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INFLUENCE OF DENSITY IRREGULARITIES ON HIGH-FREQUENCY WAVE PROPAGATION: COMPUTER EXPERIMENTS OF STIMULATED EMISSIONS

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Abstract: We study the mechanism of stimulated electromagnetic emissions, called Broad Upshifted Maximum (BUM) feature observed in high-frequency ionospheric heating experiments with the aid of two-dimensional electromagnetic particle computer experiments. The pump is set up as an O-mode wave in the computer experiments propagating through the plasma with small-scale field aligned irregularity. A proposed theoretical study shows that the irregularity is important in the excitation mechanism. High-frequency electromagnetic emissions are observed, accompanied by electrostatic upper hybrid and lower hybrid waves in agreement with the theory.

1. Introduction

Electromagnetic waves propagating through the ionosphere and magnetosphere are affected by plasma density irregularities. Ionospheric heating experiments reveal that density irregularities of scale comparable to the pump wavelength are connected to the anomalous absorption (COHEN *et al.*, 1970; UTLAUT *et al.*, 1974) and scattering of the high-frequency pump waves. Stimulated electromagnetic emissions (SEE) are characterized by signs that the induced asymmetric sidebands around the pump frequency are wide, strong and exhibit a well defined temporal evolution, leading to a rich and systematic steady state spectral peak structure. SEE cannot be explained in terms of simple three wave parametric processes (DRAKE *et al.*, 1974; FEJER, 1979) and requires fundamentally new physical processes for its explanation, expressed either by traditional theory or inspired by computer experiment. The so called Broad upshifted maximum (BUM) feature (THIDÉ *et al.*, 1983; STUBBE *et al.*, 1984; LEYSER *et al.*, 1989) is one of the steady-state SEE features. A possible theoretical explanation for the BUM which involves density irregularities in the upper hybrid layer was proposed (GOODMAN *et al.*, 1993). We study the scattering mechanism of a high-frequency electromagnetic pump wave in the inhomogeneous plasma by computer experiments, comparing to the latter theoretical study.

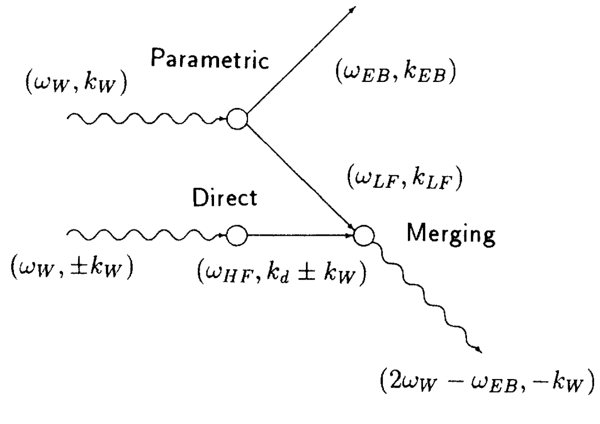


Fig. 1. Diagrammatic representation of the suggested generation mechanism for BUM feature by GOODMAN *et al. (1993).*

2. Observations and Theoretical Study for BUM

The BUM feature has been observed in narrow ranges of the pump frequency, near the third, fourth, fifth, sixth and seventh multiples of the electron cyclotron frequency. It is observed only during O-mode pumping, when $\omega_W \geq p\Omega_e$, where ω_W is the pump frequency, Ω_e is the electron cyclotron frequency and p is an integer (3, 4, 5, 6 and 7 in experiments). The frequency of the stimulated emission, ω_{BUM}, is empirically observed to follow the formula $\omega_{BUM} \approx 2\omega_W - p\Omega_e > \omega_W$ (LEYSER *et al.*, 1989). It grows on the same time scale as thermally generated field aligned density irregularities giving rise to high-frequency (HF) backscatter (HEDBERG *et al.*, 1983). The fact that the spectral feature is only observed at frequencies higher than the pump frequency suggests that higher order processes than three wave interactions are involved in the generation mechanism. This is because a three wave decay can only produce waves lower infrequency the original one.

For a possible theoretical explanation, a combination of direct conversion and parametiric decay mechanism near the upper hybrid (UH) resonance altitude are proposed (GOODMAN *et al.*, 1993). The mechanism is summarized in Fig. 1 and as follows. The upgoing pump (ω_W, k_W) decays parametically into a high-frequency electron Bernstein wave (ω_{EB}, k_{EB}), with $\omega_{EB} \simeq p\Omega_e$, and a low-frequency (LF) mode (ω_{LF}, k_{LF}) such as a lower hybrid wave. In addition, the upgoing or downgoing pump (ω_W, $\pm k_W$) is able to beat with zero-frequency field aligned density irregularity, with large wavenumber k_d perpendicular to B_0 (0, k_d), to directly convert into HF electrostatic waves (ω_{HF}, k_{HF}) $\approx$ (ω_W, $k_d \pm k_W$). One posssibility is a direct conversion to an upper hybrid, UH, wave. Merging of the UH wave with LF wave produces the upshifted emission whose frequency and wavenumber is ($2\omega_W - \omega_{EB}$, $-k_W$) as experimentally observed.

3. Models

We use a two-dimensional electromagnetic particle code called KEMPO (MATSUMOTO *et al.*, 1985) which can deal with kinetic interactions of waves and plas-

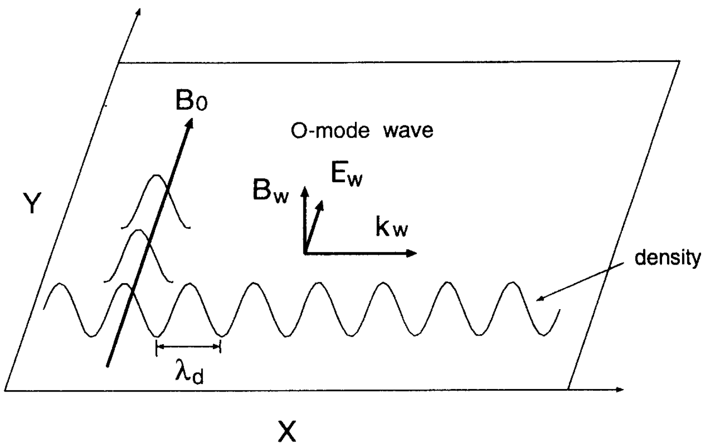


Fig. 2. Model of computer experiments.

ma particles. The code adopts the typical and sophisticated scheme for particle-grid model plasma simulation, in which electromagnetic fields are solved at grid points by integrating the difference form of the Maxwell's equations over finite time step, and equation of mortion for finite sized charged particles called *superparticles* without collision terms and relativistic effects, are explicitly solved in self-consistent manner. The periodic boundary condition for both x and y directions is assumed. The configuration of the simulation plane is shown in Fig. 2. The pump is set up as an O-mode wave propagating along the x axis, and across the static magnetic field B_0 which is along the y axis. We adopt two models for the initial density profile. One is given to be uniform everywhere in the simulation plane for both ions and electrons. The purpose of the uniform density case is to observe the pump and backscatter waves giving rise to the small-scale field aligned irregularity. In the other model, density profiles are given to be sinusoidal distributions perpendicular to B_0 with scale length $\lambda_d = \lambda_W/2$, where λ_W is the wave length of the pump, and uniform along B_0. Charge neutrality is maintained throughout the whole simulation plane. The normalized parameters used in the computer experiments are shown in Table 1. They have been chosen to best represent the ionosphere given the limitations on CPU time.

Table 1. Normalized parameters for computer experiments.

Parameters		Values
Electron plasma frequency/Electron cyclotron frequency	$\Pi_{e\ ave}/\Omega_e$	3.0
Pump frequency/Electron cyclotron frequency	ω_W/Ω_e	3.16
Field energy/Electron thermal energy	$\varepsilon_0 \mid E_W \mid^2/nkT_e$	5.0
Wave length of pump/Scale length of irregularity	λ_W/λ_d	2.0
Maximum density/Average density	n_{max}/n_{ave}	1.25
Mass ratio of electron to ion	m_e/m_i	0.01
Temperature ratio of electron to ion	T_e/T_i	1.0

4. Computer Experiments

Figure 3 shows the time evolution of the plasma density profile along the x direction and averaged over the y direction. The system length along the x direction equals 4 λ_W. The initial distributions of both electrons and ions are uniform in this

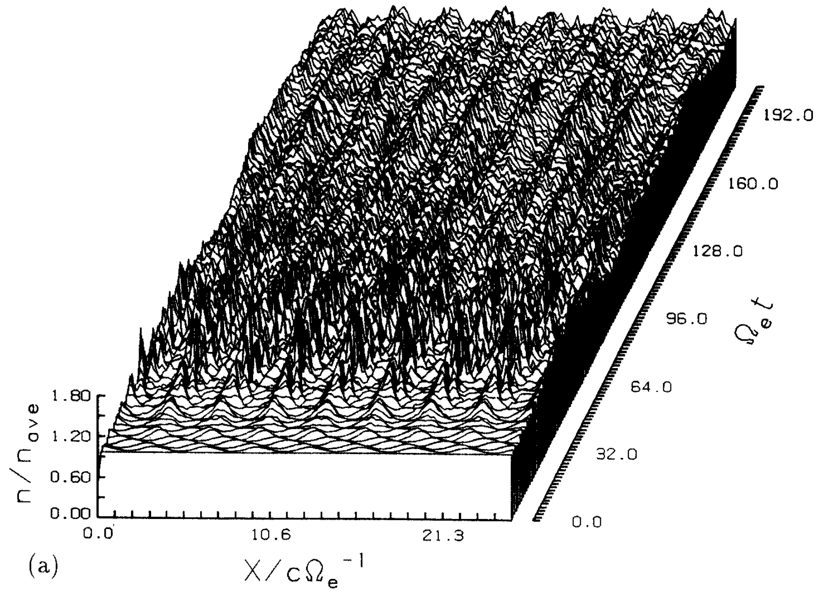


Fig. 3a.

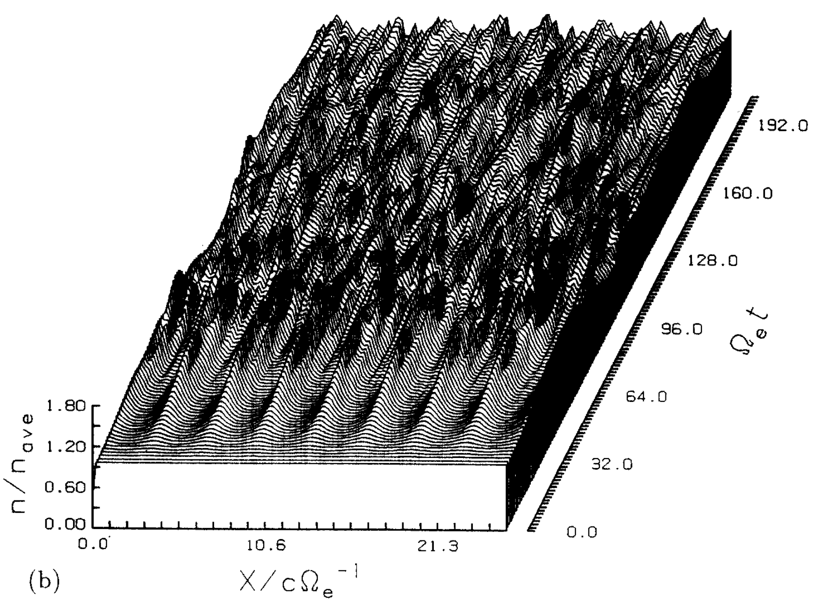
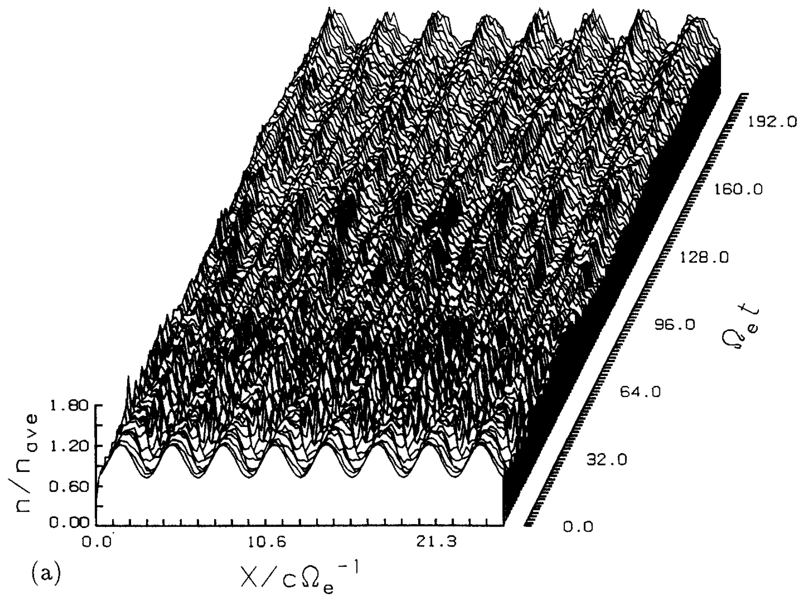


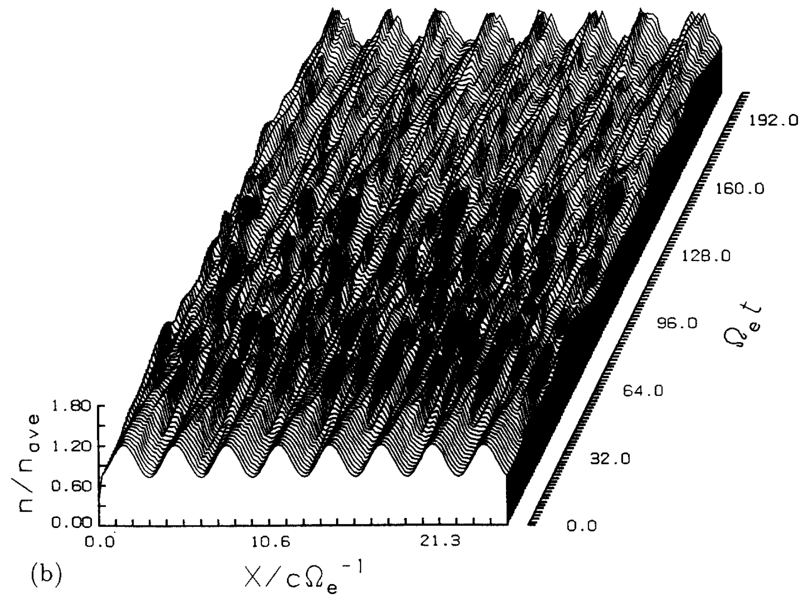
Fig. 3b.

Fig. 3. Time evolution of density profiles along the x direction averaged over the y direction in the case where initial density profiles are uniform. (a) for electrons (b) for ions.



(a)

Fig. 4a.



(b)

Fig. 4b.

Fig. 4. The same as Fig. 3 in the case where initial density profiles are periodic.

case. A periodic irregularity is generated with the scale length λ_d, which is roughly seen to be $\lambda_W/2$. This scale is as expected for high-power ionospheric heating experiments since the plasma density is modulated by the standing wave created by the pump and backscatter waves. Adopting the model with sinusoidal irregularity

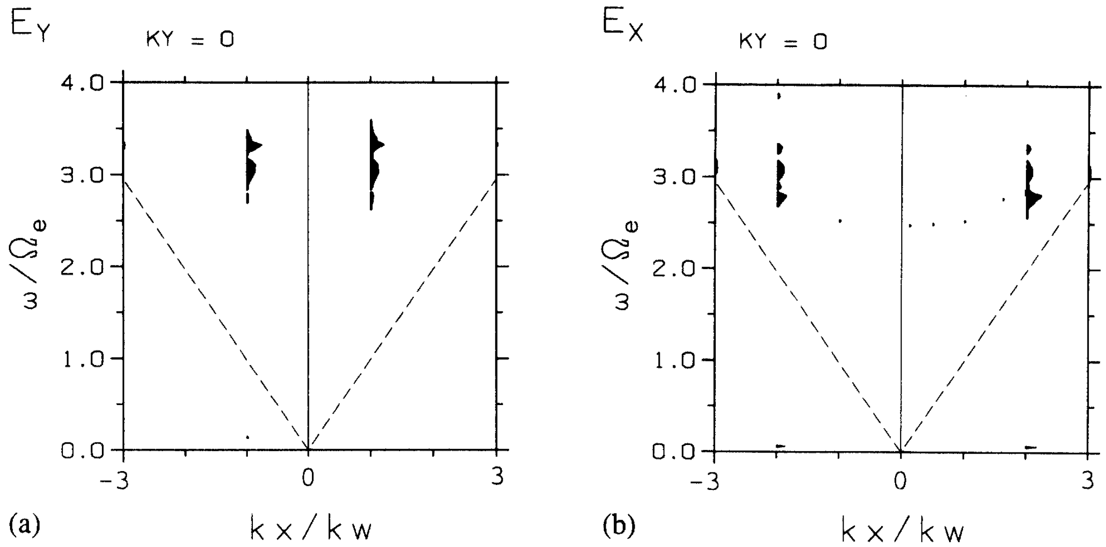


Fig. 5. ω – k diagrams of the electric field in the case where initial density profiles are periodic. (a) for parallel component E_y (b) for perpendicular component E_x.

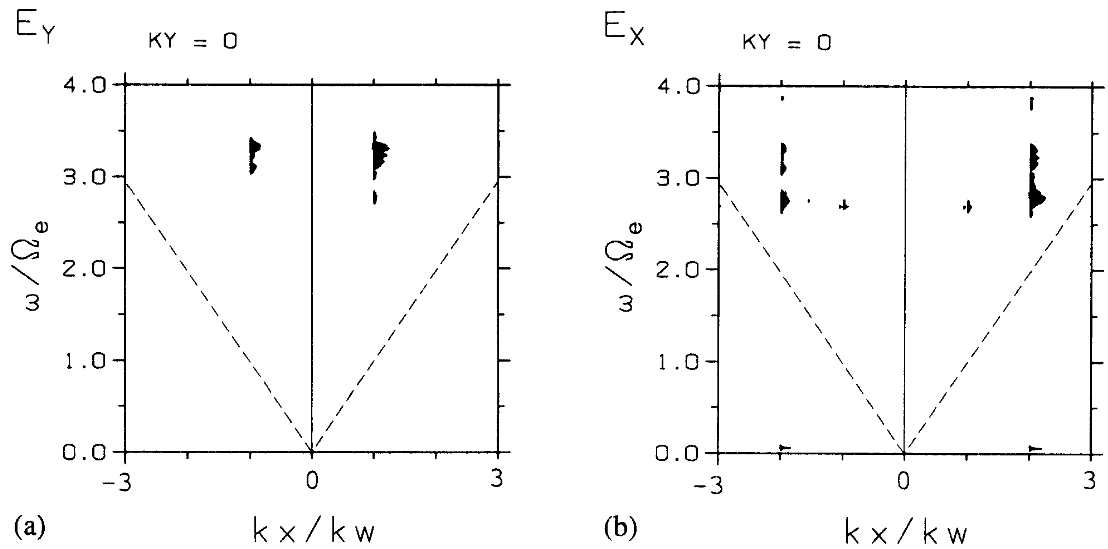


Fig. 6. The same as Fig. 5 in the case of uniform initial density profiles.

of scale $\lambda_d = \lambda_W/2$ is seen to be reasonable in light of the latter observation. Figure 4 also shows the time evolution of the density profile in the sinusoidal model. The initial irregularity is emphasized and in addition there is some fine structure. The ω – k diagrams of both parallel (E_y) and perpendicular (E_x) components of the electric field for this case are shown in Fig. 5. The abscissa stands for the wave number perpendicular to B_0 normalized by that of the pump wave, and the ordinate denotes the frequency normalized by electron cyclotron frequency. In the figures the horizontal length of hatched area with regard to vertical baseline means the relative amplitude of corresponding wave with relevant frequency and wave number. For reference purposes the obliue dashed lines correspond to light velocity. The pump and backscatter waves appear as peaks in Fig. 5a with a frequency $\omega = 3.16\ \Omega_e$ and wave numbers $k_x = \pm k_W$. Interesting emissions are evidently found whose frequencies are slightly higher than the pump's and backscatter waves while the wave numbers are approximately the same. The frequency difference between the pump and wave emission is roughly equal to the frequency of electrostatic low-frequency waves with $k_x = \pm k_d = \pm 2\ k_W$, where $k_d = 2\pi / \lambda_d$ as shown in Fig. 5b. In addition, components of an upper hybrid wave with $k_x = k_d$ are obviously excited. These emissions agree with prediction by the theory described in Section 2. Comparing to Fig. 6, the ω–k diagram for the same case as Fig. 4, the degree of irregularity is suggested to contribute to excitation of the higher frequency electromagnetic wave.

5. Concluding Remarks

The mechanism for production of the BUM feature of SEE is investigated by computer experiment. The results are not inconsistent with the proposed theory, which suggests that small-scale density irregularity is important in the mechanism. HF electromagnetic waves were excited as well as electrostatic UH and LH waves. The effect of altering the electron cyclotron frequency, pump frequency and pump strength will be examined in future work.

Acknowledgments

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