Particle Simulations in Magnetospheric Plasmas
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Technical Description of Project and Results

Brief Summary

In view of the recent remarkable advancement of computer technology and simulation software, simulation studies are one of the most powerful academic tools for establishment of quantitative space physics and modelling of our space environment. The complex nature encountered in space plasma physics has motivated considerable development in computer simulations, which have played an essential role in the development of space plasma theory.

This final technical report describe research to understand physical processes involved in plasma waves observed in the magnetospheric plasmas, and associated nonlinear phenomena such as heating, diffusion, and acceleration of particles due to excited waves. Our research have elucidated the observational data both qualitatively and quantitatively. We need further development of new simulation codes and simulation studies.

1. Simulation Study of a New Mechanism for Excitation of Kinetic Waves in a Magnetoplasma

Nishikawa et al. [1988b] have investigated the new ion-cyclotron-like waves by a localized transverse electric field by means of simulation with the assistance of the nonlocal kinetic theory [Ganguli et al., 1985a, b]. The linear theory shows that the growth rates of the kinetic Kelvin-Helmholtz (K-H) modes are strongly reduced with increasing $u = k_{\parallel}/k_y$, and they become unstable only when $b = k_y^2 \rho_i^2 < 1$ and $k_y L \approx 1$, where L is the scale length associated with the transverse electric field. On the other hand, the new modes have larger frequencies and become unstable at larger $b > 1$ and $k_y L \gg 1$ [Ganguli et al., 1988].

Simulation results show that ion-cyclotron-like waves are excited in regions where $\mathbf{E} \times \mathbf{B}$ drift is localized. Linear growth rates of several modes are obtained from the wave analysis of the simulation. This linear analysis shows that the (0, 4) mode corresponds to large b, and large $k_y L$ has the maximum growth rate. Clearly, these are not K-H modes. Further, the simulation results show that density gradients help to enhance the growth rates. This is in contrast to the established properties of the K-H instability [Satyanarayana et al., 1987]. However, like the K-H mode, the real frequencies of this instability are approximately proportional to $k_y V_E^o$, where V_E^o is the peak value of the $\mathbf{E} \times \mathbf{B}$ drift.

Nonlinear phenomena such as diffusion and coalescence of vortices are investigated. In the linear stage smaller vortices are generated and larger vortices with the lower frequencies are dominant in the nonlinear stage. In the nonlinear stage ions diffuse strongly due to large-scale vortices.

Recently, we have investigated the electrostatic waves driven by the combined effects of a localized transverse electric field and parallel electron drifts by means of simulation with the assistance of the nonlocal kinetic theory [Ganguli and Palmadesso, 1988; Ganguli et al., 1989].

We have performed a number of simulations for this instability [Nishikawa *et al.*, 1989b, 1990a]. Simulation results show that electrostatic waves are excited in the regions where the E × B drift is localized in the simultaneous presence of parallel electron drifts and transverse electric fields. Simulations with only parallel electron drifts or transverse electric fields show that no instability grows out of the thermal noise. The simulation with both the parallel electron drift and the transverse electric field shows the growing waves out of the thermal noise. The Doppler shift due to the E × B drift can lower the phase velocity of waves along the magnetic field. Then this makes wave-particle resonance possible for smaller V_d^p, which leads to this instability.

2. Simulation of Electron Cyclotron Harmonic Waves by AMPTE Lithium Release

On September 11 and again on September 20, 1984, a cloud of lithium gas was released in the solar wind upstream of the Earth's bow shock as a part of the AMPTE (Active Magneto-spheric Particle Tracer Explorers) program. Numerous effects were observed in the immediate vicinity of the release including: (1) the creation of a dense rapidly expanding cloud of ionized lithium, (2) the formation of a diamagnetic cavity, and (3) the occurrence of an intense shock-like burst of electrostatic noise in the region upstream from the cavity. A detailed analysis of the shock-like electrostatic noise and investigation of the origin of this noise is presented by Gurnett *et al.* [1986a]. Also comparisons are made with a similar type of noise observed in the Earth's bow shock [Gurnett *et al.*, 1986a].

A simulation study of the electrostatic noise in the cloud of released lithium ions has been performed [Nishikawa *et al.*, 1990b]. Using a two-dimensional electrostatic code, we have simulated plasmas consisting of four components as observed. In this study, electrons and ions are magnetized, unlike the theory [Gurnett *et al.*, 1986a; Ma *et al.*, 1987; Omidi *et al.*, 1988]. However, the gyro-radii of ions are much larger than the size of the simulation system as well as the scale size of the ion cloud. Since the gyro-radii of hot electrons are smaller than the size of the simulation system, electron cyclotron waves and upper hybrid waves are included. This is important because electrostatic electron cyclotron harmonic (ECH) waves are observed by the AMPTE-IRM plasma wave experiment following a lithium release in the solar wind [Roeder *et al.*, 1987].

The simulations show that electron cyclotron harmonic waves are excited by the solar wind protons and electrons [Nishikawa *et al.*, 1990b]. The spectra of perturbations of electrostatic potential exhibit electron cyclotron harmonic waves.

The overall frequency range is obtained by observing the electric fields at some points in the simulation region. Power spectra of the electric fields exhibit electron cyclotron frequency and higher harmonics which is simular to the spectrum obtained by the satellite.

The possible mechanisms of generation of electron cyclotron harmonic waves are discussed in the previous work [Roeder *et al.*, 1987]. In this simulation study, the possible energy sources of the instability are included automatically. The relative velocities among different species become the energy source of instabilities. The relative velocity between solar wind elec-

trons and lithium ions would be the possible energy source for the excitation of ECH waves. The fact that the instability can be excited without new-born cold electrons supports this mechanism.

According to Figure 1 by Gurnett *et al.* [1986a], the higher frequency ranges of waves look very similar in both cases with $\overline{n}_{li} \approx \overline{n}_{pr}$ and $\overline{n}_{li} \ll \overline{n}_{pr}$. In this study, we found that ECH waves are excited also in the case of $\overline{n}_{li} = \overline{n}_{pr}$. The satellite data show that ECH waves can be observed only in some range of lithium ion density (0.03 - 0.18 cm^{-3}) associated with lithium drift energy [Roeder *et al.*, 1987]. The observations show that in the case of $\overline{n}_{li} \approx \overline{n}_{pr}$ ECH waves are not found. The simulation results show that in the same case of $\overline{n}_{li} = \overline{n}_{pr}$ ECH waves are excited. This discrepancy may be explained by the setting of simulation geometry due to the two-dimensional code. If the simulation plane is set nearly parallel to the magnetic fields ($B_{oy}/B_o \leq 1$), the angle between the magnetic fields and the drift velocity of hot electrons and protons becomes very small. Then, in the case of $\overline{n}_{li} = \overline{n}_{pr}$, the parallel drift of solar wind protons and electrons may excite ion acoustic waves more dominantly than ECH waves, which is not included in this study [Gurnett *et al.*, 1986a; Ma *et al.*, 1987; Omidi *et al.*, 1988].

Related to the previous discussion, we performed the simulation with the parameter $B_{oy}/B_o = 0.371$ keeping other parameters the same as the first case. In this case, the drift velocity of protons and hot electrons along the y-direction becomes $13.9v_{prt}$ and the angle between the magnetic field and the drift velocity is 49.2°. The case of the lithium release on September 11, 1984 has much smaller angle between the magnetic field and the drift velocity (in which the drift velocity perpendicular to the magnetic field is very small). The geometry of this simulation has a qualitative resemblance with that of the observation on September 11, 1984. The simulation results show that ECH waves are not excited. Therefore, the excitation of ECH waves depends on the angle between the magnetic field and the drift velocity (the value of the perpendicular drift velocity).

3. Beam Instability in the Foreshock

As an application of the simulation method used in the proposed research (Broadband electrostatic noise), the beam instability in the foreshock has been investigated. Electrons backstreaming into the Earth's foreshock generate waves near the plasma frequency by the beam instability [Etcheto and Faucheux, 1984; Fuselier *et al.*, 1985; Lacombe *et al.*, 1985; Garnett, 1985]. Two versions of the beam instability exist: the 'reactive' version [Buneman, 1963] in which narrowband waves grow by bunching the electrons in space, and the 'kinetic' version in which broadband growth occurs by a maser mechanism [Cairns, 1887a, b; Dum, 1989, and references therein]. Recently, Cairns [1987b] has suggested that (1) the backstreaming electrons have steep-sided "cutoff" distributions which are initially unstable to the reactive instability, (2) the back-reaction to the wave growth causes the instability to pass into its kinetic phase, and (3) the kinetic instability saturates by quasilinear relaxation.

Cairns and Nishikawa [1989] have performed two-dimensional simulations of the reactive instability for Maxwellian beams and cutoff distributions. The results of the simulations are consistent with suggestions (1) and (2) above. In addition, we have demonstrated that the

reactive instability is a bunching instability, and the reactive instability saturates and passes over into the kinetic phase by particle trapping. We found that the kinetic growth occurring after saturation of the reactive instability is presumably due to the spatially localized gradients in $y - v_{\parallel}$ phase space. Both simulation results and numerical solutions of the dispersion equation indicate that the center frequency of the intense narrowband waves near the foreshock boundary may be between $0.9\omega_{pe}$ and $0.98\omega_{pe}$, rather than being above ω_{pe} as previously believed.

4. 3-D Particle simulation of Whistler Mode Driven by the Spacelab 2 Electron Beam

During the Spacelab 2 mission while an electron beam was being ejected from the shuttle, the Plasma Diagnostics Package (PDP) detected a clear funnel-shaped emission that is believed to be caused by whistler-mode emission from the electron beam [Gurnett et al., 1986b; Farrell et al., 1988, 1989]. In order to understand the mechanism of this emission, the simulations have been performed using a three-dimensional magnetostatic code for low-β plasmas [Okuda et al., 1979] in which the beam electrons are initially located in the column [Nishikawa et al., 1989a, and references therein]. In order to simulate the continuous electron ejection from the shuttle, the simulations were also performed with the recycling of the beam electrons. The beam electrons excite whistler waves and lower hybrid waves. The brief fluid theory based on the magnetostatic code was checked with the simulation results. The propagating whistler mode was identified with the theory. The simulation results show that the quasi-perpendicularly (the angle between the magnetic field and the wavenumber is larger than $50°$) propagating whistler waves have larger amplitude whose real frequencies are smaller than the local electron cyclotron frequency. This fact is consistent with the fact that the funnel-shaped emission is observed below the electron cyclotron frequency away from the beam electrons [Omura and Matsumoto, 1988a, b]. The beam electrons initially in the column diffuse radially as well as slow down due to the $E \times B$ caused by the excited waves. The acceleration of the beam electrons also takes place due to the excited whistler waves.

In order to compare with the PDP data, the local magnetic fields $B_{x,y}$ and the perturbed electric fields $E_{y,z}$ are diagnosed at the several points in the simulation system. The results show that the waves are radially excited by the beam electrons localized in the center of the system. The wave spectra of the electric fields $E_{y,z}$ diagnosed at $x = 31\lambda_e, y = 16\lambda_e$, and $z = 17\lambda_e$ show the several kinds of waves generated by the beam electrons. The analysis shows that the lower hybrid waves and whistler waves are excited. The frequency range of these spectra extends from ω_{pi} to beyond ω_{pe} which is in qualitative agreement with the PDP data. As the PDP data show, the intense electrostatic narrowband emission around the electron plasma frequency has been observed dominantly in the spectra of the electric field (E_z) with and without the recycling of the beam electrons. This wave is identified as the parallel (quasi parallel) whistler wave. This simulation result is in good agreement with the PDP data [Gurnett et al., 1986b].

At the present the maximum memory is 6 Mwords on CRAY XMP/48 at National Center for Supercomputing Applications at July, 1988. It was increased up to 100 Mwords on CRAY-2 in 1989; now we will be able to use a larger system such as $L_x \times L_y \times L_z = 128 \times 128 \times 256\lambda_e^3$.

Simulations with this size will provide more realistic comparisons with the observed data.

List of Publications Prepared under NASA Support (as of January 26, 1990)

Nishikawa, K.-I., L. A. Frank, T. E. Eastman, and C. Y. Huang,
   Simulation of electrostatic turbulence in the plasma sheet boundary layer with electron currents and ion beams, in *Magnetotail Physics*, edited by A. T. Y. Lui Johns Hopkins University Press, p. 313, 1987.

Nishikawa, K.-I., L. A. Frank, and C. Y. Huang,
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Nishikawa, K.-I., G. Ganguli, Y. C. Lee, and P. Palmadesso,
   Simulation of ion-cyclotron-like modes in a magnetoplasma with a transverse inhomogeneous electric field, *Phys. Fluids*, *31*, 1568, 1988b.

Nishikawa, K.-I., L. A. Frank, and C. Y. Huang,
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   Simulations relevant to the beam instability in the foreshock plasma, *J. Geophys. Res.*, *94*, 79, 1989.

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Nishikawa, K.-I., J. L. Roeder, and H. C. Koons
   Simulation of electron cyclotron harmonic waves by AMPTE lithium release, to be resubmitted to *J. Geophys. Res.* 1990b