Part I

Introduction

Chapter 1

Computer Experiments of Space Plasmas

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In this chapter, we would like to invite the readers into the world of the "computer experiment" (or "simulation world") of space plasmas. The first two sections of this chapter are devoted to a review of the role and the history of the computer experiment in space plasma research. The third section is devoted to an actual example of where a computer experiment based on a particle model played a vital role in a real space active experiment.

Whilst it would be an exaggeration to claim that the computer has proven itself to be the ultimate problem solver in any field, physics or not, we can with certainty say that the computer experiment does yield clues and hints to complicated problems otherwise opaque to more traditional methods of investigation. The computer experiment is close in method to traditional laboratory experiments where physical parameters are easily changed and controlled. Though there exist many pit holes into which researchers often fall and which lead to erroneous results, such as boundary conditions, initial conditions, models and accuracy of numerical schemes, the computer experiment is a new and potentially powerful tool. By combining conventional theory, space experiment or observation (and sometimes lab experiments) and computer experiment, researchers can discover new and unsolved aspects of physical processes. These aspects could often neither have been understood nor revealed by traditional theory and or space (or laboratory) experiments alone.

1.1 Role of the Computer Experiment

Traditionally the scientific method involves a mutual interplay between experiment and "pen and paper" theory. The former attempts to collect "factual" information by repeated experiments. The latter trys to order the accumulated factual knowledge and thus propose a new paradigm of description of physical processes. New experiments and the interpretation of observations are in turn often based upon the new theoretical descriptions available. These two activities - theory and experiment - naturally interact with each other via mutual stimulation and feed back. A third new approach came to be available to fill the gaps between the two traditional approaches in accordance with the advent of modern high speed computers. The third category of approach is called computer experiment (or computer simulation). The computer experiment can bridge the gap between experiment and the ability of theorists to encompass observations into an acceptably consistent pattern. The basic idea of computer experiments is to simulate the physical behavior of complicated natural systems by solving an appropriate set of mathematical equations based on an accepted and fundamental physico-mathematical model.

The physical processes are thus recorded onto computer memory as consequences of fundamental physical laws adopted in the physico-mathematical model. As one can easily change the set or sub-set of the mathematical equations as well as the boundary and initial conditions, the computer simulation is a perfectly controlled experiment. Diagnostics of the physical processes can be made as detailed as one wishes without disturbing the physical system. In real experiment the process of diagnosing a physical system to some desired level of detail always involves a simultaneous disturbance and alteration of the physical processes one imagines oneself to be studying. The main advantage of computer experiments is that complicated physical systems including nonlinearity and non-uniformity or inhomogeneity can be treated without difficulty as easily as much simpler linear and homogeneous systems are dealt with. Nonlinearity and/or inhomogeneity is thus no longer an obstacle to prediction and exploitation of phenomena in physical systems.

The advantage and value of computer experiment is maximized when the gaps between theory and experiment are largest. In space plasma physics, the experimental facts are mainly collected by satellite observations, space active experiments and ground based active or passive remote diagnostics. The accumulation of factual information from these experiments is an extremely expensive and time consuming task. Moreover, the object of space plasma research is ever changing both in time and space, exhibiting very complicated phenomena. The sheer volume of exploration in space is so large that the essentially point observations by spacecraft alone often leads to misunderstanding or mis-interpretation of the data. Some type of physico-mathematical models for computer experiment can reproduce the global large-scale structure which can never be measured even by a whole fleet of spacecraft. On the other hand, theory, which usually relies on simplifying assumptions in the pursuance of a necessary symmetric beauty, often fails to correctly interpret highly complex nonlinear processes appearing in the space plasma environment.

The role of the computer experiment in space plasma physics is not only important but now demonstrably indispensable. The combination of computer experiment with theory and space experiments turns out to be much more effective and useful than expected in early times in understanding large-scale phenomena and highly nonlinear kinetic microscopic processes in space plasmas. Computer experiment, theory and experiment cover mutual weakness of each method. Computer experiment compliments the theory's weakness against nonlinearity, inhomogeneity and lack of simplicity and symmetry. It can also complement space experiments by acting as a large and long time scale planning guide. Specific test simulations, with real measured data as input, are able to indicate what would have been expected as an observation, rather than what was actually "observed", and thus point out areas of possible instrumental interference or malfunction, or other failings of real experiments.

1.2 History of the Computer Experiment

The first example of a computer experiment using the particle model can be found in the electronic microwave device studies, such as the magnetron and TWT (traveling wave tube) design and development, which were carried out in the 1940's and 1950's [1]. The electrical engineers and physicists traced electron motion within the microwave device. They developed methods of advancing electrons and of computing the corresponding electromagnetic fields. Computer plasma experiments then followed in the late 1950's and early 1960's. The pioneers of computer experiments in plasma physics were O. Buneman [2] and J. M. Dawson[3]. Many investigations then followed during the 1960's and 1970's establishing a full framework of plasma simulations. During the 1960's the computer simulation was extended in its application to space plasma research and also to the drive towards nuclear fusion. Here at Kyoto University during this decade we made our first simulations on nonlinear dynamics of the ionosphere and wave-particle interactions of the magnetosphere. During the 1970's and 1980's various types of simulation codes in addition to the early-time explicit particle code were introduced and established. Among these were; a Magneto-Hydro-Dynamic (MHD) code, Fluid code, Vlasov code, hybrid (particle + fluid) code, and implicit particle code. The MHD code has been extensively used both to carry-out local MHD simulation for a study of elementary physical processes and to simulate the global structure and dynamics of the large-scale magnetosphere. The former is called "Local MHD simulation", while the latter "Global MHD simulation". The ionospheric nonlinear Rayleigh-Taylor instability and Kelvin-Helmholtz instability along the magnetopause boundary were investigated using the fluid code. The challenging problem of microscopic kinetics has been studied both by particle simulations and the Vlasov code. For lower frequency phenomena, which are not much affected by electron kinematics, a hybrid code has been developed and used. The hybrid code adopts the particle model for ions but treats the lighter electrons as a fluid. An implicit particle code has also been devised to treat low frequency wave-particle interactions. This code was invented to overcome a drawback of the full electromagnetic particle code. The full electromagnetic code solves all the kinetics of both electrons and ions under the self-consistent electromagnetic and electrostatic fields and thereby is most accurate with least artificial assumptions. However it consumes a huge amount of CPU time resources and needs lots of computer memory if it is applied to a large-scale and low-frequency (heavy ion time scale) phenomena. The implicit particle code was invented to avoid solving the electron Langmuir oscillation (or electron plasma waves) and yet retain appropriate electrostatic interactions in the system.

Based on the active development of simulation codes and on a rapid advancement of supercomputer technology, an explosive growth of research of space plasma physics via computer experiments was achieved in the late 1970's and 1980's. Space plasma physicists have come to recognize the computer experiment as a powerful research tool. In consequence new inroads have been made into previously intractable nonlinearly coupled space plasma processes such as collisionless shocks, double layers, magnetic reconnection, nonlinear wave generation and propagation, nonlinear wave-particle interactions, nonlinear wave-wave interactions, acceleration and heating of particles, radiation and emissions from the Earth, planets and comets, nonlinear dynamics of beams and plasma cloud injected by Space Active Experiments, space vehicle interaction with the plasma environment, nonlinear dynamics of boundary layers, magnetosphere-ionosphere couplings, and global structure of planetary structures.

During the early 1980's, discussions at URSI (International Union of Radio Sciences), led to the establishment of an international space plasma simulations school. The first International School for Space Simulation (ISSS-1) was held in 1982 in Kyoto (Japan) [4], followed by ISSS-2 in 1985 in Hawaii (USA) [5], and then by ISSS-3 in 1987 at Toulon and Nice (France) [6] [7]. The schooling activities at the initial phase of the ISSS's were limited to information exchange of academic achievement on space physics via computer experiments, and to instruction of principles and fundamental skills and technologies on software for computer experiments. Courses of practice and exercises using working computer codes for simulation was introduced at ISSS-3. The code provided at ISSS-3 was the Electrostatic Particle Code (ES-1) developed by C. K. Birdsall and A. B. Langdon [8]. Participants and students were able to gain hands on experience using PC's and terminals which were provided on site.

At ISSS-4, which was held in Kyoto and Nara in 1990, more convenient schooling facilities were prepared for the practice of the lectured codes which appear in this book. About 50 UNIX terminals linked to multiple mini-super-graphic computers were available. The attendants quickly mastered these codes and the associated graphic software so that they were able to visualize the results of the computer experiments they ran. The provided codes had advanced from the previous ES1 to Electromagnetic particle Codes (KEMPO1 and TRISTAN), 1-D hybrid code and 2-D MHD code. Easy access to the codes was given and attendants were able to run simulations on the spot. The codes provided were simple enough for the attendants to alter whatever parameters they wanted in order to simulate particular systems conceived in their own minds. The practice course of the ISSS-4 was a mile stone in the spread of software skills and technologies because the code developers or their colleagues did give the instructions of the codes' usage as well as their background physico-mathematical models.

In 1991, a Simulation Promotion Office for the International Science Program of STEP (Solar-Terrestrial Energy Program) was established at RASC, Kyoto University. The office is called STEP-SIMPO and issues News Letters on research topics, software and hardware for computer experiments for STEP and space plasma physics. Another important move is that space plasma researchers have started to use computer experiments as a tool to interpret data brought back by Space Missions or even to contribute to those mission designs by predicting sophisticated nonlinear processes, to which the relevant mission is oriented. These are called "mission-oriented computer experiments".

1.3 Theory, Space- and Computer-Experiments

In this section, we present an example of how a computer experiment has been used to fill a gap between theory and space experiment, and has played a complementary role in interpreting observations.

1.3.1 Nonlinear Plasma Effect caused by Intense Monochromatic Microwave

The topic which we take as an example is an active space experiment on nonlinear interaction of an intense monochromatic microwave beam with the ionospheric plasma. The research topic was initiated by a motivation to study the possible impact on the ionospheric plasma environment of an intense microwave beam used for wireless energy transmission from the future Solar Power Station (SPS) to the ground. The major role of SPS will be as an alternative energy source during the fossil fuel crisis anticipated for the 21'st century.

The frequency of the microwave energy beam currently allotted to the SPS is 2.45 GHz which is much higher than characteristic frequencies of of the ionospheric plasma such as the electron plasma frequency f_{pe} or electron cyclotron frequency f_{He}. For such high frequency electromagnetic wave, the ionospheric plasma is believed to be essentially transparent unless the amplitude of the electromagnetic wave is huge. The estimated electric field of the SPS microwave is of the order of 100 V/m and is four or five orders of magnitude higher than the electric field of natural electrostatic wave fluctuations in the ionosphere. Therefore nonlinear effects of the SPS microwave beam need to be investigated. A nonlinear effect caused by a thermal filamentation instability was studied by

Perkins and Roble [1978] [9]. Another filamentation instability caused by a ponderomotive force due to the gradient of the envelope of the microwave energy beam was recently studied by Shklyar and Matsumoto [1993] [10]. These two nonlinear effects appear over a large spatial scale of the order of several km and are therefore macro-instabilities. Matsumoto [1982] [11] theoretically calculated the growth rate of electron plasma waves and ion acoustic waves through Raman and Brillouin scatterings and showed that much smaller scale micro-instabilities are also stimulated by the intense SPS microwave energy beam.

1.3.2 Theory of Nonlinear Excitation of Plasma Waves by Intense Monochromatic Electromagnetic Wave

As the microwave for energy transmission from the SPS is essentially of monochromatic nature, the most plausible nonlinear plasma effect predicted by theory is the excitation of electrostatic plasma waves through energy and momentum flow from the pumping microwave due to nonlinear three wave coupling. The three wave coupling takes place most easily when the excited electrostatic plasma waves suffer no damping. Therefore, we consider two cases where the excited electrostatic waves propagate in the direction parallel or perpendicular to the external magnetic field.

The three waves involved in the nonlinear coupling are often referred to as the pump, idler and excited waves. In our case the pump and idler waves correspond to the intense microwave and backscattered microwave, respectively. We use suffices (0, 1, 2) for the pump, idler and excited waves, respectively. The nonlinear coupling equations are then expressed by

$$\begin{aligned} \frac{dE_0}{dt} &= i\beta_0 E_1 E_2 \\ \frac{dE_1}{dt} &= i\beta_1 E_0 E_2^* \\ \frac{dE_2}{dt} &= i\beta_2 E_0 E_1^* \end{aligned} \tag{1.1}$$

where E_s (s=0, 1, 2) and are the complex electric field and the coupling coefficients, respectively, and "*" denotes the complex conjugate.

It is well known that the initial growth rate and the saturation amplitude of the waves excited by the nonlinear three wave coupling can be estimated by

$$\gamma = \sqrt{|\beta_1||\beta_2|}|E_0| \tag{1.2}$$

and

$$|E|_{sat} = \sqrt{|\beta_2|/|\beta_0|}|E_0| \tag{1.3}$$

respectively. The coupling coefficients can be derived by combining the Maxwell equations and equations of plasma dynamics such as the Langevin equation for

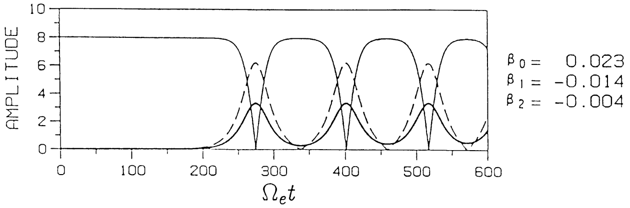

Figure 1.1: Time evolution of amplitudes of pump, idler and excited waves in the nonlinear three wave coupling predicted by theory.

cold plasma or the Vlasov equation for hot plasma. The calculation of the coefficients have been carried out [12] for two cases where either the electron plasma wave (i.e., the Langmuir wave) or the electron cyclotron harmonic waves (ECHW) are excited by the pump microwave. The result of the theoretical study predicts the following points.

1. The 2.45 microwave energy beam with the electric field intensity of the order of several hundreds volts per meter excites both Langmuir waves (LW) and ECHW's in the ionospheric plasma.
2. The excited electrostatic plasma waves essentially exhibit a line frequency spectrum determined by the conservation laws of energy (frequency) and momentum (wavenumber) and the plasma dispersion relation.
3. The estimation by (1.3) shows that the amplitude of the excited Langmuir wave is larger than that of the ECHW.
4. The Manley-Rowe relation, which is derived directly from the nonlinear coupling equations (1.1), predicts that the energy exchange between the pump, idler and excited waves takes place periodically as depicted in Figure 1.1.

1.3.3 MINIX Rocket Experiment

Based on the theoretical prediction [10], a rocket experiment was proposed. The experiment was the first in situ experiment in the ionosphere on microwave energy transmission for the study of the SPS. It was named "MINIX" (Microwave Ionosphere Nonlinear Interaction eXperiment) and was carried out in August, 1983. A high power ($\sim$ 830 w) transmitter of 2.45 GHz radiated the microwave beam from the mother section of the rocket toward the separated daughter rocket (Figure 1.2).

The microwave pulsed with 5 seconds on and 5 seconds off. The nonlinear plasma response of the ionospheric plasma was measured by HF and VLF wave

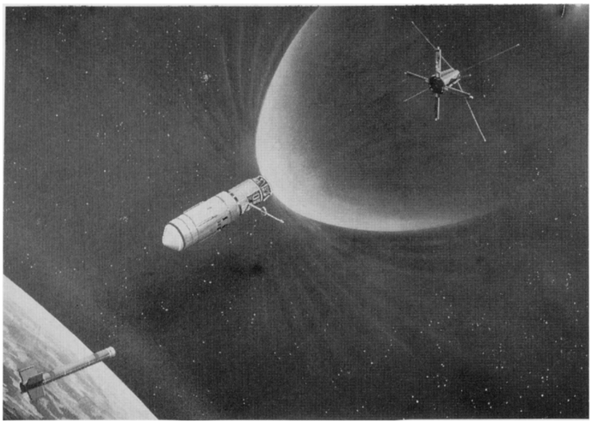

Figure 1.2: MINIX Rocket Experiment. A high power ($\sim$ 830 watt) microwave of 2.45 GHz was radiated toward the target daughter rocket. Plasma wave detectors were installed on the daughter section.

receivers and a Langmuir probe installed on the daughter section of the rocket (Figure 1.2).

The experimental results are summarized as follows;

1. Ion acoustic waves through the Brillouin scattering were not detected.
2. Langmuir waves and ECHW's were detected by the HF receiver installed on the daughter section. Figure 1.3 shows the frequency spectrum of the electric field component of the waves receive by the HF receiver in the ionosphere. The upper line shows the spectrum of the waves when the microwave is transmitted to the ionospheric plasma and the lower curve shows that for the period of the pause of the microwave. The shaded area between the upper and lower lines are the components enhanced by the plasma nonlinear processes caused by the microwave. The peak near 1.5 MHz is located between the local electron cyclotron frequency $f_{He}(F_H)$ and its second harmonics $2f_{He}(2F_H)$. The waves around the peak extending up to 4MHz are ECHW's excited by the microwave energy beam. The waves above 5MHz have frequencies near the local electron plasma frequency and the Langmuir waves.
3. The amplitude of the detected ECHW's is higher than that of the Langmuir waves. This is not consistent with the theoretical prediction described in §1.3.2.
4. The frequency spectra were not the "line spectrum" but were broad as

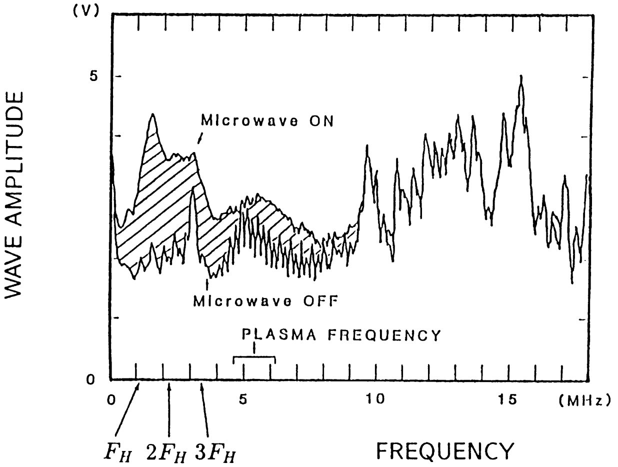

Figure 1.3: Frequency spectra of the waves in the HF range observed by the MINIX rocket experiment. The upper and lower lines are spectra when the microwave was on and off, respectively.

seen in Figure 1.3. This contradicts the prediction of the simple theory of nonlinear three-wave interaction.

1.3.4 Computer Experiment

In order to interpret the MINIX result, which contradicts the nonlinear three-wave coupling theory, we carried out several computer experiments with the hope of obtaining some clue which would then guide us in further theoretical consideration. The code used for the computer experiment was KEMPO [13] (Kyoto university Electro Magnetic Particle cOde). One-dimensional version of the KEMPO (KEMPO-1: with periodic boundary) is described in detail in Chapter 2. The used version of KEMPO is of one- and two-dimension. The boundary conditions are changed depending on the model we used. We used both the periodic and open boundary conditions. In the latter case, we added damping regions at both ends of the simulation area. In the damping regions all waves are artificially attenuated to avoid reflection from the end points of the whole simulation area.

The first attempt naturally started with the simplest type of computer experiment model. Two cases were dealt with. In the first case, all the pump EM wave, backscattered idler EM wave and excited electrostatic waves are assumed to propagate along the external magnetic field B_0. In the second case, they are assumed to propagate in a perpendicular direction to B_0. Hereafter we call the former case as "Parallel Case" and the latter case as "Perpendicular Case".

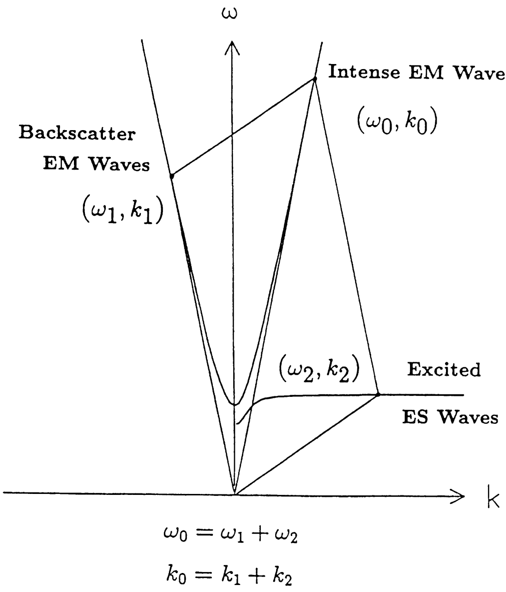

Figure 1.4: A schematic illustration of the relation between the pump, idler and excited waves in the $\omega - k$ diagram.

Figure 1.4 shows a schematic illustration of possible three wave nonlinear interaction between the pump (transmitted EM wave), the idler (backscattered EM wave) and the excited electrostatic waves. The simulation parameters are as follows;

electron plasma angular frequency	$\Pi_e = 2.0$
electron cyclotron angular frequency	$\Omega_e = 1.0$
external magnetic field strength	$B_o = 1.0$
charge to mass ratio of electrons	$q_e/m_e = -1.0$
total number of electrons	$N_p = 32768$
parallel thermal speed of electrons	$v_{th,\parallel} = 0.02$
perpendicular thermal speed of electrons	$v_{th,\perp} = 0.02$
speed of light	$c = 100$
time step	$\Delta t = 0.01$
grid spacing	$\Delta x = 1.0$
number of grids	$N_x = 256$

The frequency and amplitude of the pump EM wave were chosen to be $\omega_o \simeq 20$ and $B_w = 0.5$, respectively. The amplitude of the pump is higher than the real amplitude of the microwave used in the MINIX rocket experiment. This choice was made to make the nonlinear interaction take place much earlier than

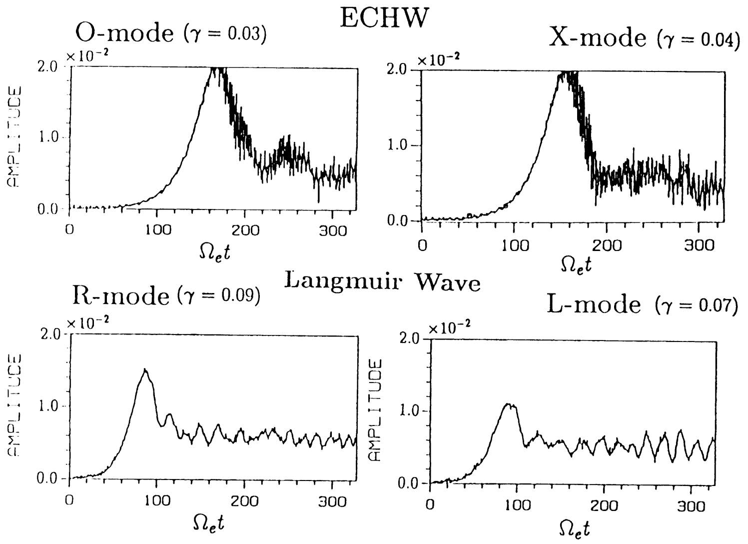

Figure 1.5: Time evolution of the excited electrostatic waves for Parallel and Perpendicular Cases. The lower and upper panels show the results for the Parallel and Perpendicular Case, respectively. Four figures correspond to cases with a pump EM wave in the R-,L-, O- and X-mode, respectively.

in the real case so that we can save CPU time for the computer experiments.

Figure 1.5 shows the results of the computer experiments. The lower and upper panels show the time evolution of the amplitude of the E_x component of the excited electrostatic waves for the Parallel Cases and Perpendicular Cases, respectively. In each case, two modes of the pump EM wave were attempted; R- and L-mode for the Parallel Case and O- and X-mode for the Perpendicular Case. The initial growth rate of the Langmuir waves for the Parallel Case and that of the electron cyclotron harmonic waves (ECHW) for the Perpendicular Case agree quite well with the value predicted by the nonlinear three wave interaction as described in the previous theory section. However, the saturation level of the ECHW (first peak in the upper panels) is higher than that of the Langmuir waves(LW) (first peak in the lower panels). This result is quite interesting in the sense that it agrees with the rocket experiment and not with the analytic theory of the nonlinear three wave interaction. The computer experiment actually reproduced the inconsistency between the rocket experiment and theory. Longer time evolution of the amplitude of the excited electrostatic waves are not similar at all with the theoretical prediction based on the Manley- Rowe relation as depicted in Figure 1.1. The interchange of energy is not repeatable and the energy and momentum transfer from the pump to the excited waves are irreversible. These two differences between the computer experiments and

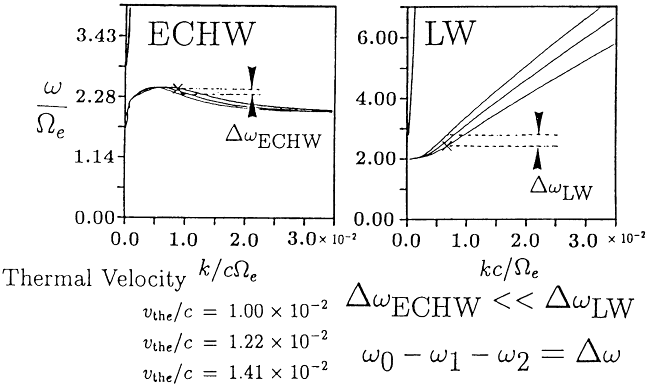

Figure 1.6: Comparison of the change of the dispersion relations of LW and ECHW due to the change of electron temperature. $\Delta\omega$ is a measure of the frequency mismatch in the three-wave interaction.

theory are the key to solve the discrepancy between the theory and the rocket experiment MINIX.

In order to get a clue to understand the physical mechanism of the nonlinear process, we made diagnostics of the electron velocity variation in the velocity phase space. It then turned out that the time of the saturation of the excited electrostatic waves takes place when the plasma electrons are heated by the excited electrostatic waves. The saturation takes place much before the saturation which is predicted by the theory of the three wave interaction. This means that the saturation is brought in via plasma heating. We then examined the change of the dispersion relation as a function of the plasma electron temperature. It was demonstrated that the dispersion relation of the Langmuir waves has higher susceptibility to the change of electron temperature, while the ECHW has less.

Figure 1.6 shows the change of the dispersion relation on the $\omega - k$ diagrams under the temperature change of electrons observed in the computer experiments. As indicated in the figure, the change of the dispersion relation from the original temperature gives the frequency mismaching as represented by $\Delta\omega$. The $\Delta\omega$ is much bigger for the LW case than the case of the ECHW. This can explain why the Langmuir waves reached saturation earlier in time and thereby saturate at a lower level than ECHW.

The reason for the broad band nature of the excited electrostatic waves has also been investigated by computer experiments. It turned out that the sequential three wave interaction can take place after the first saturation takes place, if the simulation can provide such a sufficiently large system length (in x-direction) that the resolution in k space can be fine enough for the subsequent sequential three-wave interaction. The sequential three wave interaction takes

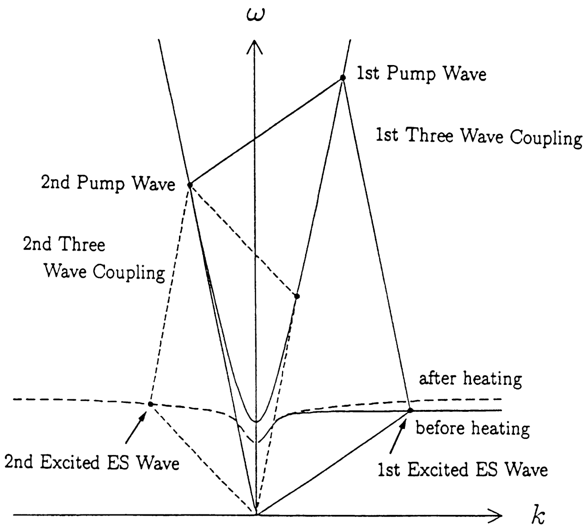

Figure 1.7: A schematic illustration of the sequential three wave interaction. First three wave interaction excites the first ES waves which heat up the plasma electron. Then a new set of the pump, idler and excited waves are selected automatically in the heated plasma.

place in such a way that the original pump wave or the idler wave in the previous three wave interaction plays the role of a new pump and finds out its partners of the new idler and excited waves in the heated plasma. The newly excited electrostatic waves have naturally a different frequency and wavenumber from the old ES waves. The relation of the frequency and wavenumber between the old set and new set of the pump, idler and excited waves are schematically shown in Figure 1.7.

This sequential three wave interaction can explain the result of the MINIX rocket experiment where the frequency spectrum of the excited ES waves is not of the line spectrum nature but of the wide band structure.

As demonstrated above, the computer experiments have provided the key to solve the discrepancy between the simple theory of nonlinear three wave interaction and the space active experiment MINIX. Of course, much more detailed analyses have been made for the series of computer experiments but are not shown here.

Figure 1.8 is illustrated to demonstrate that the two-dimensional computer experiment with open boundaries can reproduce more realistically the nature of the nonlinear effects caused by the intense microwave in the ionosphere like in the MINIX experiment. An array of the high frequency current sources is placed on the left edge of the physical region in order to radiate a monochromatic

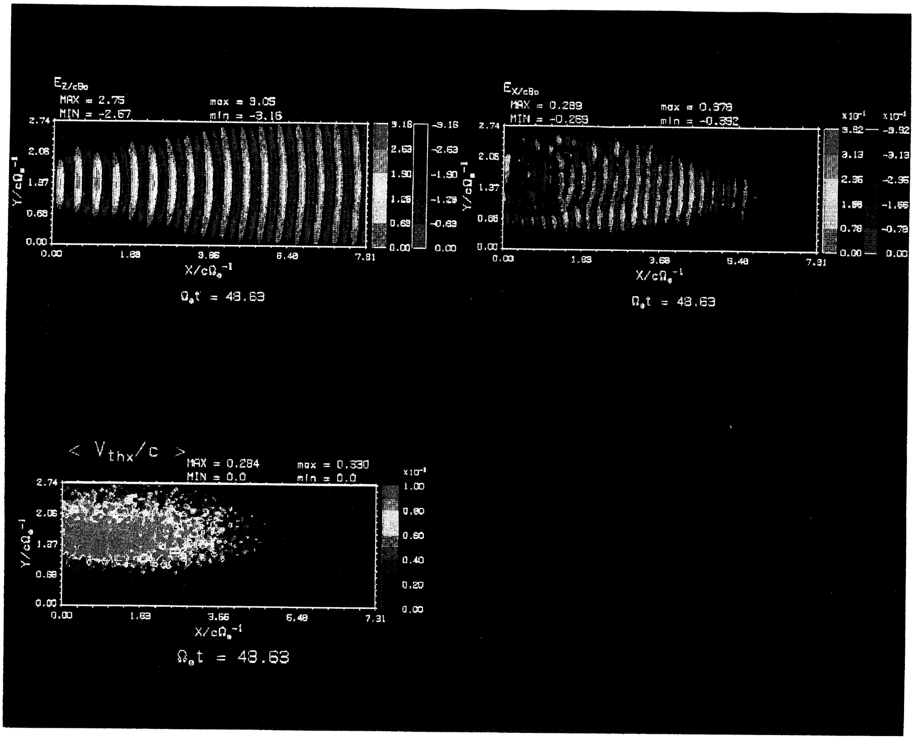

Figure 1.8: A set of the result of two-dimensional computer experiment by KEMPO on the nonlinear effects caused by the injected intense EM wave. The upper left panel shows the intensity contour of the electric field of the pump EM wave injected by an array of current source placed on the left boundary. The upper right panel shows the intensity of the excited ES waves. It is interesting to note that the plasma electrons are heated in a region where the ES waves are intense.

electromagnetic wave into the physical system. The array of the high frequency current plays a role of the array antenna and inject the desired monochromatic EM wave into the plasma. The left upper panel in Figure 1.8 is a contour map of the intensity of the injected pump EM wave in the x-y plane. The upper right panel shows the intensity contour map of the excited E_x waves and the lower left panel indicate the temperature of electrons which have been heated by the ES waves.

1.4 Conclusion

In this chapter, I have attempted to show one example of the active participation of computer experiment to the actual data analysis of a real space active experiment, with the aim of complementing the weakness of theory. The example shown here has been successful and has contributed even to the new design of the next stage of the new rocket experiment after MINIX. In February of 1993, before this report has been published, another rocket experiment on the Microwave Energy Transmission in Space (METS) will have been conducted. I hope this short invitation to the world of computer experiments of space plasmas will stimulate some of the readers and interest them enough to make their own contribution to space plasma simulation.

Acknowledgments

Examples shown in this chapter are the results of the collaborative research with my students, H. Hirata, T. Hashino and H. Yashiro. The KEMPO code has been developed at RASC, Kyoto University to which Y. Omura and many other staff and students had contributed. I would like to express my thanks to their contribution and efforts. The MINIX rocket experiment was carried out by the ISAS rocket. I would like to thank to Dr. N. Kaya and Mr. Miyatake for their collaboration with me on this project. Finally I thank Dr. S. Goodman for his careful proof-reading of the manuscript and his suggestions for better English expression.

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