Numerical Simulation of Ion Waves in Dusty Plasmas

Gyoo-Soo Chae

Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy
in
Electrical Engineering

Wayne A. Scales, Chair
Chris Beattie
Ioanis M. Besieris
Gary S. Brown
Ting-Chung Poon

September, 2000
Blacksburg, Virginia

Keywords: Dusty Plasmas, Particle-In-Cell Code, Numerical Simulation
Copyright 2000, Gyoo-Soo Chae
Numerical Simulation of Ion Waves in Dusty Plasmas

Gyoo-Soo Chae

(ABSTRACT)

There has been a great deal of interest in investigating numerous unique types of electrostatic and electromagnetic waves and instabilities in dusty plasmas. Dusty plasmas are characterized by the presence of micrometer or submicrometer size dust grains immersed in a partially or fully ionized plasma. In this study, a two-dimensional numerical model is presented to study waves and instabilities in dusty plasmas. Fundamental differences exist between dusty plasmas and electron-ion plasmas because of dust charging processes. Therefore, a primary goal of this study is to consider the unique effects of dust charging on collective effects in dusty plasmas. The background plasma electrons and ions here are treated as two interpenetrating fluids whose densities vary by dust charging. The dust is treated with a Particle-In-Cell PIC model in which the dust charge varies with time according to the standard dust charging model. Fourier spectral methods with a predictor-corrector time advance are used to temporally evolve the background plasma electron and ion equations. The dust charge fluctuation mode and the damping of lower hybrid oscillations due to dust charging, as well as plasma instabilities associated with dust expansion into a magnetized background plasma are investigated using our numerical model. Also, an ion acoustic streaming instability in unmagnetized dusty plasmas due to dust charging is investigated. The numerical simulation results show good agreement with theoretical predictions and provide further insight into dust charging effects on wave modes and instabilities in dusty plasmas.
Acknowledgments

I would first like to express my sincere gratitude to my advisor, Dr. Wayne Scales for his valuable advice, guidance and encouragement during the course of this work. I sincerely appreciate for his enthusiasm and patience in helping me learn the basic plasma physics and in solving the many problems I encountered during this research work.

I would like also to acknowledge Dr. I. Besieris, Dr. G. Brown, Dr. T. C. Poon and C. Beattie for serving in my advisory committee. I would like to acknowledge Dr. Ganguli for his useful suggestions and comments during this research work.

I would like to thank my family. Thanks to my parents who have always encouraged and supported me. I know they take as much pride in this accomplishments as I do. And special thanks to my wife and son, Hee-Jung and Daniel, for their continuing love and patience during my study.

This work was supported by the U.S. National Science Foundation NSF and Department of Energy DOE under grant DE-FG02-97ER54442 and the U.S. Office of Naval Research ONR.
Contents

Abstract .................................................................ii
Acknowledgement .........................................................iii
Contents .......................................................................iv
List of figures ..........................................................vi

Chapter 1: Introduction ................................................1

Chapter 2: Basic dusty plasma principles

2.1. Debye shielding .........................................................6
2.2. Intergrain spacing ......................................................7
2.3. Coulomb coupling parameter ........................................7
2.4. Dust charging ..........................................................8

Chapter 3: Numerical methods

3.1. Theoretical model .......................................................10
3.2. Spectral methods .......................................................15
    3.2.1. Spectral methods using Fourier series .........................16
    3.2.2. Differentiation ......................................................19
    3.2.3. Convolution .........................................................21
    3.2.4. The Gibbs phenomenon ..........................................25
3.3. Theoretical model in spectral domain ..........................25
3.4. Time integration methods ............................................30
    3.5.1. Predictor step ......................................................32
    3.5.2. Corrector step ......................................................35
3.6. Simulation initialization .............................................37
    3.6.1. Normalized dust charging equation ..........................37
    3.6.2. Charge equilibrium and neutrality .............................38
    3.6.3. Calculation of production rate $q_s$ ..........................40
Chapter 4: Numerical results in magnetized plasmas

4.1. Dust charge fluctuation mode .............................................. 41
  4.1.1. Theory ................................................................ 41
  4.1.2. Results .......................................................... 42
4.2. Damping of lower hybrid oscillations ....................................... 43
  4.2.1. Theory .......................................................... 43
  4.2.2. Results ................................................................ 49
4.3. Plasma instability associated with streaming dust ...................... 50
  4.3.1. Theory .......................................................... 50
  4.3.2. Results .......................................................... 54
4.4. Plasma instability associated with expanding dust clouds ........... 56
  4.4.1. Theory .......................................................... 56
  4.4.2. Results .......................................................... 61

Chapter 5: Numerical simulation in unmagnetized plasmas

3.1. Theory ................................................................ 74
  3.2. Results .......................................................... 76

Chapter 6: Summary and conclusions ............................................. 87

References ............................................................................. 89

Vita ....................................................................................... 93
List of figures

Figure 1.1 : A space shuttle orbiting in the ionosphere [Courtesy of NASA]. .3

Figure 1.2 : A schematic diagram of the exhaust plume [Bernhardt et al., 1995]. 3

Figure 1.3 : Noctilucent clouds [Photographed by P. A. Dalin, Space Research Inst., Russia, 1999]. ...........................................4

Figure 1.4 : The Alwin 50MHz radar backscatter in dB and the dust charge density inside a noctilucent cloud [Havnes et al., 2000]. ..........4

Figure 1.5 : Meteor shower [Photographed by Juraj Toth, Modora Observatory, 1998]. ..........................................................5

Figure 2.1 : Charging on a dust particle. ................................. 9

Figure 4.1 : a. Dust charge fluctuation temporal decay for a specific dust particle. b. Spatial dust charge fluctuation decay for ̃η=0.05. ......44

Figure 4.2 : Current temporal decay for a specific dust particle for ̃η=0.05, ̃η=0.25, and ̃η=0.50. .........................................................45

Figure 4.3 : Spatial current temporal decay and density for ̃η=0.05. ....46

Figure 4.4 : Lower hybrid oscillation damping rate ̃ν = ν/ω_{lh}. ..........51

Figure 4.5 : Temporal damping of lower hybrid oscillation potential and ion density and growth of dust charge fluctuations. ̃η = 1.0. ..........52

Figure 4.6 : Plot showing temporal phase lag of dust charge relative to ion density for lower hybrid oscillations with ̃η = 1.0 and ̃β = 0.003. .53

Figure 4.7 : LHS instability dispersion relation and growth rate. ...........57
Figure 4.8: Time history of electric field energy and average floating potential for the LHS instability. ............................................................ 58

Figure 4.9: Electron, ion, and dust densities and dust charge for the LHS instability. ................................................................. 59

Figure 4.10: Numerical simulation results showing the development of the LHS instability. Note charge phase space as well as velocity phase space modification produced by the nonlinear evolution of the instability. 60

Figure 4.11: EIH instability dispersion relation and growth rate vs wavenumber. 64

Figure 4.12: EIH instability growth rate vs frequency. ....................... 65

Figure 4.13: EIH instability growth rate vs $\bar{\beta}$ for $\bar{\eta} = 0.01, 0.1, \text{ and } 1.0$. ....66

Figure 4.14: Electron and ion densities and dust charge at $\bar{\beta} = 0.15$ for EIH instability. ................................................................. 67

Figure 4.15: Electron and ion densities and dust charge at $\bar{\beta} = 0.7$ for EIH instability. ................................................................. 68

Figure 4.16: Electron flow velocities at $\bar{\beta} = 0.15$ and $\bar{\beta} = 0.7$ for EIH instability. 69

Figure 4.17: Time evolution of EIH instability electrostatic field energy at $\bar{\beta} = 0.15$. ................................................................. 70

Figure 4.18: Time evolution of EIH instability electrostatic field energy at $\bar{\beta} = 0.7$. ................................................................. 71

Figure 4.19: EIH instability 2-D plasma density and dust charge for $\omega_{lh}t = 12.6$ at $\bar{\beta} = 0.15$. ................................................................. 72

Figure 4.20: EIH instability 2-D plasma density and dust charge for $\omega_{lh}t = 12.6$ at $\bar{\beta} = 0.7$. ................................................................. 72
**Figure 5.1:** Damping rate $\omega_i$ vs $\tilde{\beta}$ for $\tilde{\eta}=0.001$, $\tilde{\eta}=0.05$, and $\tilde{\eta}=0.1$ for ion acoustic waves. .........................................................78

**Figure 5.2:** Dispersion relation and growth rate for the ion acoustic streaming instability due to dust charge fluctuations. .........................79

**Figure 5.3:** Growth rate $\omega_i$ vs $\tilde{\beta}$ at $\tilde{\eta}=0.001$, $\tilde{\eta}=0.05$, and $\tilde{\eta}=0.1$ for the ion acoustic streaming instability. .........................80

**Figure 5.4:** Growth rate $\omega_i$ from equation (5.1) for ion acoustic waves showing growth for $\tilde{v}_d = v_d/C_s > 1$ and damping for $\tilde{v}_d = v_d/C_s < 1$. . .81

**Figure 5.5:** Temporal damping of ion acoustic oscillation potential, ion density, and dust charge fluctuations. $\tilde{\eta} = 1.0$. .........................82

**Figure 5.6:** Ion and electron densities and dust charge with $\tilde{\beta} = 0.01$ for ion acoustic streaming instability for $\tilde{v}_d = 1.5$ at $\omega_{pi}t = 0$ and $\omega_{pi}t = 60$. 83

**Figure 5.7:** Numerical simulation of the ion acoustic streaming instability due to dust charge fluctuations. For $\tilde{v}_d = 0.5$ ion acoustic waves are damped. The instability produces growth in ion acoustic waves for $\tilde{v}_d = 1.5$. .........................................................84

**Figure 5.8:** Numerical simulation of the ion acoustic streaming instability due to dust charge fluctuations. Note damping and growth of dust charge fluctuations for $\tilde{v}_d = 0.5$ and $\tilde{v}_d = 1.5$, respectively. ......85

**Figure 5.9:** Ion density power spectrum of the ion acoustic streaming instability. The waves of frequency $\omega/\omega_{pi} = 0.2$ damp for $\tilde{v}_d = 0.5$ and grow for $\tilde{v}_d = 1.5$. .........................................................86