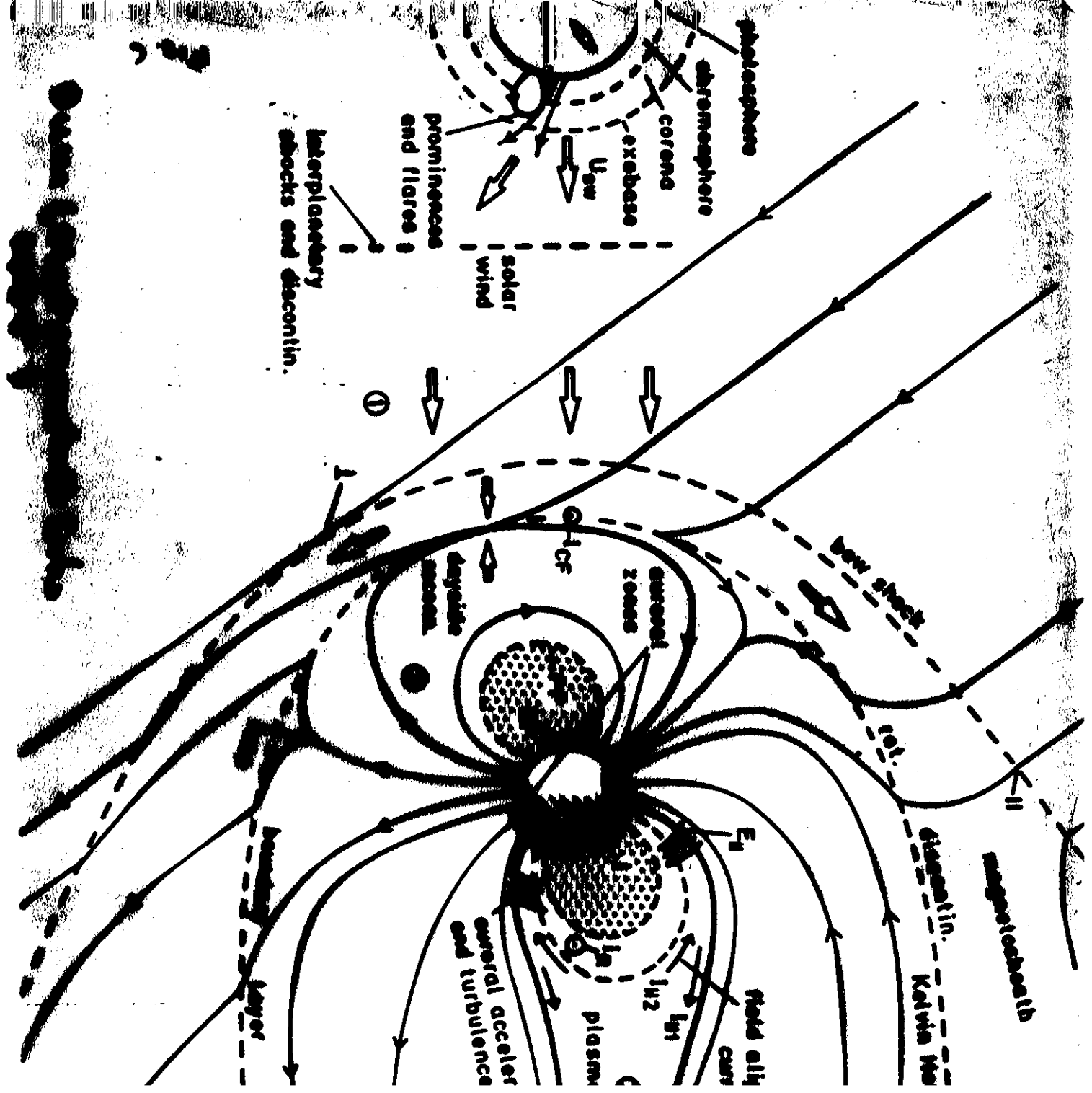# AUTUMN COLLEGE ON PLASMA PHYSICS

13 October - 7 November 1997

LECTURE NOTES (3rd set)

C.T. DUM

Max Planck Institut für Extraterrestrial Physik,
Garching, Germany

photosphere
chromosphere
corona
exobase
U_{sw}
prominences
and flares
Interplanetary
shocks and discontin.
solar
wind
Θ
cusp
depletion
zone
entry
layer
bow shock
plasma
field alig.
curr.
dissipation
region
magnetosheath
Kelvin Hel.
boundary layer
auroral acceler.
and turbulence
plasma
$E_\parallel$
I_{P1}
I_{P2}
q_{P1}

Beam-plasma interaction in a magnetic field: theory and simulation

C. T. Dum, M.P.E Garching &

M.I.T Cambridge, U.S.A

Observations: Auroral Acceleration

Precipitating electrons (beam)
$$\sim keV$$

cold ionospheric plasma $\sim 0.5 eV$
$$O^+, H^+, He^+$$

auroral hiss $\quad \omega > \omega_{LH} = \dfrac{\omega_i}{[1 + \omega_e^2/\varkappa_e^2]^{1/2}}$

cutoff

transverse ion heating

magnetic mirror force $\quad F = -\mu \nabla B$

$\downarrow$

upward acceleration, ion conic
$$\uparrow^{v_\parallel} \quad S(v_\parallel, v_\perp) \quad O^+ \quad (tails)$$

Cold Plasma Resonances

$$\epsilon_\rho = 1 - \frac{\omega_\rho^2 (\omega^2 - \Omega_e \Omega_{i})}{(\omega^2 - \Omega_e^2)(\omega^2 - \Omega_i^2)} \sin^2\theta - \frac{\omega_\rho^2}{\omega^2} \cos^2\theta$$

$\epsilon_\rho = 0$

small θ:

$$\omega_1^2 \approx \omega_\rho^2 + \frac{\omega_\rho^2 \Omega_e^2}{\omega_\rho^2 - \Omega_e^2} \sin^2\theta \qquad \omega_\rho > \Omega_e$$

$$\omega_2^2 \approx \omega_\rho^2 - \frac{\omega_\rho^2 \Omega_e^2}{\omega_\rho^2 - \Omega_e^2} \sin^2\theta \qquad \omega_\rho < \Omega_e$$

nb,wce,theta: 1.00E-002   8.944E-001 60.00
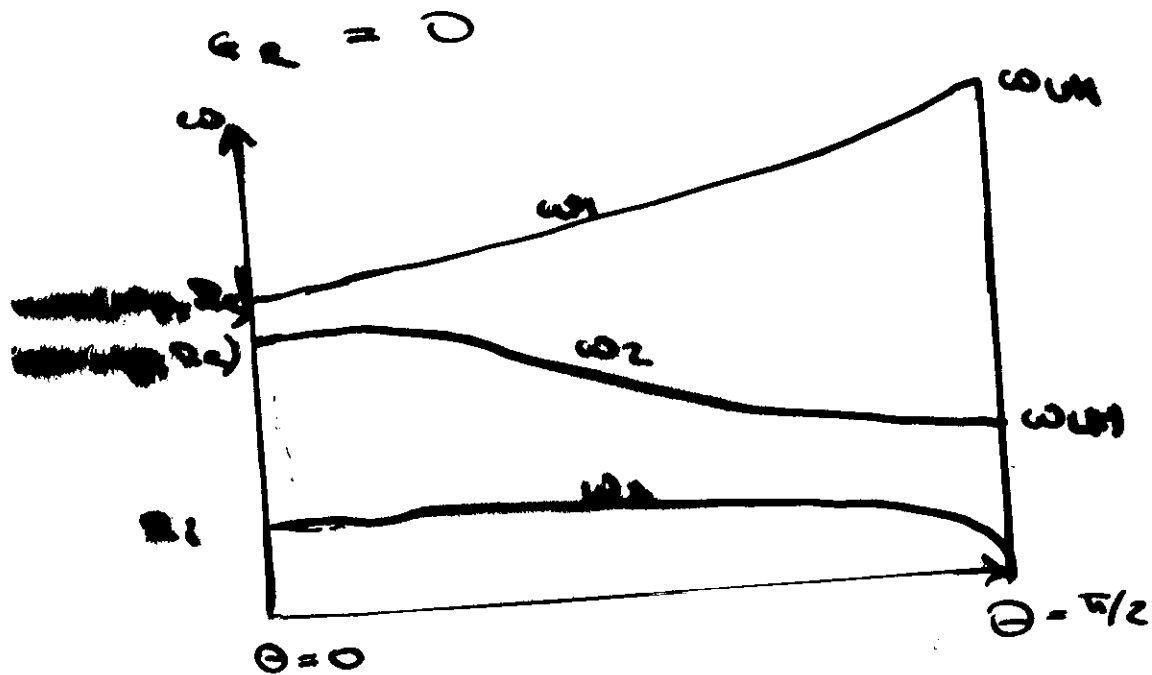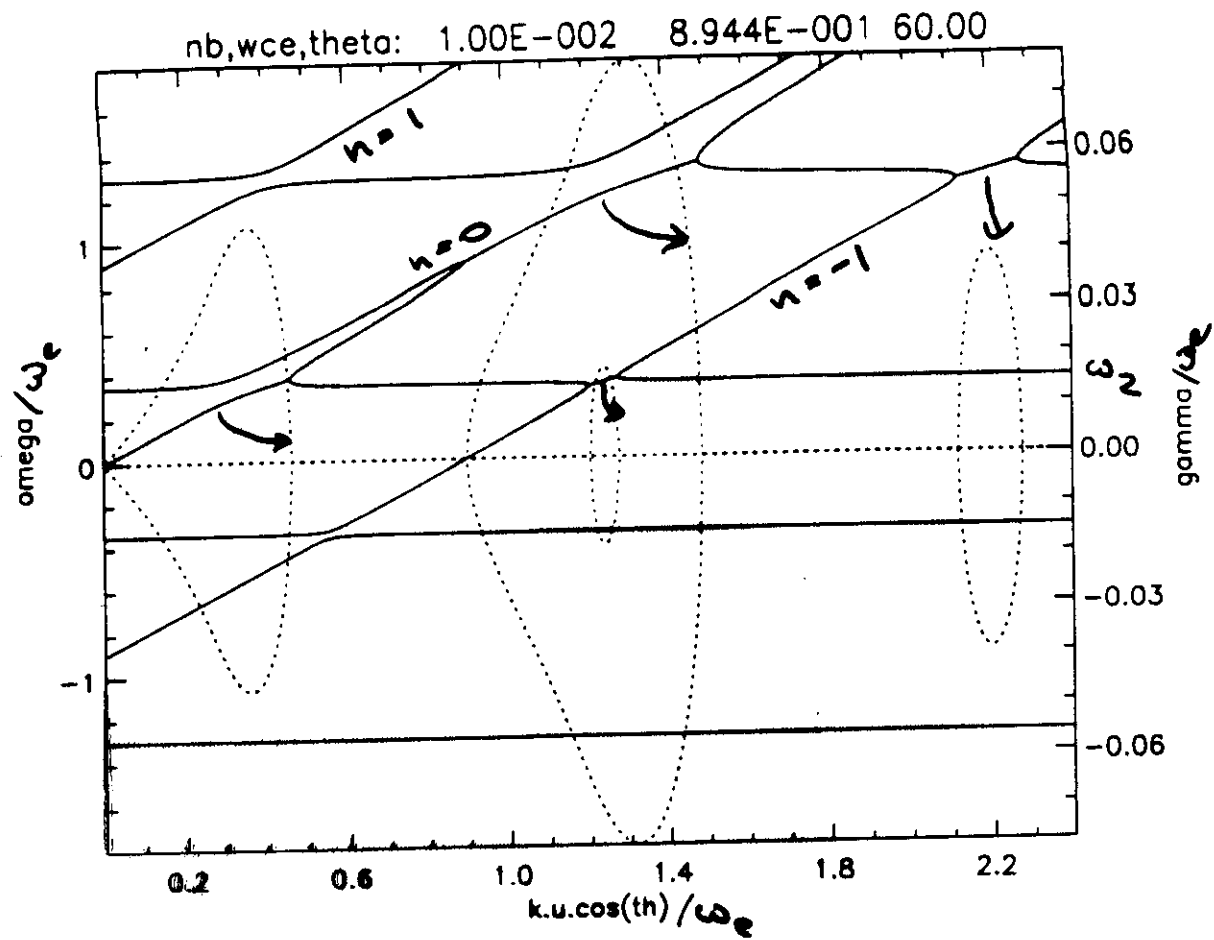
dispersion relation for
a cold plasma and a cold
drifting beam   nb/n = 0.01
Ωce/ωe = 0.8944

Beam Driven Hybrid Waves and Anomalous Doppler Effect

C. T. DUM[*]

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P.O.Box 1603, 85740 Garching, Germany

- **Observations:** Auroral electron beam → auroral hiss; ion conics, double streaming electrons.

  transverse ion acceleration

  longitudinal electron acceleration

- **Auroral hiss** $Min[\omega_e, \Omega_e] > \omega > \omega_{LH} = \dfrac{\omega_i}{\sqrt{1+(\omega_e/\Omega_e)^2}}$

  unmagnetized beam, magnetized electrons

- **Linear instability theory:**

  a.) Landau resonance $\omega - k_\parallel v_\parallel = 0$ $\dfrac{\partial f}{\partial v_\parallel} > 0$; beam

  b.) Anomalous Doppler effect: $\omega - k_\parallel v_\parallel - n\Omega_E = 0$; $n = -1, -2 \ldots \dfrac{\partial f}{\partial v_\perp} < 0$ (elongated tail).

- **Quasilinear theory: 2 stages**

  a.) Landau: Beam → plateau $\dfrac{\partial f}{\partial v_\parallel} \approx 0$

  b.) Anom. Doppler: isotropization

Anomalous Doppler interaction

$$\omega - V_{1u} \nu_u - n \Omega_e = 0$$

$\quad n = 0 \quad$ Landau

$\quad n = -1, -2 \quad$ Anom. Doppler

$\quad n = 1, 2 \quad$ Doppler

$$-\operatorname{Im} \varepsilon_j = \pi \frac{\omega_p^2}{k^2} \int d v_\perp \, J_n^2 \left(\frac{k_\perp v_\perp}{\Omega} \right) \frac{1}{|k_u|} \times$$

$$\left[n \Omega_j \frac{1}{v_\perp} \underbrace{\frac{\partial S}{\partial v_\perp}}_{AD} + k_u \frac{\partial f}{\partial v_u} \right]$$

$$V_u = \frac{\omega + \Omega_e}{k_u}$$

need elongated tail

Fusion: electron runaway

Kadomtsev, Pogutse 1967
Shapiro Shevchenko 1968
Omelchenko et al 1994 fan instab.

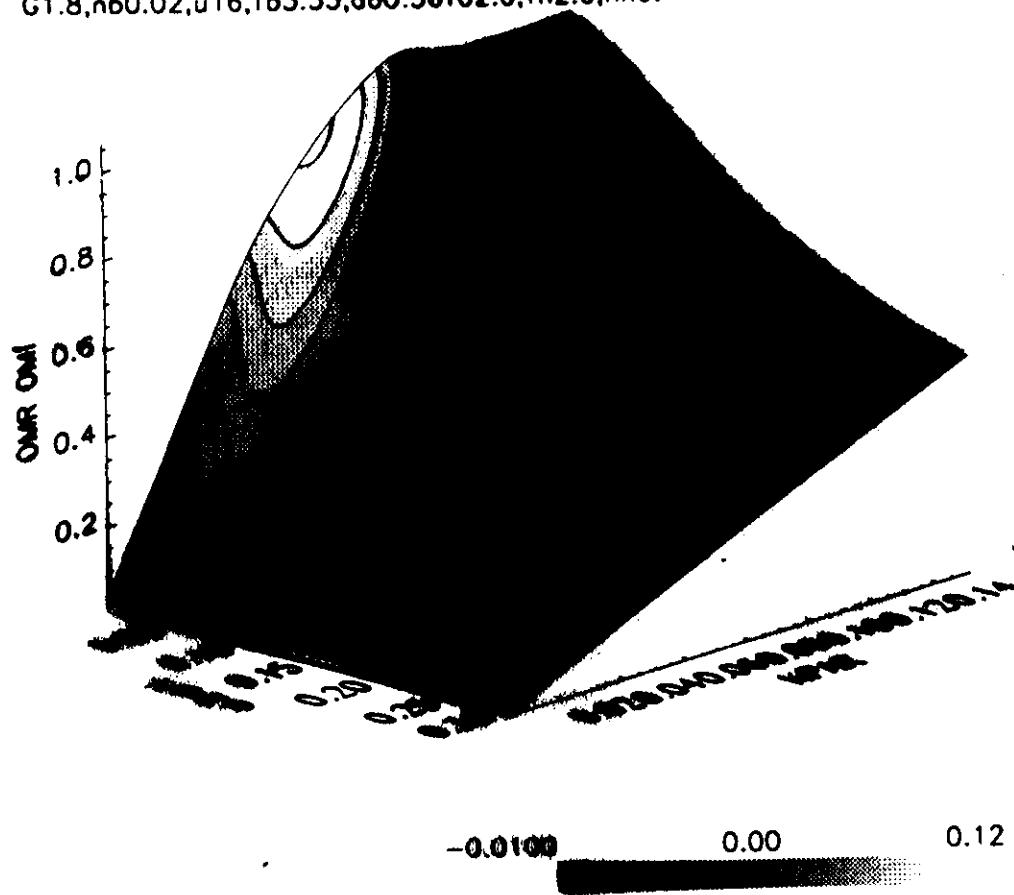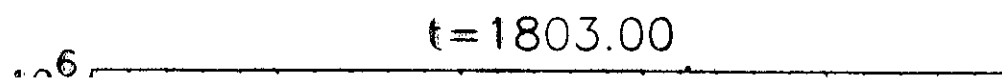ΛT_e

G1.8,nb0.02,u16,Tb3.33,ob0.36To2.0,Th2.0,nh0.1

OMR OMI
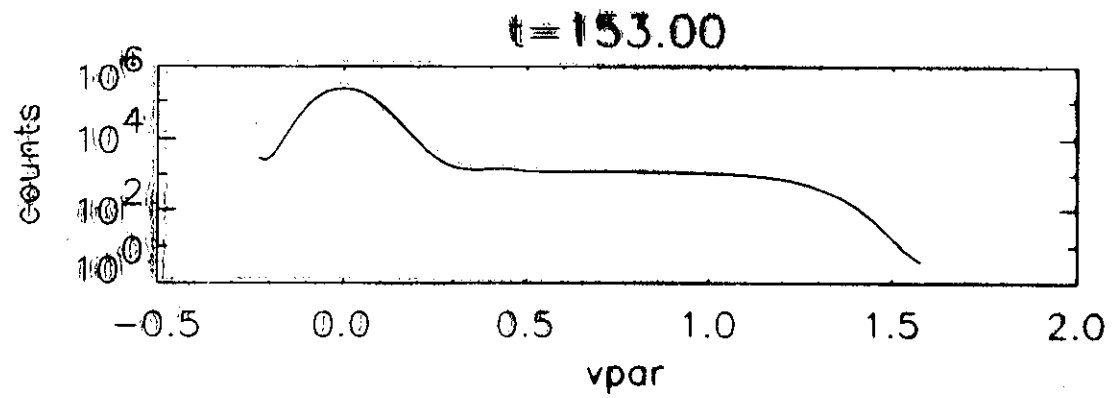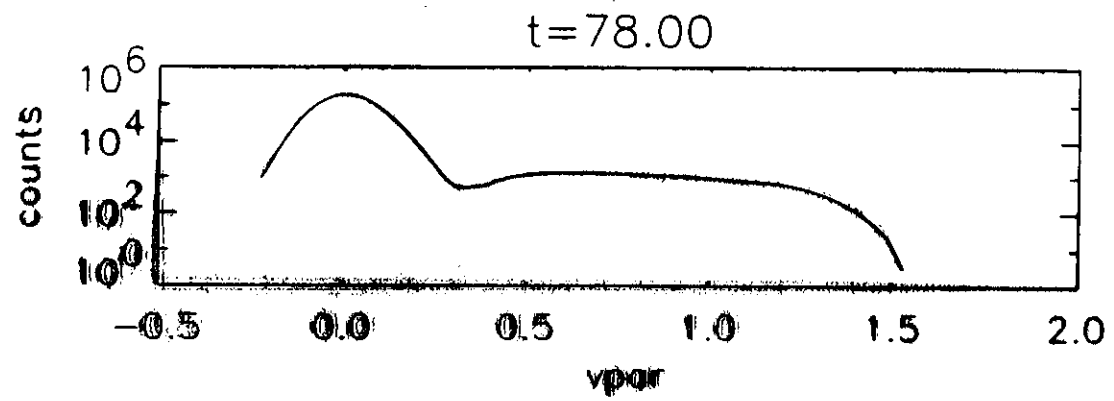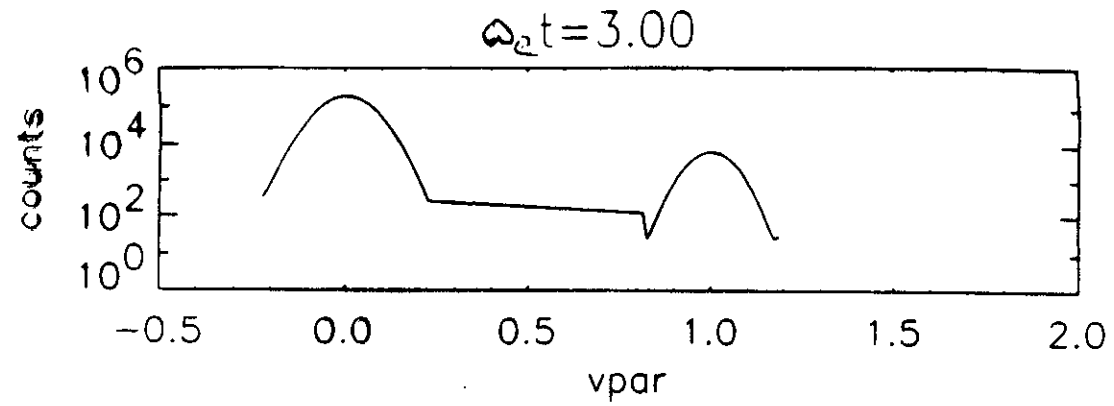
1.0
0.8
0.6
0.4
0.2

−0.0100   0.00   0.12

Fig. 1: Real frequency ω/ω_e and growth rate (contours and shades) for a beam with relative density $n_b/n = 0.02$, drift $u/v_e = 16$ and $T_b/T_e = 3.33$ in an Oxygen-Hydrogen Plasma ($n_H/n = 0.1$) with $\omega_e/\omega_e = 1.8$. The wave numbers are normalized to the electron

$\omega_e t = 3.00$

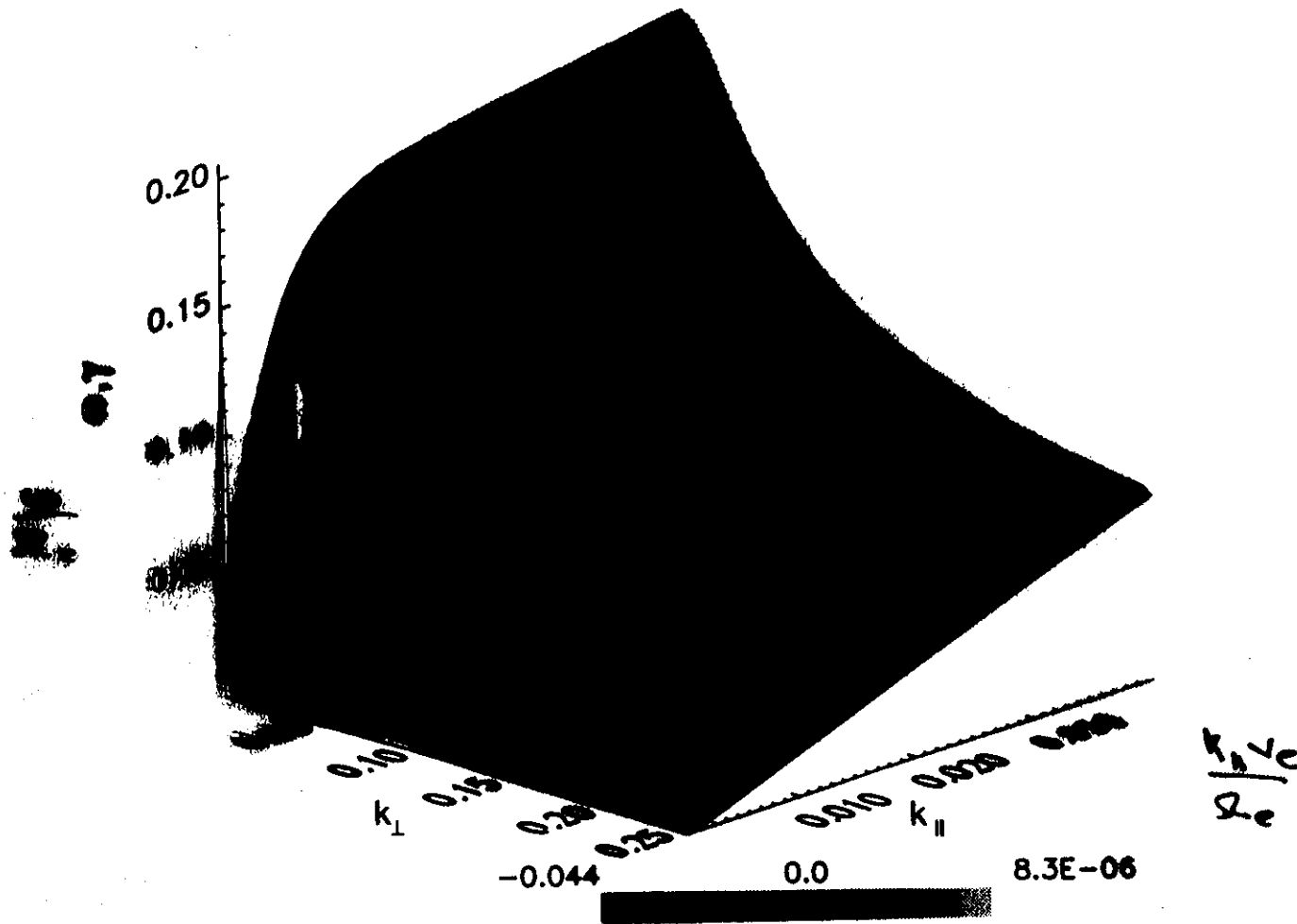$t = 78.00$

$t = 153.00$

$t = 1803.00$

Figure 3. a. Dispersion relation for a oxygen-hydrogen plasma with $\omega_{pe}/\omega_{ce} = 0.1945$, $n_H/n_e = 0.1$ and a flat topped beam with $n_b/n = 0.005$, $= 200v_e$, $T_\perp = T_c$. The ions are cold. Normalization is in terms

3 time=153.000

counts

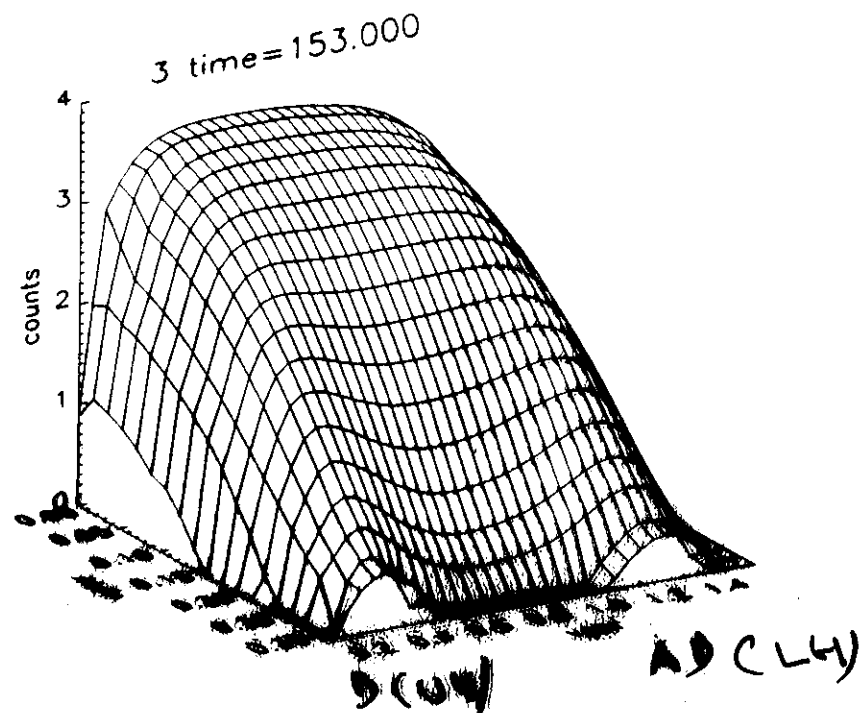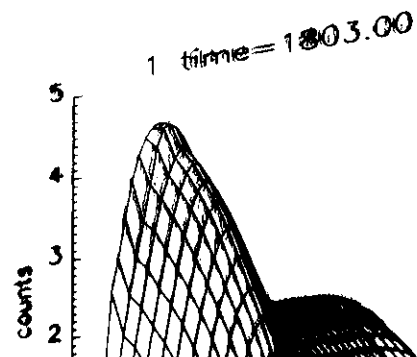Ɔ (℩Ɔↄ) A) (L4)

Fig. 3 **Beam distribution with anomalous** *Doppler Effect at large velocities and the normal Doppler effect at small velocities due to the simultaneous excitation of the lower* and *upper hybrid branches.*

1 time=1803.00

counts

SPECTR   78.0

8000

6000

4000

2000

0

B

SPECTR   453.0

400

300

200

100

0

SPECTR   1803.0

60

40

t: 378.00   ny:0

	0.00919
	0.0887
	0.0407
	0.138
	0.569
	0.976
	1.26
	2.59
	81.1
	24.0
	30.1
	6.04
	7.28
	33.4
	6.30
	232.

ω/ω_*

t: 378.00   ny:6
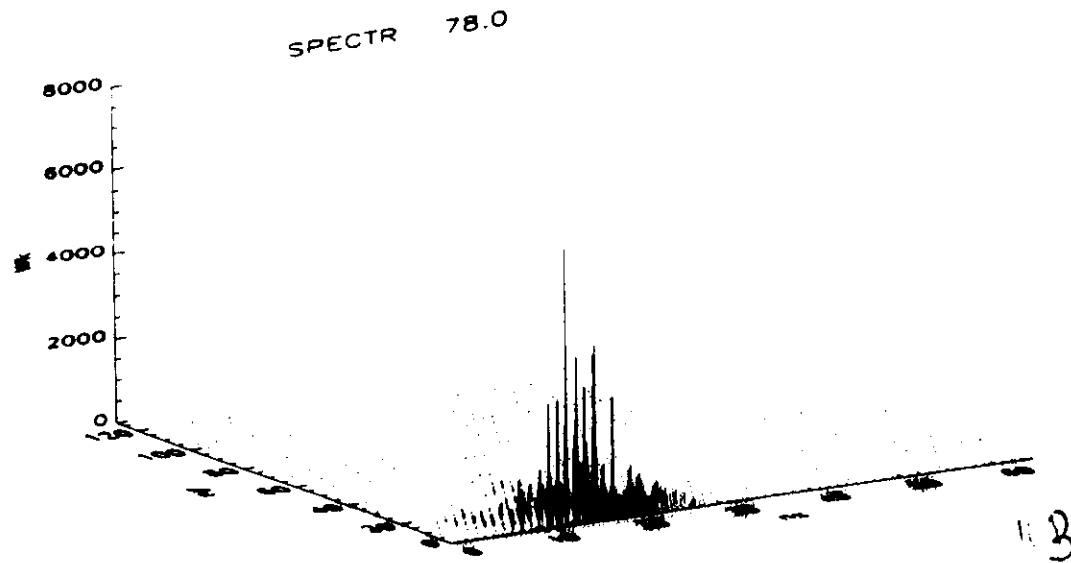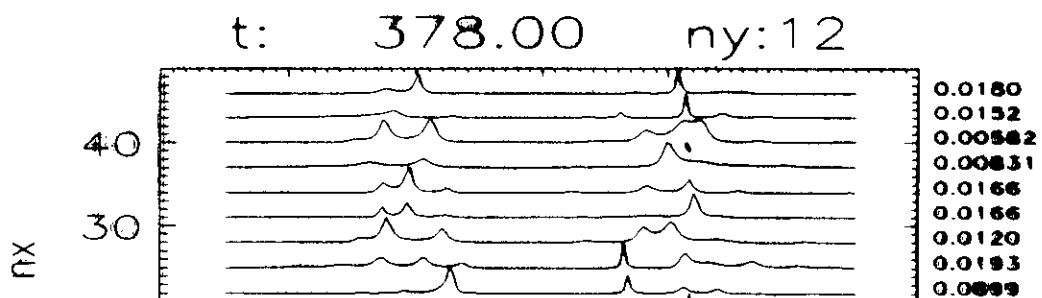
	0.0174
	0.0171
	0.0219
	0.0206
	0.0191
	0.127
	0.0525
	0.0382
	0.116
	0.110
	1.09
	2.47
	11.4
	107.
	1.02
	86.0

ω/ω_*

t: 378.00   ny:12

	0.0180
	0.0152
	0.00582
	0.00831
	0.0166
	0.0166
	0.0120
	0.0193
	0.0899
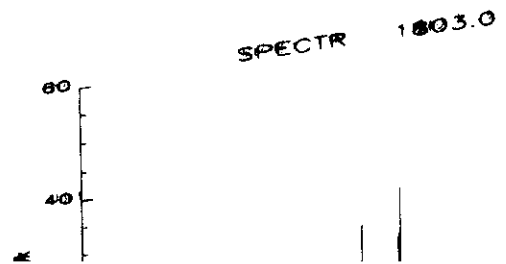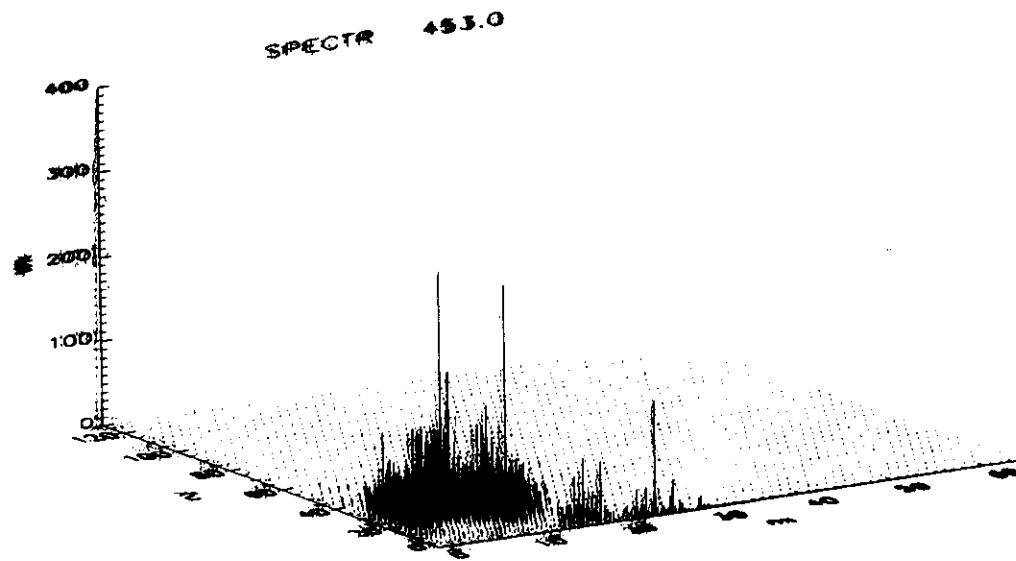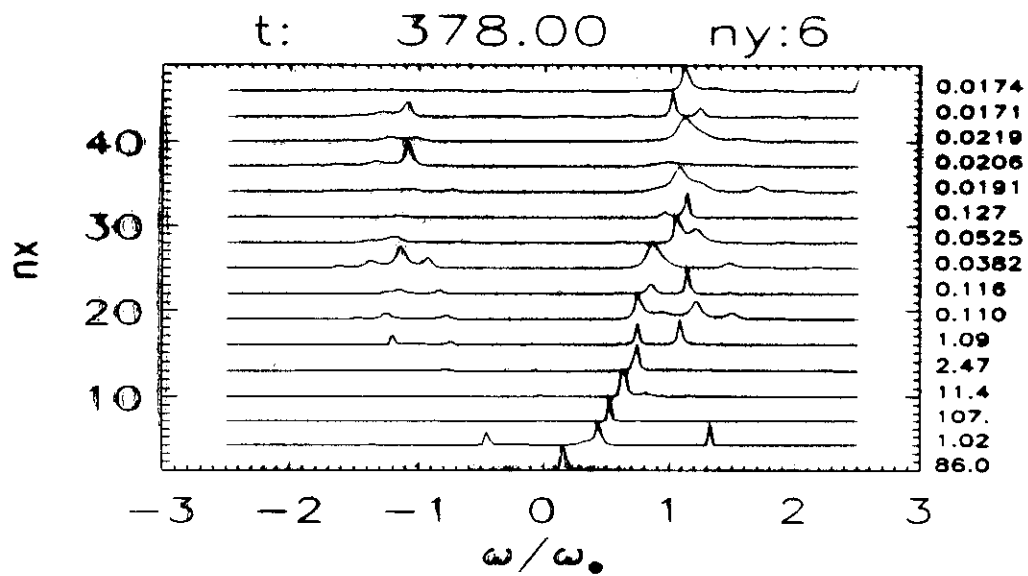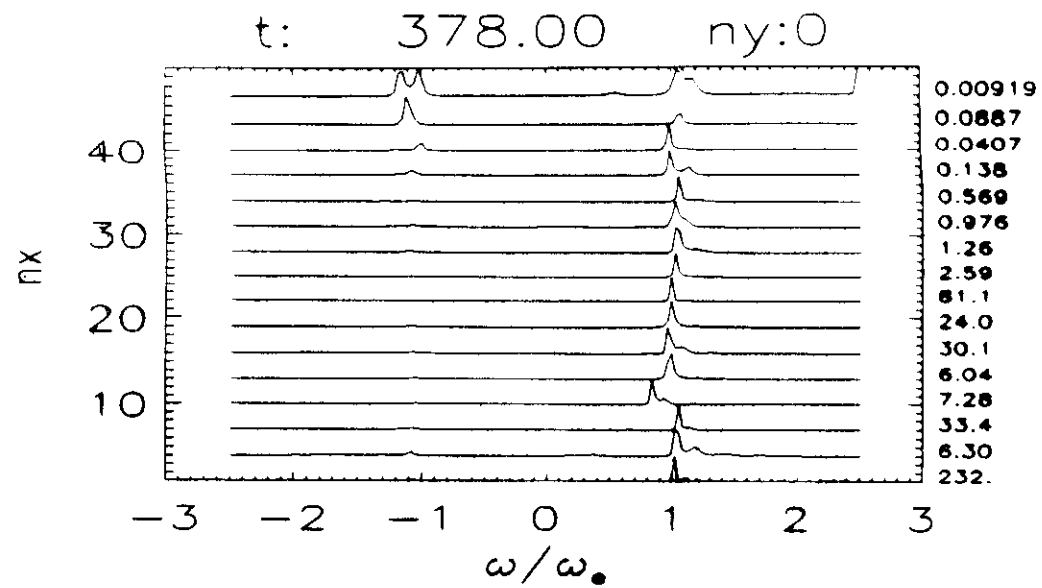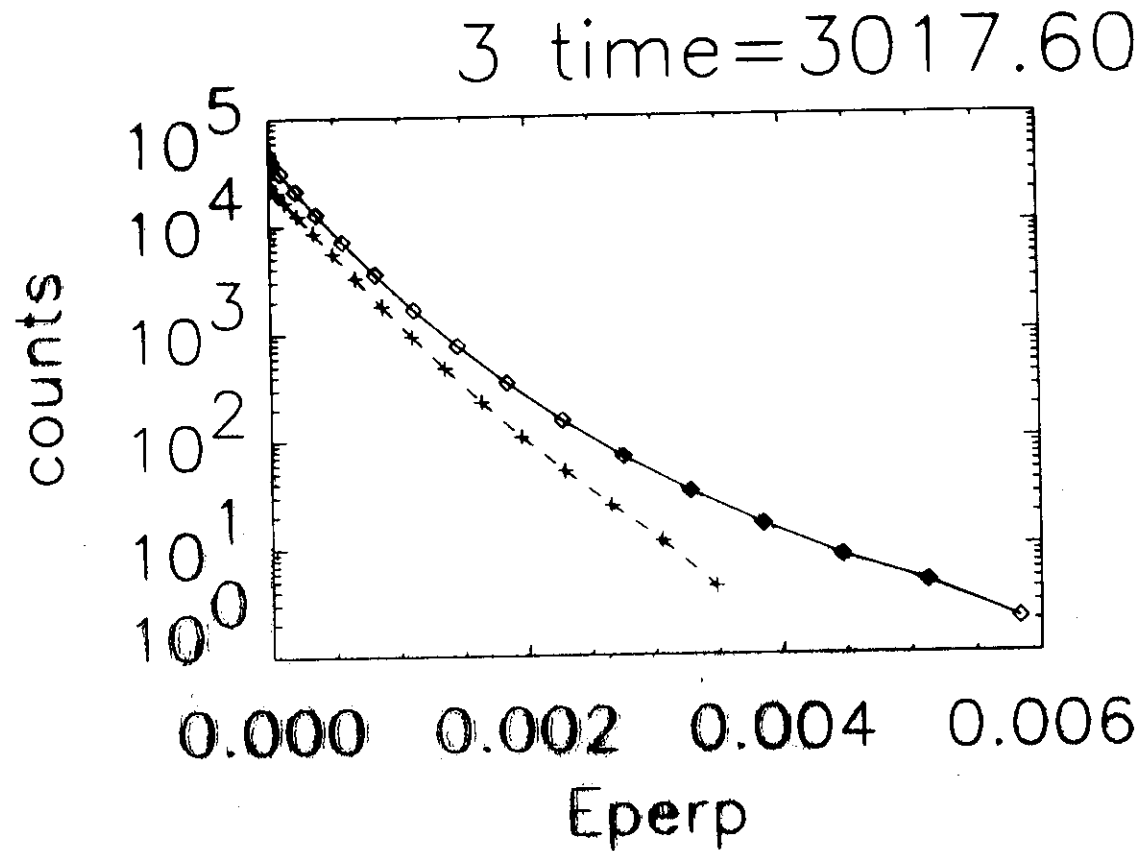
Fig. 8 Perpendicular ion energy distribution (energy in units of mu^2) for a run in which only strongly oblique modes can be excited (representing reflection). The magnetic field is tilted out of the simulation plane (at an angle of 84.3 degrees with x axis). $\Omega_e/\omega_e = 1.8$, $n_b/n = 0.02$, $v_b/u = 0.1$, $v_e/u = 0.06$, $v_i/u = 0.012$, $M/m = 100$. The times $\omega_e t = 777$, 3017 are shown.

SPECTR   777.5999
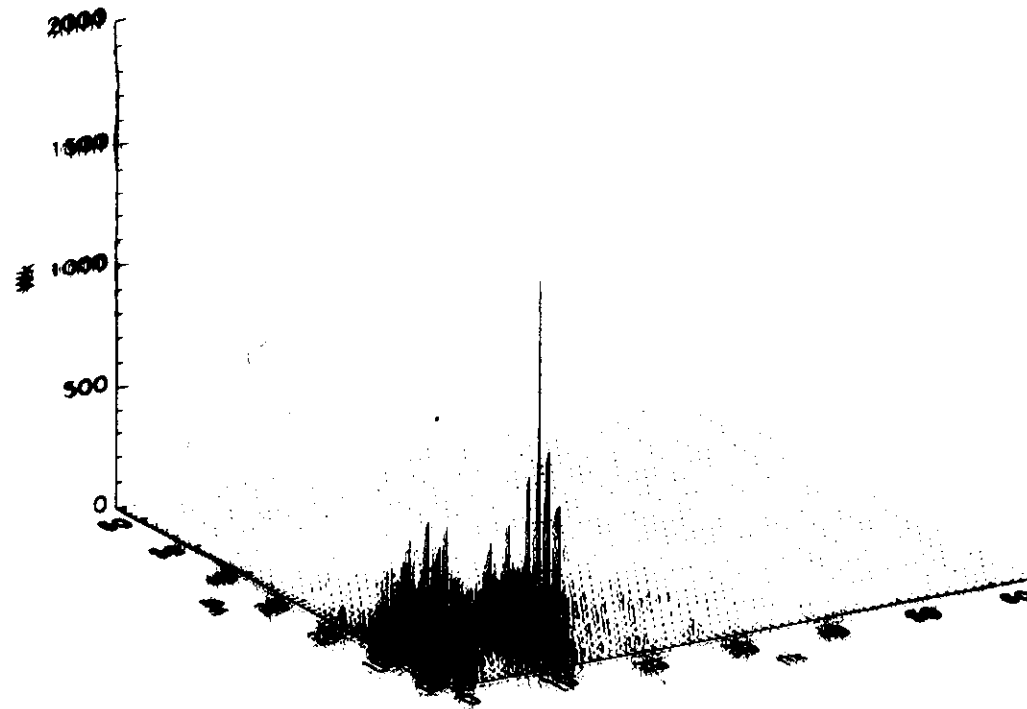
SPECTR   3017.5
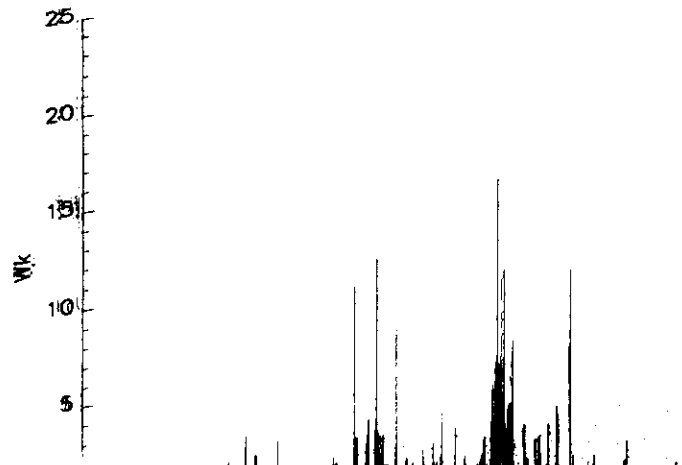
Conclusions

██████ parameter studies have been carried out for the elec-
██████ driven hybrid modes in a magnetized plasma.

- **Linear instability theory:**

The lower and upper hybrid bra██ ███ ██ █████ simultane-
ously by an electron beam, resulting ██ ██████ which are also
separated in wave number space.
Resonant ███████████ with ██████ is ████████ at best.

- ████ ██ particle and
hy███████████████████████████████████████ents) confirm fea-
██████████████████████████████ ██████ion. Evolution ap-
███████████████████████ ██ █████ beam drifts the parallel
██████████████████████ a plateau and in a second stage
█████████ ████████████ and wave evolution proceed by the
██████ Doppler effect. For modest drifts acceleration of
██████ from the electron bulk is significant. Perpendicular
█████ration of bulk particles can arise from the Doppler effect
██ upper hybrid waves.

[text unclear] and may also be associated with SAH waves [text unclear] structure at the hydrogen gyrofrequency was not [text unclear].

4. TOPAZ 2 OBSERVATIONS

[The sounding] rocket payload TOPAZ 2 was launched from [text unclear], Alaska, on January 19, 1988, to an altitude of 927 [km during] an auroral substorm. The substorm began as a [text unclear] overhead which rapidly moved northward and then [text unclear] at the apogee foot point. The arcs continued to be [text unclear] but relatively stationary until the payload arrived [text unclear] minutes later. The payload contained pitch angle [text unclear] electron and ion analyzers, a thermal ion mass [spectrometer], and a VLF receiver employing a 5.5-m double-[text unclear] antenna. There was a rich variety of plasma phenomena [during] this flight, including large quasi-static electric fields [up] to 300 mV/m, electrostatic [text unclear] waves, ion [text unclear] up to 700 eV, and [text unclear] of [text unclear] layers [Kintner et al., [text unclear]]. [text unclear] were observed [text unclear] the [text unclear] and discussed [next].
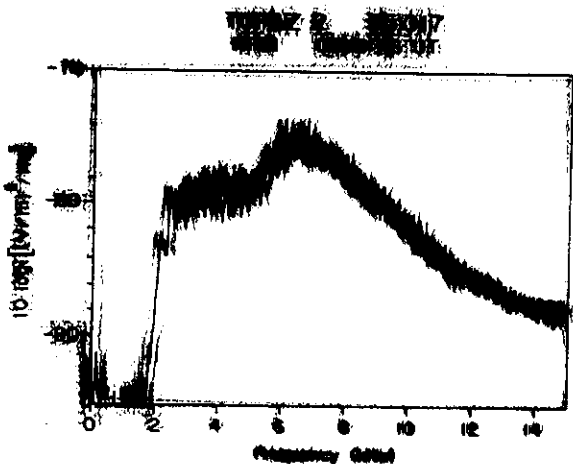
In Figures [text unclear].

Fig. 11. [text unclear] VLF power spectrum near 900 km altitude within an [text unclear].

TOPAZ 2   35.017
HF21   0849:46 UT

observed during the high-altitude portion of the flight. The power spectrum was measured near apogee when the payload was nearest the most intense auroral arcs. In Figure 11 the power spectrum altitude increases about 15 dB at 2 kHz, which we assume to be the lower hybrid frequency. Structure at the hydrogen gyrofrequency is evident between 2 kHz and 7 kHz. For high frequencies the spectrum appears to be a typical auroral hiss spectrum. In Figure 12 an expanded view of the power spectrum between 2 kHz and 6 kHz is presented along with [markers] at multiples of the hydrogen gyrofrequency (f_{H^+}). Clearly the [structure appears] to be ordered by f_{H^+} with [apparent "nulls" near multiples of] f_{H^+}. These features were [observed continuously for about 100 s] during the flight. We [conclude from these] that the wave phenomenon [text unclear] (described in the [text unclear]) was [text unclear] during the TOPAZ 2 [text unclear].

[text unclear] we wish to establish the [text unclear]. TOPAZ 2 carried a VLF [text unclear] located only 50 cm from the [text unclear] suffered from payload-[interference (EMI)]. Nonetheless, [text unclear] to determine if a magnetic [component was present] in the SAH waves. Figure [text unclear] power spectrum taken early in the [flight below] 500 km. This appears to be the [text unclear] hiss spectrum with a peak at the [lower hybrid frequency, roughly 6 kHz, and power extending] above 10 kHz. Figure 14 contains the [simultaneous magnetic] power spectrum. In addition, a background magnetic [field spectrum measured] during the quiet portion of the flight [is also plotted] to indicate the instrument sensitivity in the [presence] of EMI. The narrow emission lines are produced by [EMI.] The simultaneous magnetic spectrum was a broad VLF [spectrum peaking] at 9 kHz in agreement with the broad peak [in the electric] spectrum, also near 9 kHz. However, the sharp [peak at 6 kHz] in the electric spectrum is absent from the [magnetic] spectrum. We conclude that the electric peak at 6 kHz was produced by wave power on the electrostatic lower [hybrid] resonance cone to which the search coil was not [sensitive.] On the other hand the search coil was sensitive to the magnetic component of the whistler mode auroral hiss not on the LHR cone which exhibited a broad peak with a maximum near 9 kHz. From the data in Figures 13 and 14 we conclude that electric and magnetic sensors are operating properly and responding appropriately to auroral hiss.

qualitatively described by (8). We see in Figures 1b and 1c
that increasing the H+ temperature allows Bernstein modes at
higher harmonics to connect with the lower hybrid mode.

Figure 2 shows the effects of varying the value of $k_\parallel$ on the
structure of the wave modes. In all cases the H+ temperature is
0.5 eV. For the case $k_\parallel = 0$ we obtain the classical pure
Bernstein modes [Chen, 1984]. As is predicted by (8) for $k_\parallel =$
0, the frequency shift is positive above ω_{LH} and negative
below. In Figures 2b and c, we note the connections of the
lower hybrid and Bernstein modes at values of finite $k_\parallel$ as
roughly predicted by (10). We note in Figure 2c that our
numerical calculations show that electron Landau damping is
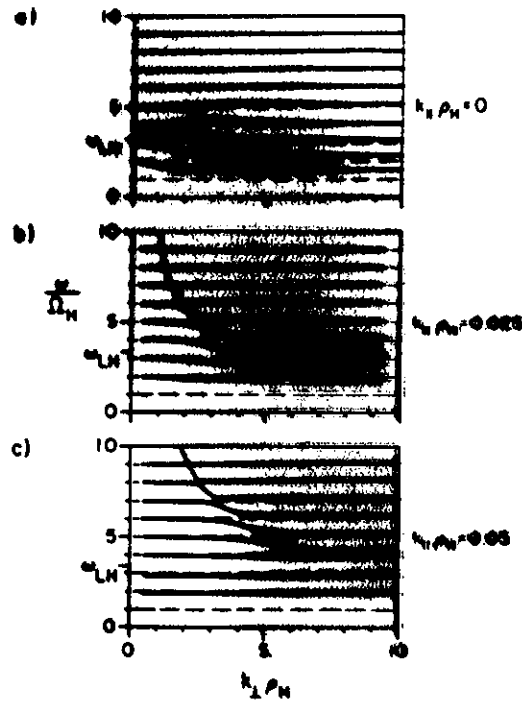becoming significant at this value of $k_\parallel$.

Fig. 2. Dispersion relations of ω/Ω_{H^+} versus $k_\perp \rho_H$ for different values: (a) $k_\parallel \rho_H = 0$, (b) $k_\parallel \rho_H = 0.025$, and (c) $k_\parallel \rho_H = 0.05$.
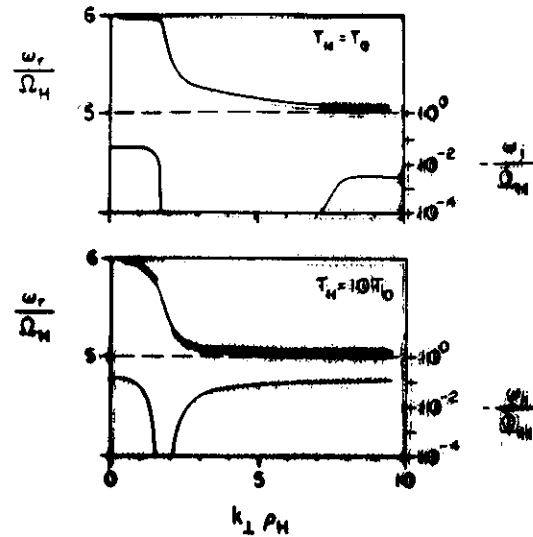

Fig. 3. H+ cyclotron damping of wave modes between 5 and 6 Ω_H shown in Figures 1b and 1c with varying T_H.

$$\chi_b \equiv i\left(\frac{\pi}{2}\right)^{1/2}\frac{\omega_b^2(\omega-k_\parallel v_d)}{k^2 k_\parallel v_b^3}\exp\left\{-\frac{1}{2}\left(\frac{\omega-k_\parallel v_d}{k_\parallel v_b}\right)^2\right\} \quad (11)$$

Here all of the notation is the same as in (2) with the beam
drift velocity denoted by v_d. Waves will be driven unstable
when their parallel phase velocity is near the beam velocity,
i.e., $\omega_r/k_\parallel \sim v_d$.

Figure 4 shows the linear growth rate as a function of
frequency for $k_\parallel \rho_H = 0.04$. The electron beam density is 1% of
the background electron density, and the drift energy is 250
eV. In this case the H+ temperature is 5 eV, and the O+
temperature is 0.5 eV. We clearly see that the shifts in wave
growth result from the thermal H+ in the background plasma.
Also, these shifts occur in the harmonic bands just above the
lower hybrid frequency, ω_{LH}.

In summary, we have considered the effects of thermal H+ on
the lower hybrid mode at frequencies near the lower hybrid
resonance frequency. We have shown that inclusion of H+ of
only eV energies may cause waves to be damped near the H+
gyroharmonic frequencies above ω_{LH}. This is ultimately due
to the connection between the lower hybrid and
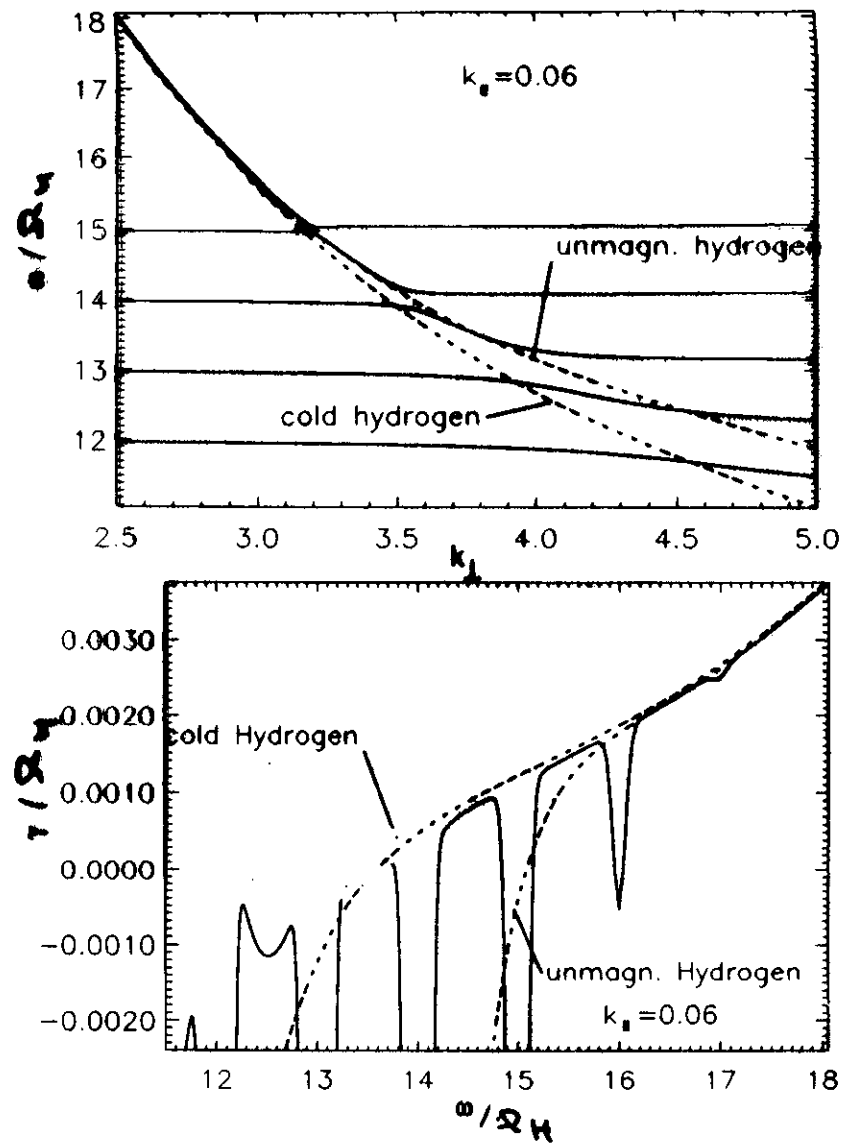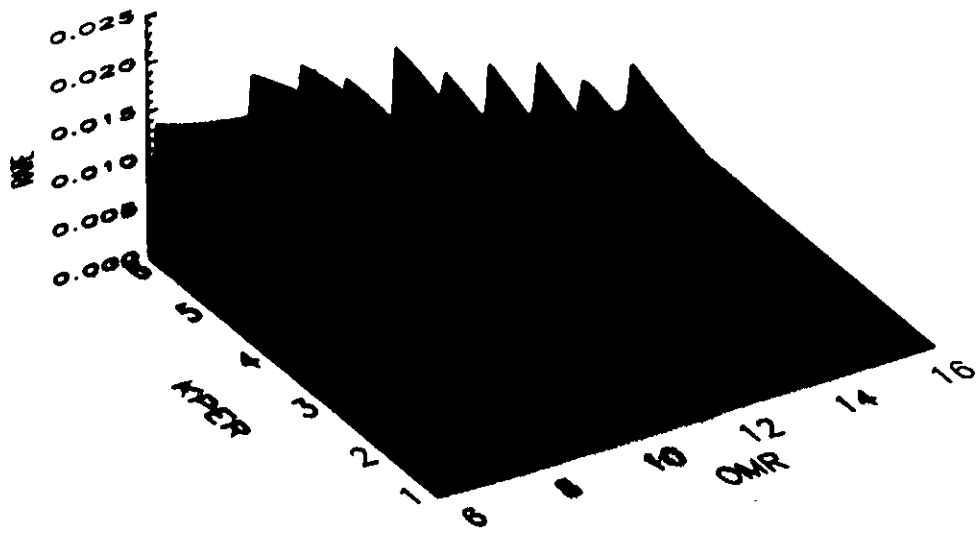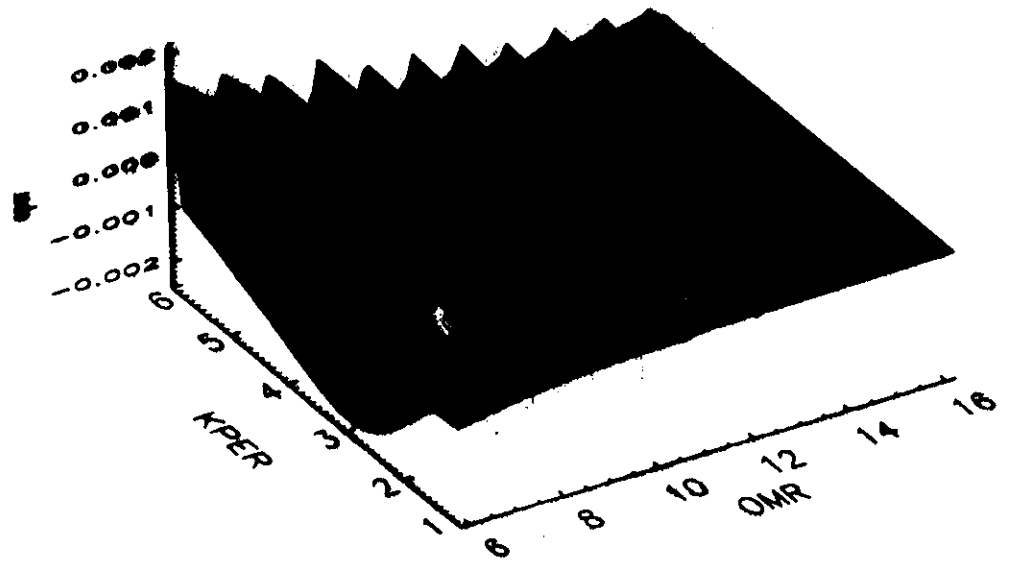Bernstein modes. In the absence of the thermal H+ a

Figure 2. a. Dispersion relation for a oxygen-hydrogen plasma with $\omega_e/\omega_{ce} = 0.4$, $n_N/n_e = 0.1$, $T_e = T_O = T_H$, $k_\parallel = 0.06$; Approximations using cold hydrogen and unmagnetized kinetic hydrogen are also shown
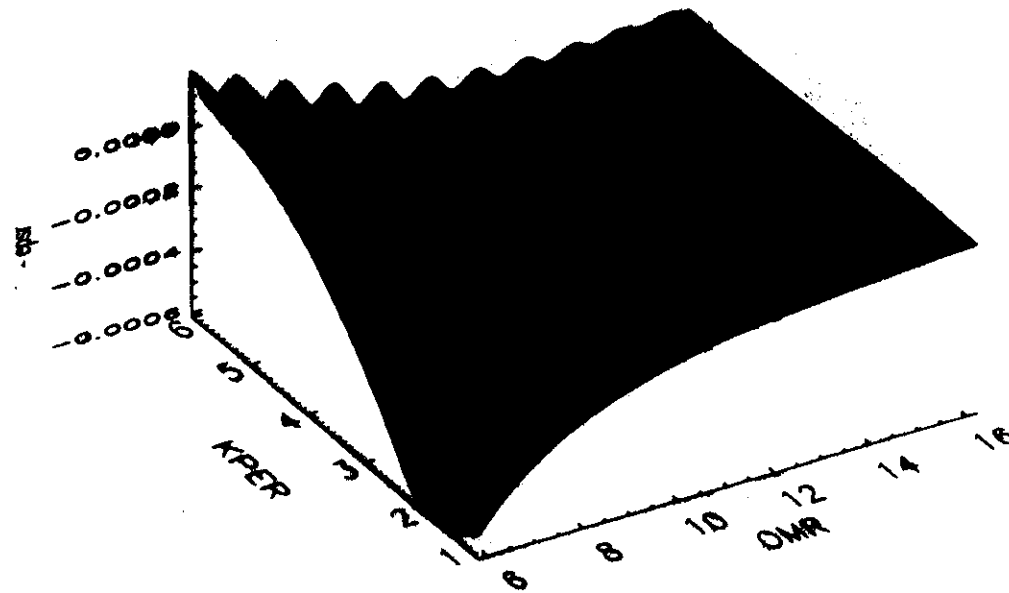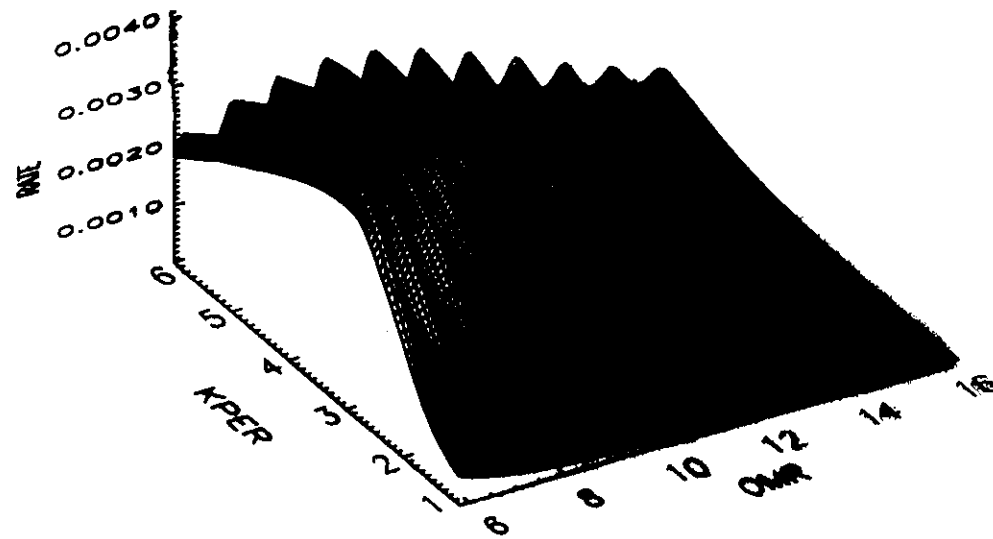
$$\frac{CD}{K V_H} \times 3$$

Figure 3. Hydrogen heating rate and real part of susceptibility for

Conclusions

1. Ion Heating

   req. kinetic theory of
   __magnetized__ Plasma
   cyclotron resonance absorption
   $\omega \rightarrow n\Omega_H, \quad K_\perp \uparrow$
   propagation effects in
   in homogen. plasma $\quad n(x), B(x)$

2) $\underline{k}, \underline{\omega}$ range restricted by
   Landau damping on electron
   bulk + medium energy components
   (secondary electrons)

3) destabilization by
   electron beam Landau damping
   $\gamma \ll \gamma_{max}$
   propagation
   $J_0^2(K_\perp v_\perp / \Omega_e)$

4. destabilization ...