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Dusty Plasmas

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The objective of this project has been to develop a fundamental understanding of dusty plasmas at the Laboratory. While dusty plasmas are found in space in galactic clouds, planetary rings, and cometary tails, and as contaminants in plasma enhanced fabrication of microelectronics, many of their properties are only partially understood. Our work has involved both theoretical analysis and self-consistent plasma simulations to understand basic properties of dusty plasmas related to equilibrium, stability, and transport. Such an understanding can improve the control and elimination of plasma dust in industrial applications and may be important in the study of planetary rings and comet dust tails. We have applied our techniques to the study of charging, dynamics, and coagulation of contaminants in plasma processing reactors for industrial etching and deposition processes and to instabilities in planetary rings and other space plasma environments. The work performed in this project has application to plasma kinetics, transport, and other classical elementary processes in plasmas as well as to plasma waves, oscillations, and instabilities.

1. Background and Research Objectives

Plasmas often contain dust particles (solid objects less than micron-size in the laboratory, less than centimeter-size in space), which can acquire a net charge and hence form with the background a "dusty plasma." Dusty plasmas played a major role in the formation of the solar system, as dust in the solar nebula coagulated into the planets. Dusty plasmas persist in space as planetary rings (e.g., around Saturn) and in cometary dust tails. Dust also occurs in laboratory plasmas, as contaminants in radiofrequency (rf) and glow discharges. Such discharges are used for plasma processing in the fabrication of microelectronics. Through the

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use of laser light-scattering techniques, the dust can be seen to hover above the electrodes and near the walls of the discharge [1]. The dust particles are a serious problem for industrial applications, because they can affect the properties of the deposition films and can degrade the quality and reproducibility of the fabrication process.

Understanding of dusty plasmas is at a fairly elementary level compared, for example, to plasmas studied for magnetic and inertial confinement fusion applications. Much effort has gone into determining the charge on an isolated dust grain and the electrostatic potential distribution for an ensemble of dust grains embedded in a plasma (see [2] for a review and references). Even so, the models remain very simplified and usually assume spherical dust grains of uniform size and charge-to-mass ratio. In practice, the dust grains have a wide range of sizes, shapes, and charge-to-mass ratios and are subject to both electromagnetic as well as gravitational forces (and in the case of cometary dust, to solar radiation pressure). The problem is also complicated by the fact that when the interparticle spacing becomes small, collective effects can also occur [3], and even lattice-like structures may form [4]. Work has been done on calculating the forces on dust particles and determining their orbits and transport in planetary rings [5], but truly self-consistent calculations are limited. Study of the motion of charged dust particles in discharge plasmas has been conducted [6], but how the dust is transported through the discharge, collects in various places, and coagulates are presently still under investigation.

Thus, dusty plasmas are a relatively new and little studied regime of plasma physics. It is an exciting area with many potential applications in both space and the laboratory, where the Los Alamos expertise in plasma modeling can make major contributions. The purpose of this project has been to build up a Laboratory capability in theoretical and numerical modeling of dusty plasmas and to apply this capability to fundamental problems associated with dusty plasmas in both astrophysical and industrial environments. This report summarizes the work that has been accomplished during the three years of this project.

2. Importance to LANL's Science and Technology Base and National R & D Needs

As discussed above, dusty plasmas occur naturally in space and are unwantingly produced in industrial plasma applications. As these plasmas are not completely understood, this project has served to develop Laboratory expertise in this area. Our work has been directed toward improving basic understanding of these plasmas and building appropriate numerical and theoretical tools to study them in a self consistent manner. One of our eventual goals is to devise general computational techniques that can be used for space/astrophysical studies, commercial applications for plasma processing, and possible use in plasma assisted cleanup of contaminated surfaces. One particularly important application is for commercial plasma processing reactors, where the reduction of contaminants is a relatively unsolved problem. We have developed collaborations between several groups in the Laboratory and with industry (IBM) to develop methods to model plasma processing reactor physics that include contaminant dynamics and to explore ways to reduce contaminant buildup. We have used these collaborations to seek outside support from both ARPA and Sematech to construct computational models to be used as analysis and design tools for specific manufacturing processes.

3. Scientific Approach and Results

During the three years of this project, we have worked on a number of different problems related to dusty plasmas. These problem areas are: (1) forces on dust in a plasma, (2) charging of dust grains, (3) coagulation of grains, and (4) instabilities involving dusty plasmas. In addition, a review article discussing the status of numerical simulation of dusty plasmas has been completed. This work is summarized below; details can be found in the appropriate published references.

3.1. Forces on dust grains in a plasma

Dust particles occur in rf discharges used for plasma processing applications. Laser scattering techniques show very dramatically that the dust tends to collect in certain regions of the discharge **[1]**; the location of these particle traps is rather sensitive to the design of the electrodes. Because dust in a plasma becomes charged, the dust particles in such devices are subject to a number of forces **[6]**, including the electric force due to the rf-powered electrodes modified by the presence of the plasma in the discharge, the ion drag force due to the Coulomb attraction between the negatively charged dust ions and the positive ions of the discharge that are collected by the electrodes, the neutral drag force due to the fact that the plasma is only weakly ionized and gas is pumped in and out continuously, and gravity. The balance of the various forces causes the particles to migrate to and reside in specific regions of the discharge.

Similar types of force balance occur in astrophysical environments, where the electromagnetic and gravitational forces are supplemented by other processes, such as radiation pressure **[5]**. We have studied the various forces that occur in a simple rf discharge to indicate the nature of the force balance that is set up, and how sensitive this balance is to the various expressions that are used to characterize each component of the force **[7]**. We have shown that the major contributors to the force are the electrical force and the ion drag force. The electric force pushes the negatively charged dust away from the electrodes, while the ion drag force draws the dust ions toward the electrodes. The net effect is a shallow potential well at the outer edge of the sheath that extends out from the electrodes. Test particle simulations show that particles migrate into these potential wells and become trapped. The minimum of this potential well is sensitive to the size of the dust grains, such that larger particles tend to reside closer to the electrodes, as measurements indicate **[8]**.

3.2 Charging of dust grains in a plasma

The above work related to forces experienced by dust particles in rf discharges neglects several important effects that are relevant to the development of an accurate model of contaminant dynamics. First, it is assumed that the particles are instantaneously charged. In practice, grain charging occurs over a finite interval of time. We have shown analytically that the charging time depends inversely on the plasma density and the radius of the grain (which is assumed to be spherical) **[9]**. This means that small grains located in the low-density sheath region of the discharge charge up much slower, and the charging can be affected by the rf period of the discharge. Test particle simulations demonstrate that large dust grains introduced into the plasma in the sheath tend to remain there, while small particles can escape from the potential well at the edge of the sheath before they become fully charged. Moreover, the analysis has been extended to nonspherical particles. Elongated particles tend to charge up more slowly, to a larger net charge. They also have a larger polarization associated with them, which can affect how they grow and move through the discharge.

3.3. Coagulation of dust grains

A third important aspect of dust grains in a plasma is how they grow in time. While laser light-scattering techniques have shown the presence of dust ions larger than about 200 nm in plasma processing reactors, electron microscopy techniques are used to measure particles of smaller size, which fall out onto collector plates when the discharge is turned off. These measurements show that the larger particles seem to consist of agglomerates of smaller (1-10 nm) particles, which grow in time **[10]**. We have modeled this growth process with a simple coagulation model **[11]**.

The basic premise of the model is that there exists two populations of contaminant particles: one population is composed of very small particles continuously produced via various reactor processes (involving the wafers that are being processed or the walls of the device), and a second population whose size, but not density, grows at the expense of the first population. The smaller particles, which we refer to as "protoparticles," are supplied at a constant rate, which we infer from published data. As these protoparticles grow in size, they become charged, and when charged, they are unable to overcome the Coulomb barrier and coalesce with similar particles. Thus after charging occurs, continued growth of these particles is possible only by the slower adsorption of smaller, neutral (or weakly charged) protoparticles. Concurrent with the creation of the protoparticles is their depletion by adsorption onto the larger particles. This competition between creation and depletion produces the time evolution of the protoparticle density and the predator particle mass density.

Figure 1 shows an example of the results of the model for the experimental conditions of Boufendi et al. **[10]**. Plotted is the radius of the predator particles R as a function of time; the closed circles are the experimentally measured sizes. The model reproduces the observed rapid growth at early time, as well as the slower growth at later time. It can also account for the various limiting sizes of the protoparticle population that can also be inferred in different experiments, as well as the limited range of sizes at any one time of the predator particle population.

3.4. Dust/ion acoustic instability in dusty plasmas

The presence of dust in a plasma leads to new sources of free energy that can drive plasma instabilities. Generally, instabilities involving the relatively massive dust grains occur at very low frequencies and are most likely to be excited in astrophysical systems that remain in relative equilibrium states for long periods of time. We have investigated one such instability that can occur in the rings of Saturn **[12]**. In the inner magnetosphere of Saturn the plasma rotates with the planet, while the dust grain orbital motion is determined by gravity. This leads to a relative drift between the dust grains and the plasma; the relative drift can exceed the ion thermal velocity and excite an ion acoustic instability.

We have modeled the development and evolution of the instability with a particle-in-cell code, in which both the dust and plasma ions are treated as particles and the electrons are assumed to have a Boltzmann distribution [13]. The growth rate of the instability is roughly the dust plasma frequency and the wavelength is the Debye length. Figure 2 shows an example of the development of the instability. The top panel is a plot of the electrostatic field fluctuations as a function of time. The time is expressed in the figure in terms of the ion plasma frequency; for parameters relevant to Saturn, the time interval shown is about 500 seconds. The rapid growth of the instability to a relatively low amplitude (fluctuating potential energy comparable to the ion temperature) is displayed. The other panels show the plasma (middle panel) and dust (bottom panel) ions in v_X-x phase space about the time that the instability saturates.

The plasma ions with small positive velocities are affected most, as some of these ions become trapped by the growing waves, which eventually causes the wave growth to saturate. The dust ions, on the other hand, are merely modulated by the waves on this time scale, although when averaged over space, the effect appears as strong heating of the dust. The fact that the relative dust/plasma-ion drift speed increases with distance from the planet suggests that stronger plasma heating should occur at larger radius, which is consistent with measurements made by the Voyager spacecraft [14]. The presence of the instability also helps explain the relatively isotropic velocity distribution of the plasma ions which, in the absence of some sort of scattering process, should be more ring-like in nature.

3.5. Review article on the numerical simulation of dusty plasmas

In March 1995, the 6th biennial workshop on dusty plasmas was held in San Diego, at which we gave a review talk on the use of numerical simulation methods to model dusty plasma behavior; the talk has been written up for the proceedings of this meeting [15]. The paper summarizes work that has been done in three areas of dusty plasma research. The first area involves grain charging. A number of recent particle simulations have investigated, on a very fundamental level, how the grain charging process operates. A second area concerns situations where dust grains interact with the plasma in which they are embedded in a very weak manner so that they can be treated as test particles. Examples include dust in planetary magnetospheres and plasma reactors. The third area involves cases where the dust interacts with the plasma in a stronger manner such that the simulation must include both dust and plasma dynamics. For example, plasma instabilities involving dust and crystalline structures formed in dusty plasmas fall into this category. For each area, a summary of recent work is given, and unresolved physics and numerical issues are discussed. This review should serve as a useful guide to those presently engaged in, or are planning to do, simulations of dusty plasmas in the next few years.

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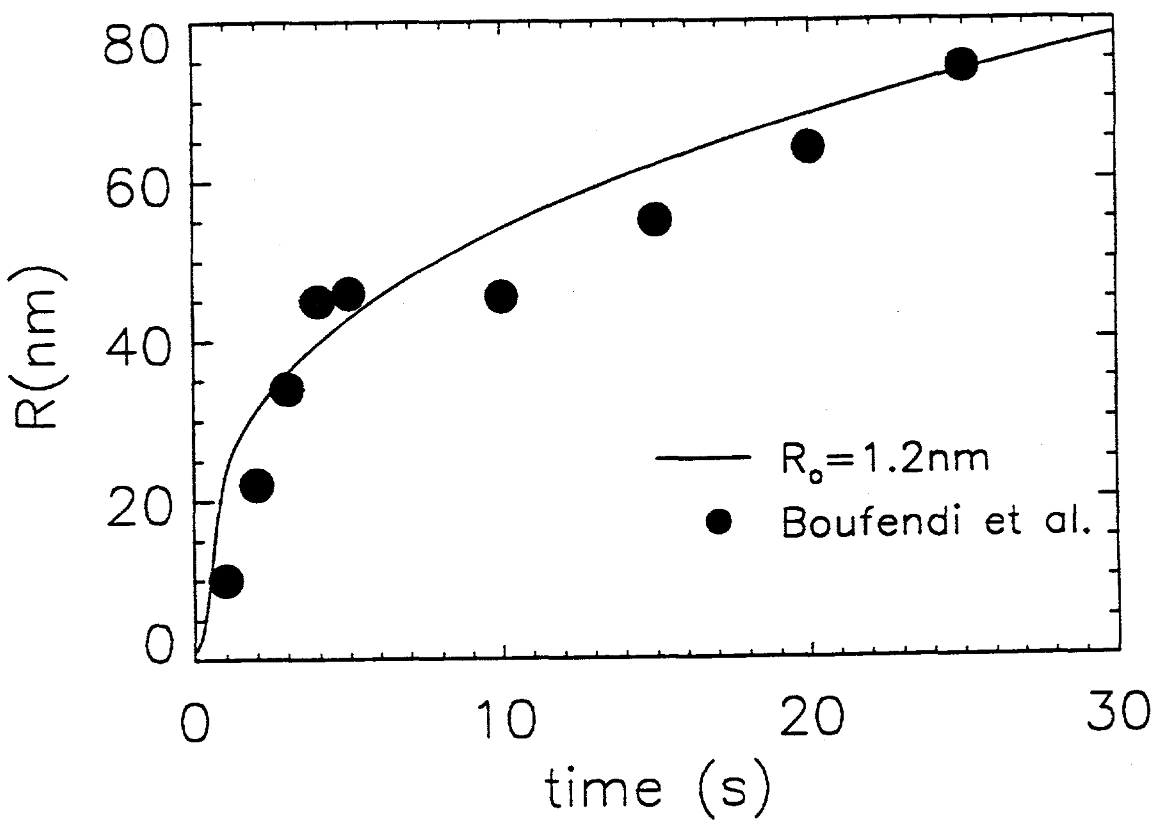

Fig. 1. Results of calculations of dust grain coagulation model [11], showing particle radius R versus time; solid circles are the experimental data from [10].

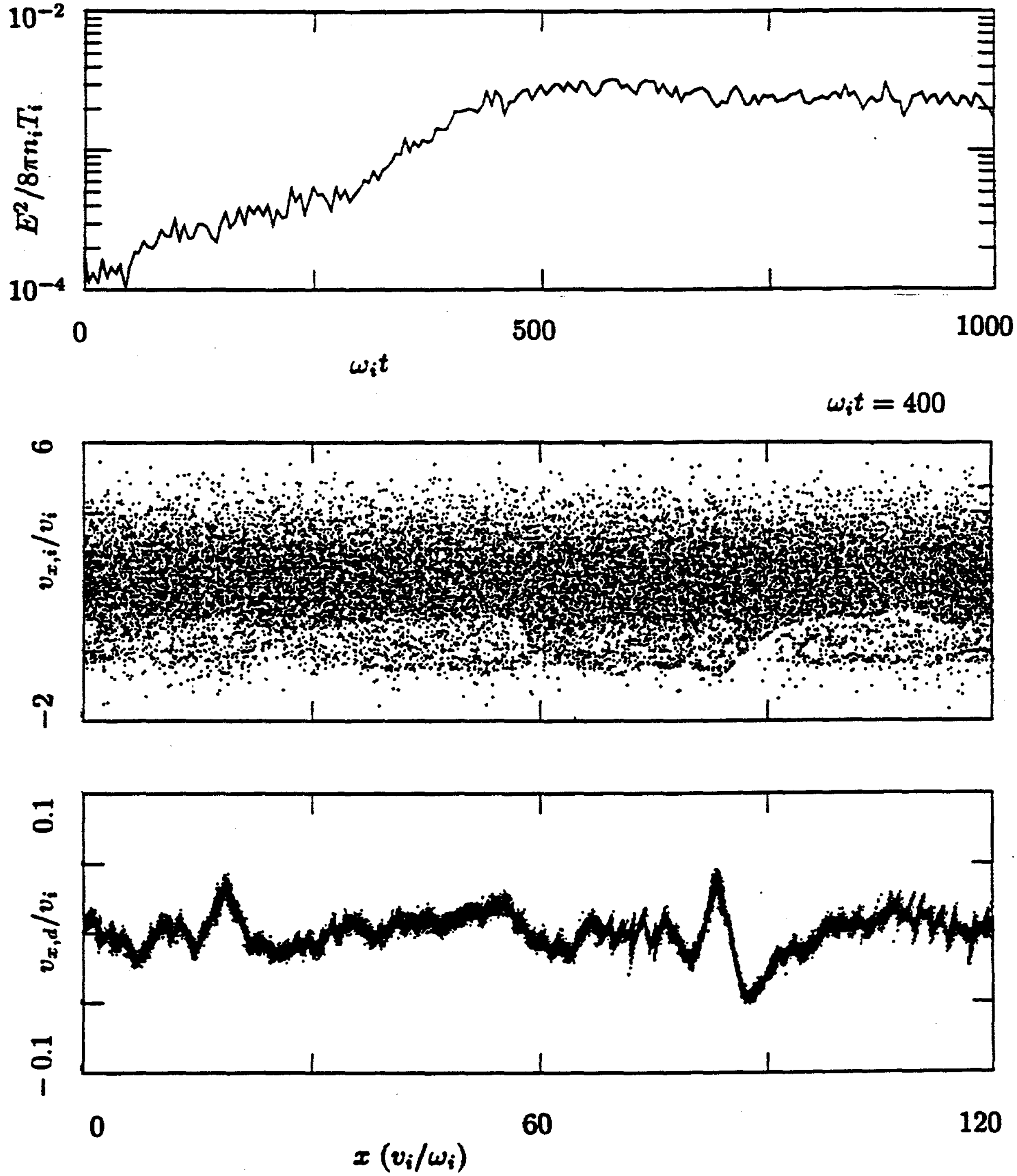

Fig. 2. Results of particle simulations [13] of a dust/ion acoustic instability showing: (top) time history of electric field fluctuations and phase space plots of plasma ions (middle panel), some of which are trapped by the waves, and dust ions (bottom panel), which are mostly just modulated by the waves.