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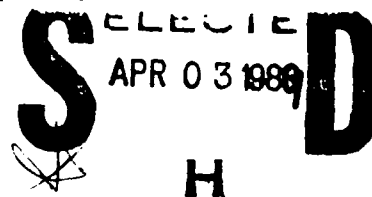
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## MENTATION PAGE

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## PLASMA SIMULATION OF ION ACCELERATION BY LOWER HYBRID WAVES IN THE SUPRAAURORAL REGION

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**Abstract.** The generation of lower hybrid waves below field-aligned potential drops and the effect of the resulting turbulence on the ion population in the supraauroral region are studied using particle plasma simulations. To describe the ion acceleration observed in the simulation, a theoretical model is developed using mode-mode coupling processes to generate the low-phase-velocity VLF waves with which the ions first interact. By scaling the simulation results, we show that interaction between the ions and the lower hybrid waves can account for the acceleration necessary to produce supraauroral energetic ion conic events.

### Introduction

It is becoming more widely accepted that the energetic ion conics [Mizera et al., 1981] observed below field-aligned potential drops in the supraauroral region are produced as the result of ion acceleration by the VLF turbulence observed there [Mozer et al. 1980]. The turbulence is generated through the instability of the auroral electron distribution accelerated parallel to the geomagnetic field by the parallel electric field [Maggs and Lotko, 1981]. A model for the formation of ion conics in this way was proposed by Chang and Coppi [1981]. Acceleration nearly perpendicular to the field line by VLF turbulence near the lower hybrid frequency is followed by the adiabatic folding of velocities as the ions mirror and travel up the geomagnetic field line, creating the conic velocity distribution. Detailed calculations of conics using a Monte Carlo technique to model the wave-particle interaction were carried out by Retterer et al. [1983], while Crew and Chang [1985, see also this conference] have pursued analytical calculations.

Considerable uncertainty remains in the model, however, because of the difficulty in estimating the rate of the wave-particle interaction process. Empirical estimates of the

velocity diffusion tensor based on observed wave amplitudes suffer because the lack of wavenumber measurements prevents us from determining the phase velocities of the waves. We cannot rely on linear calculations to give us the wave spectrum either, because there appears to be a real difficulty in linearly exciting waves of small enough phase velocity so that the resonant portion of the ambient ion distribution can account for the observed number of particles in the conics. In addition, the self-consistent evolution of the wave spectrum has been ignored in previous work.

### Plasma Simulation

To address these problems, a plasma simulation was performed [Retterer et al., 1986] to provide an independent, self-consistent means of studying the generation of the turbulence and the resulting ion acceleration. The supraauroral situation was modeled by allowing a weak ( $n_b/n_o \lesssim 10^{-2}$ ), energetic ( $E_b = 1$  keV), warm ( $T_b = 125$  eV) electron beam traveling along the magnetic field to destabilize a cool electron-ion plasma ( $T_e = T_i = 2$  eV). We set the direction of propagation of the waves to be nearly perpendicular to the magnetic field, with  $\cos^2 \theta_B = m_e/m_i$  to reflect the commonly observed wave spectral peak near 1.5 times the lower hybrid resonance frequency. The velocity of the 1 keV electron beam projected onto the propagation direction is then about 32 times the initial ion thermal velocity. The phase velocities of waves excited by this beam will be far out on the tail of the ion velocity distribution, where few ions can resonantly interact with them.

Nevertheless, a finite fraction of the ions are significantly accelerated in the course of the simulation. We found that tails of energetic ions formed, emerging from both sides of the initial velocity distribution at about three times the ion thermal velocity; some ions are accelerated to velocities comparable to those of

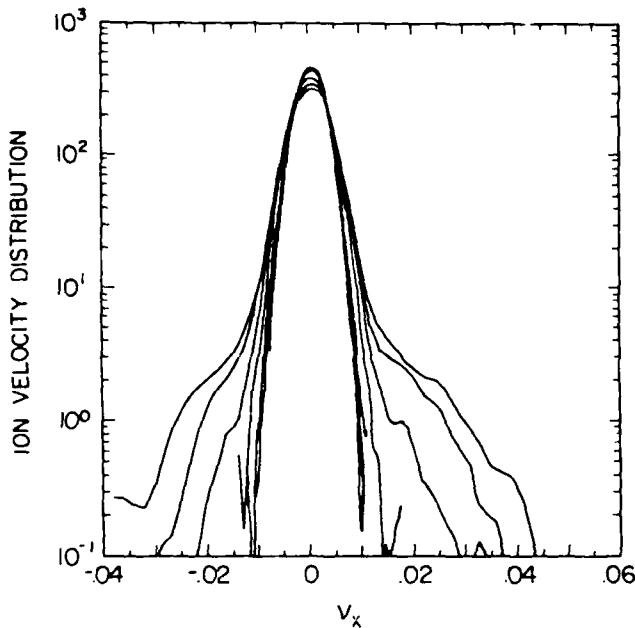


Fig. 1. The ion velocity distribution. Each curve is a plot of the ion velocity distribution at a fixed time. The times run from zero to  $400/\omega_{LH}$  in increments of  $40/\omega_{LH}$ ; the velocities are in arbitrary units in which the beam velocity is 0.08333.

the electron beam. This is illustrated in Figure 1, which presents a series of overlaid snapshots of the ion velocity distribution at different times. In addition to the tails, the core of the velocity distribution showed evidence of nonresonant heating. It can be fitted by a Maxwellian velocity distribution, in which changes in the fitted thermal velocity reflect the changes in the total wave energy. But the tails account for most of the energy transferred to the ions in the course of the instability; following wave saturation, they already contain 4% of the ions and account for half of the ion energy. In addition, electron acceleration parallel to the magnetic field (in both directions) is also observed, with the electrons reaching energies comparable to those of the ions. These accelerated electrons correspond to the Type 1 counterstreaming electrons, observed by DE-1 [Lin et al., 1982] in conjunction with ion conics.

The evolution of the fluctuation spectrum is illustrated in Figure 2. In this Figure we have plotted  $|E(k,t)|^2$  as a function of  $k$  at four times,  $t$ , where  $E(k,t)$  is the spatial transform of the electric field. At early times ( $t \leq 240$ ), we see the linearly unstable modes (centered at  $k=16$ ) emerging from the background noise. From this concentration in a relatively small region of  $k$  space, we subsequently see the wave energy redistribute itself throughout  $k$  space, through

the action of mode coupling processes. The result is an approximately steady-state spectrum, achieved at  $t=400$ , which at smaller  $k$  takes the Rayleigh-Jeans form,  $|E(k,t)|^2 = \text{constant}$ .

#### Interpretation

The interpretation of these results is clear, following from the extensive work devoted to the high-frequency analogue of the problem: electron tail formation in strong Langmuir turbulence [Kruer, 1976; Goldman, 1984; and references therein]. The intense VLF waves linearly excited by the beam parametrically decay into lower phase velocity VLF waves by coupling through nonresonant quasi-modes which are driven to finite amplitude in the turbulent state. These lower phase velocity VLF waves are then Landau damped by the plasma, accelerating the ions perpendicular to the magnetic field and the electrons (because of their restricted perpendicular mobility) parallel to the field.

Several calculations support this interpretation of our simulation. First, an analysis of the nonlinear dispersion relation [Porkolab, 1977] for the coupling of two lower hybrid waves through nonresonant quasimodes was performed. Using the amplitude and other parameters of one of the linearly excited waves in our simulation

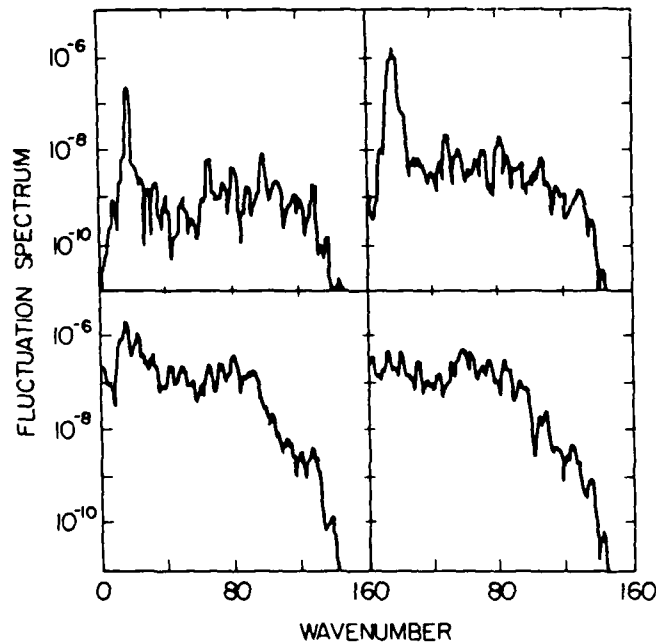


Fig. 2. The wave spectrum. In each panel is plotted  $|E(k,t)|^2$  vs wavenumber  $k$  at a fixed time. In the upper row, the times are 160 and 240; in the lower row, 320 and 400. The wavenumbers are expressed in multiples of the fundamental wavenumber of the length of plasma included in the simulation.

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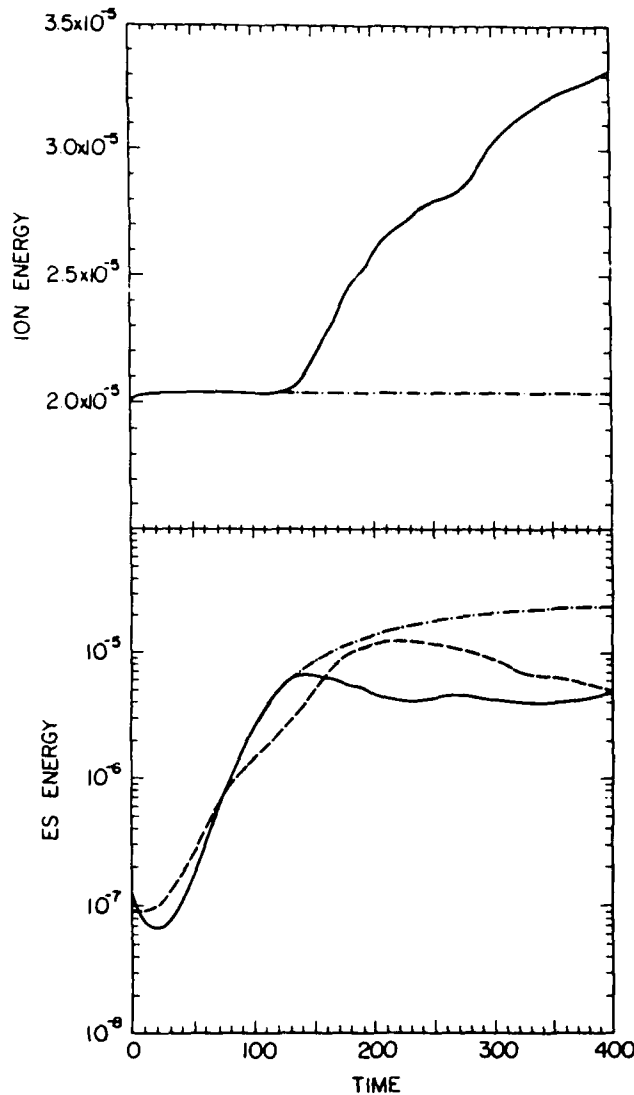


Fig. 3. The energetics of the theoretical model. The top panel gives the ion kinetic energy (in units in which the beam energy is  $2.9 \times 10^{-4}$ ) as a function of time; the solid line gives the ion energy when mode coupling is included in the model, the dot-dash line the result without mode coupling. The bottom panel gives the electrostatic energy of the waves with the same coding of the lines as the top panel, with the addition of the dashed line showing the result from the particle simulation.

as a pump wave, we calculated the phase velocities of the sideband waves excited by the three-wave coupling process. We found that these velocities agreed well with the velocities at the points where the tails emerge from the background distribution, supporting the argument that Landau damping of these sidebands accelerates the ions. We then formulated a simple set

of kinetic equations, beginning with the quasi-linear equations and adding mode coupling terms to describe the nonlinear processes [Retterer et al., 1986]. Numerical solution of these equations produces an ion velocity distribution with high energy tails and a wave spectrum similar to the ones observed in the simulation. Figure 3 illustrates the energy budget of the resulting calculation, with the top panel giving the ion energy as a function of time and the lower panel the electrostatic energy of the waves. The units of energy are such that the initial beam energy density is  $2.9 \times 10^{-4}$ . We experimented with the model by removing the mode-coupling terms from one run to judge its effect on the evolution. The dot-dash lines are the results without the mode-coupling term; all the energy released by the beam instability remains concentrated at long wavelengths and little is shared with the ions. In contrast, with mode-coupling active most of the energy liberated is transferred to the ions, leaving much less in the waves, in agreement with the results of the particle simulation, presented here as the dashed line. In form, we see at initial times the exponential growth associated with the linear phase of the instability. Once the threshold for mode-mode coupling has been exceeded, a turbulent steady state in the waves is soon reached, while energy continues to be

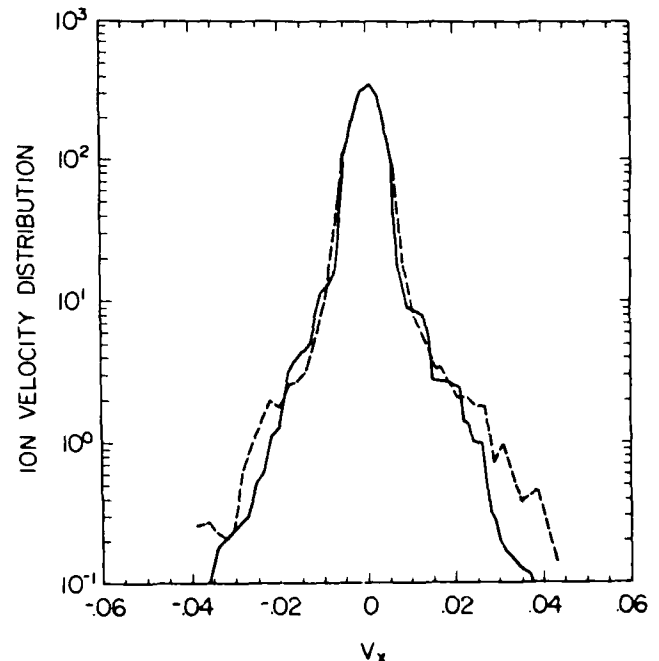


Fig. 4. The ion velocity distribution in the theoretical model. The solid line is a snapshot of the ion velocity distribution at  $\omega_{LH} t = 400$ . The dashed line gives the ion velocity distribution from the comparable time in the particle simulation.

transferred through the waves from the beam to the ions. In the solution without mode coupling, on the other hand, the wave energy continues to grow, although the growth rate slows as the beam velocity distribution forms a plateau at the phase velocities of the fastest-growing modes. Without mode coupling, the energy transferred to the ions is negligible.

The detailed ion velocity distribution in the mode coupling calculation shows the high-velocity tails characteristic of the particle simulation. Figure 4 shows a snapshot of the ion velocity distribution at  $\omega_{LH}t=400$ , illustrating the acceleration of the tails. The dashed curve here gives the comparable ion velocity distribution from the particle simulation.

We conclude from these comparisons that our theoretical model with mode-coupling does satisfactorily describe the phenomena observed in the particle simulations. While the simple resonant-quasilinear-diffusion model is adequate to describe the effect of the turbulence on the particles, a full nonlinear treatment is necessary to describe the evolution of the turbulence.

#### Conclusion

Scaling of our simulation results to suprathermal conditions gives results which agree well with data from observed ion conics; fraction of accelerated ions  $\sim 10^{-3}$  to  $10^{-2}$ ; average energy  $\sim 50$  eV; maximum energy  $\sim 1$  keV. The one-dimensional model presented here does overestimate the wave electric field, predicting values of the order of 100 mV/m for the total spectrum. It does agree with the observations in demonstrating that an overwhelming portion of the energy removed from the beam goes into particle acceleration rather than waves, the proportion here being roughly ten to one. The simulation and analysis of the phenomena of lower hybrid acceleration in two or three dimensions must be postponed to a later report. As a preliminary, we note that an analysis of lower-hybrid parametric decay under suprathermal conditions has been performed by Koskinen [1985, see also this conference]. He reports that decay through nonresonant quasimodes is the dominant process and that the threshold of wave amplitude may be one mV/m or smaller, insuring

that the mode-coupling processes which we have discussed can operate in the suprathermal region.

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