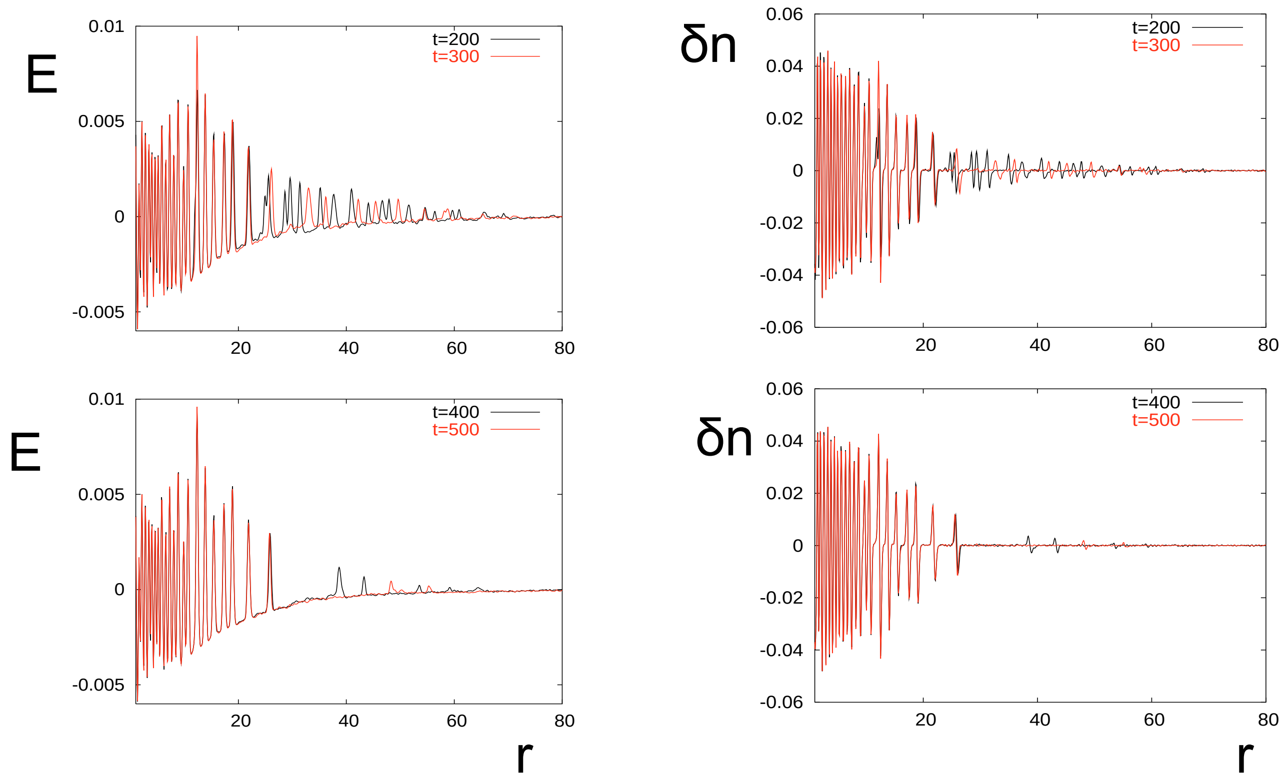
We obtained the following results:

- Modulational instability of drift modes,
- Excitation of a zonal flow,
- Solitary wave structures drifting outwards.

Simulation Results – 1

Radial e.s. field and plasma density fluctuations versus radius r :

- **Excitation of a zonal flow for small r, i.e. small background density gradients,**
- **Propagation of "zonal" solitons towards larger r, i.e. regions with higher gradients.**



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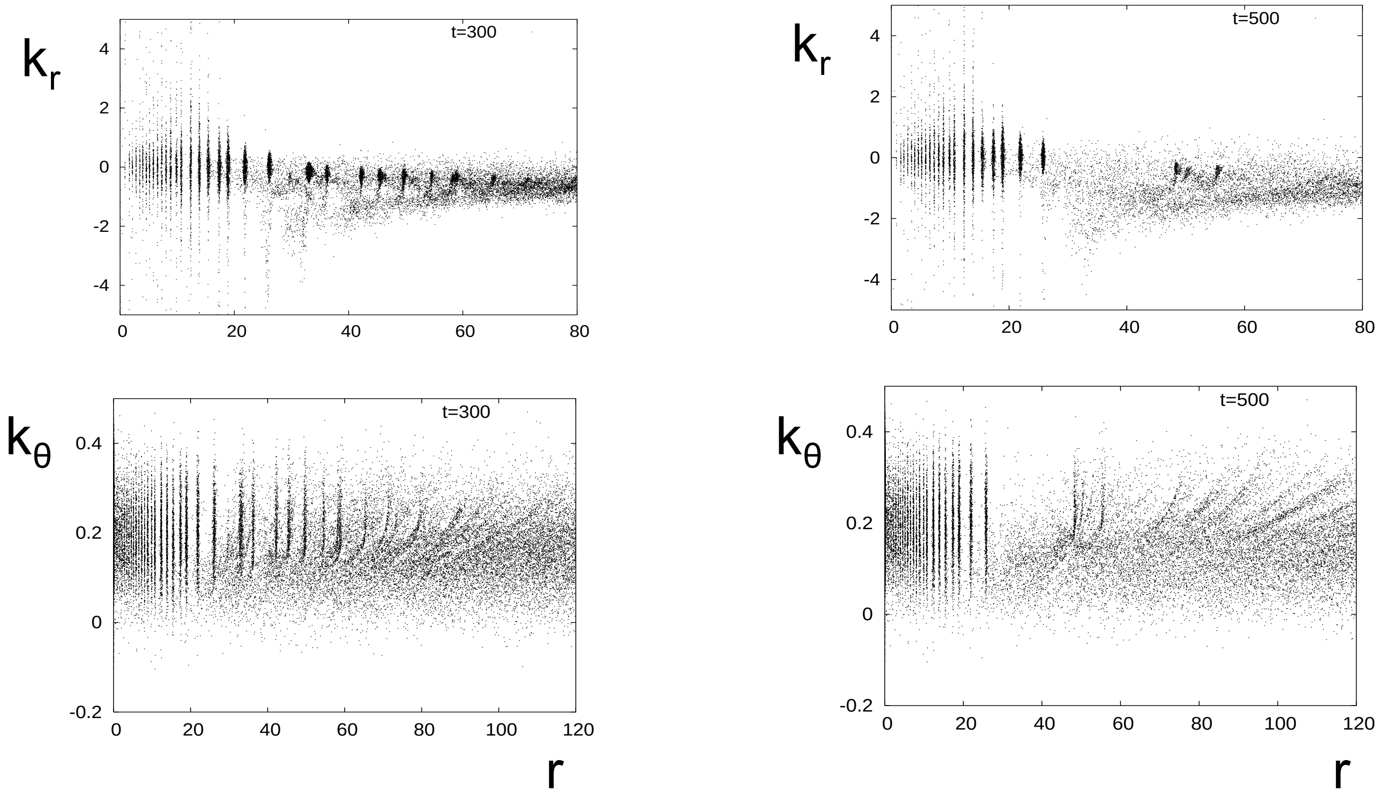
Simulation Results – 2

Radial and azimuthal wave numbers versus r:

- Bunching and drift of driftons under influence of zonal flow,
- Some drifton turbulence visible at later times.



Wave kinetics…

- Allows one to study the interaction of a vast spectrum of 'fast' waves with underdense plasmas,
- Provides an easy description of broadband, incoherent waves and beams, e.g. L-H drift, magnetosonic modes, solitons
- Helps us to understand drift wave turbulence, e.g. in the magnetosphere,

Future work: progress towards 2-D/3-D simulations and even more applications of the wave kinetic scheme

Wave kinetics: a valuable new perspective on wave-plasma interactions!

Conclusions

- Lower-Hybrid waves play a unique role in all areas of space plasmas.
- Ideal for energizing ions/electrons and transferring free energy from ions (electrons) to electrons (ions).
- Non-Linear physics very rich
  - e.g. cavitons
  - e.g. strong turbulence theories