

Interactions of Dust Bilayers in a GEC Plasma Environment

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Abstract— To further understand the ion wake field effect in dusty plasmas, the dependence of interlayer spacing and interactions upon system power and pressure of like-charged dust bilayer crystals was studied experimentally in a Gaseous Electronics Conference rf reference cell. These interlayer distances were analyzed in light of values predicted for the distance from the top layer of dust particles to the first potential maximum in the ion wake field generated by this layer. It was found that the vertical component of the wake field effect is relatively weak, and indeed was dominated by other forces in this experimental setup.

Index Terms— Complex plasmas; Dusty plasmas; Monomer bilayers

I. INTRODUCTION

DUST in plasmas can be observed in various physical systems, and research of dusty plasmas has applications both in astrophysical studies and in industry. Indeed, dusty plasmas can be found in many celestial objects such as comet tails, nebulae, and Saturn's rings [1, 2, 3], and the coagulation of dust in plasma environments is the birth of planetary and stellar objects [4]. On Earth, dust is often considered a contaminant in plasmas. While this contamination is benign in neon lights and plasma televisions, dust contamination leads to problems such as electrical shorts in the creation of integrated circuits [1, 3, 5].

The study of bilayers of discrete charges also has many disparate, but related applications, such as the modeling of thin films, various crystals, ion traps and semiconductors [6, 7, 8, 9]. The study of charged dust bilayers in plasma is therefore doubly important to the integrated circuit industry, among others. A better understanding of plasma characteristics and dynamics may lead to more advanced techniques of contaminant removal, and a better understanding of charge bilayers may lead to more sophisticated semiconductor products.

Dust and other objects in plasma become charged because of one of the defining characteristic of plasma: negative electrons and positive ions are free to move dynamically within the system. These electrons move a great deal faster

than the ions and therefore collide with objects in the plasma more frequently, giving these objects a negative charge. Charged macroscopic objects in plasma significantly redistribute charges in the immediately surrounding region. This region of redistributed charges is known as the plasma sheath [10]. In the case of dust in the sheath above the lower electrode in a GEC reference cell, negatively-charged dust is repulsed upwards by the electrode, which is also negatively charged, on average. The dust thus floats at an equilibrium height: where the Coulomb force and the gravitational force are balanced.

In plasma environments that involve streaming positively-charged ions, negatively-charged dust particles attract the streaming ions, bending their trajectories and causing these ions to converge in a region below the dust particle, as depicted in Figure 1. This region of convergence has a higher

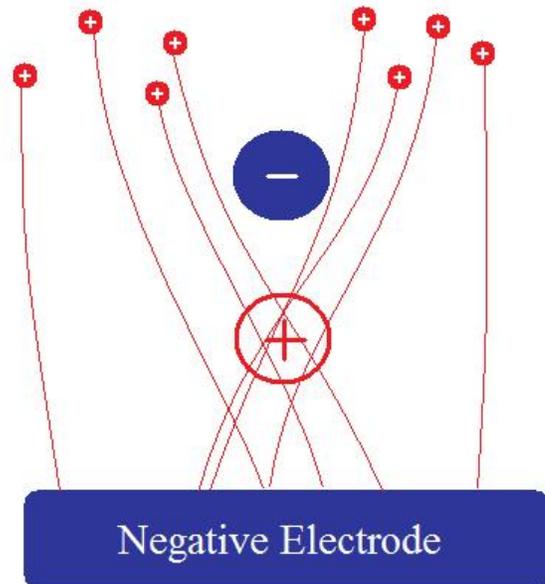


Figure 1: Negative dust bends the trajectories of streaming positive ions, creating regions of positive charge.

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ion density than the surrounding area, and therefore has an effective positive charge. Other negatively-charged dust particles in the vicinity are attracted to this positive region [2]. Because of this occurrence, dust particles tend to form wake field pairs, or even wake field chains that have unusual characteristics. In particular, the wake field interaction of these chains is non-Newtonian in that the interactions are non-reciprocal: the ion wake of a particle can only affect those particles which are downstream. In some cases, wake field chains have been observed to propel themselves upstream against the ion flow due to the non-reciprocal nature of the wake field force [11].

Vertical effects of this ion wake field upon the spacing of two discrete layers in the plasma sheath in a GEC reference cell were studied experimentally and results were compared to predictions based on a numerical model.

II. EQUIPMENT AND METHODOLOGY

A. GEC Radio Frequency Reference Cell

The Gaseous Electronics Conference (GEC) radio frequency reference cell is a basic standard environment for the study of dusty plasma which allows for comparison of data between research groups. In a GEC cell, plasma is energized by the lower of two capacitively positioned electrodes in a vacuum cell with design considerations for plasma control and camera viewing, as depicted in Figure 2. This same lower electrode also provides the electric force to keep the dust afloat. The experimental data of this paper were collected out in a GEC cell which has been modified to allow for pictures to be taken from directly above the plasma [12, 13].

The lower electrode in the GEC cell has a shallow circular cutout in the center that creates a parabolic potential well. The parabolic nature of this potential well confines the particles horizontally, keeping them from “sliding” off the side of the electrode and being lost [13].

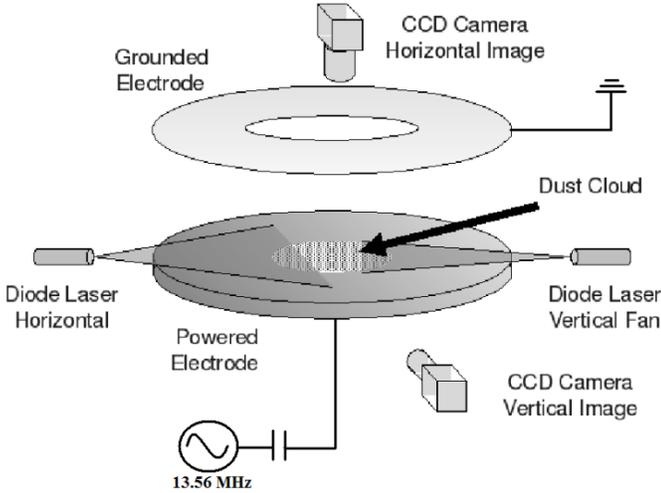


Figure 2: Gaseous Electronics Conference RF Reference Cell

The charge-coupled device (CCD) cameras take grayscale images at 60 frames per second. Only the side-mounted CCD camera was used in taking the data reported in this paper. The lower layer was illuminated by a 636 nm diode laser rated at 80 mW. Light from this laser passed through a vertically oriented cylindrical lens, which fanned the light out horizontally. The top layer was illuminated by a Coherent Verdi-V5 laser. This laser is a dual-frequency, ND: YAG laser with variable power. It was set to put out a beam of 532 nm light at a power of 1W, with an external ND filter that cut the effective power down to 100mW. This laser’s beam was also horizontally fanned.

CASPER’s GEC cell is connected to a cryo pump, which is used to pump to high vacuum conditions for cleaning and maintenance purposes, and a weaker physical pump that is used during experimentation. The physical pump is controlled by a butterfly valve that keeps the cell at constant pressure.

In addition to a radio-frequency signal generator, the bottom electrode in the cell is connected to a Kepco external DC power supply. This allows the experimenter to adjust the DC bias of the power supplied from the system to the lower electrode.

B. Bilayer Melamine Formaldehyde Dust

Melamine Formaldehyde is a polymer often used in dusty plasma research. 6.35- and 8.89 micron diameter dust particles of this material were used in this experiment.

When dust of multiple species is in a common system, the particles often organize themselves structurally by size, density, or other variable characteristics [1]. In the GEC reference cell with two sizes of non-conducting dust of uniform density, such a distribution occurs as a result of the two strongest forces acting upon the dust particles, the gravitational force and the Coulomb repulsive force between the dust and the lower electrode. The upward Coulomb force,

$$F_e = QE \quad [1]$$

depends on the electric field and the charge on the particle. The particle’s charge, in turn, depends on the particle’s surface area, as shown in Equation 2.

$$F_e \propto Q \propto R^2 \quad [2]$$

The downward gravitational force,

$$F_g = mg \quad [3]$$

depends on mass, which, because density is constant, depends on the particle’s volume, as shown in Equation 4.

$$F_g \propto m \propto R^3 \quad [4]$$

As one increases the radius of a sphere, its volume increases by R^3 while its surface area increases by R^2 . At equilibrium, when the gravitational force and Coulomb force are equal,

$$QE = mg \quad [5]$$

And the electric field in the GEC cell depends on distance from the lower electrode. Thus, as particle radius increases, the point of equilibrium between these two forces approaches

the lower electrode. And so, large particles float lower in the cell than smaller particles.

C. Experiment

For two different system pressures in the GEC cell, equilibrium heights for the two dust sizes were found over a range of voltages applied across the lower electrode. These data were recorded for each particle size individually, and again with both particle sizes simultaneously in the cell.

To minimize discrepancies between iterations of the experiment, the impedance between the power supply system and the GEC cell was consistently held to such a value as to allow 90% or greater of the power from the system to reach the cell, and a DC current was applied to hold the power supplied by the system to the lower electrode constant. For comparison, data was also collected without holding the DC bias constant, and no significant differences were observed.

Data regarding the vertical positions of each layer of dust were analyzed to better understand how these positions differed when each layer was in the cell individually versus when both layers were in the cell simultaneously. This information was then compared to distances from the top layer to first maximum of the ion wake field potential, as predicted by fluid model.

D. Model

The potential of the wake field from the top particle was modeled by

$$\Phi_w(z, r) = \frac{2(-Q/\lambda)}{(6\pi)^{1/2} \epsilon_0} \frac{J_1\left(\left[\frac{R^2}{M}\right]^{1/3}\right) \sin\left(\frac{z}{M} - \frac{\pi}{4}\right)}{(Mz)^{1/2} R} [2]$$

Where Φ is the normalized wake field potential, z is the vertical distance below the particle, r is the radial distance away from the particle, Q is the charge of the particle, λ is the electron Debye length, and M is the axial ion mach number of the plasma [14]. The appropriate values for M and λ were obtained from inputting experimental parameters into a fluid model [15]. As seen in Figure 3, this model for the

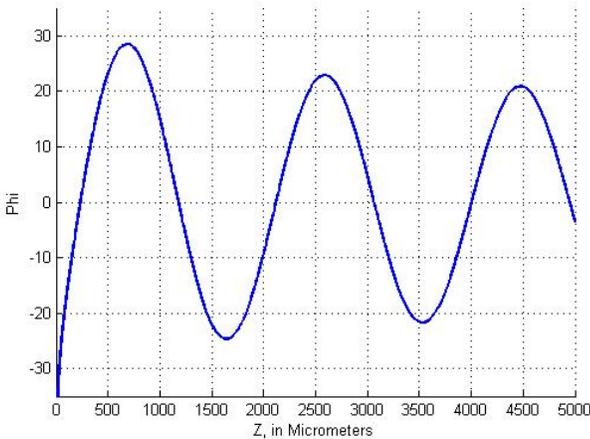


Figure 3: Normalized potential with respect to distance below a dust particle, in micrometers.

potential oscillates with z and falls off relatively slowly, in relation to the Debye length of the plasma. In the case of all recorded experimental data, the lower layer of particles was close enough to the upper layer to be in the regime of the first potential maximum, and therefore all other maxima were ignored. The region in the regime of this first potential maximum is in agreement with previous studies [2, 11, 14].

III. RESULTS

As shown in Figure 4, when the dust was run at 75 mTorr, the bilayer interactions caused the lower layer to shift upwards with respect to its position when in the cell without the upper layer. This is a shift away from the predicted locations of the first maximum of the wake field potential curve, which are shown on the same figure. The distances between the layers, regardless of whether these layers were run together or separately, were significantly less than the distance from the top layer to the predicted location of the first potential max, which is shown most clearly in Figure 5.

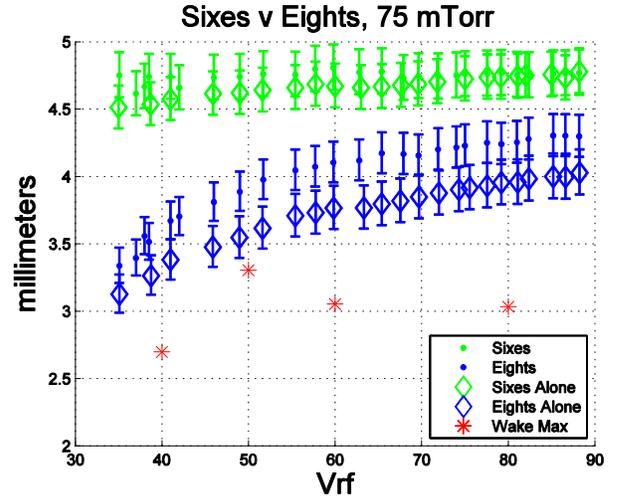


Figure 4: Experimental heights vs. predicted wake field maximum potential at 75 mTorr

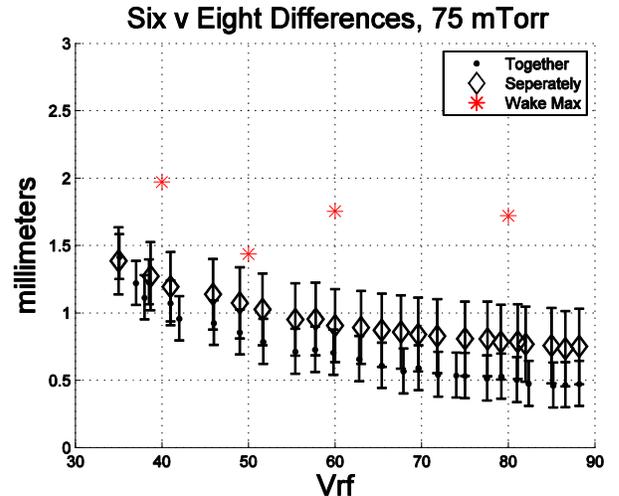


Figure 5: Height differences between layers vs. distance from top layer to predicted wake field maximum potential at 75 mTorr

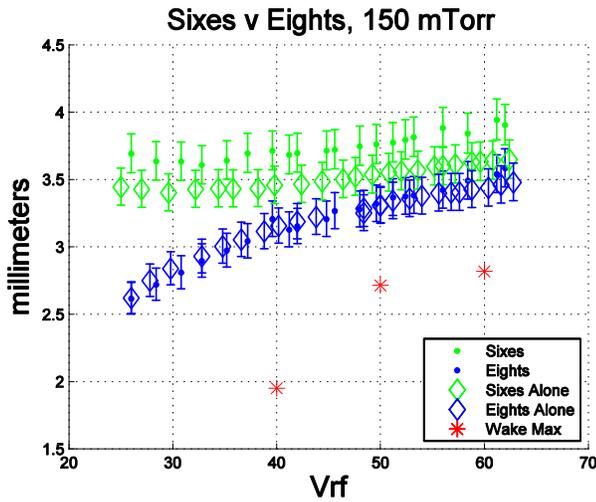


Figure 6: Experimental heights vs. predicted wake field maximum potential at 150 mTorr

When the experiment was repeated at 150 mTorr, because of the potential for error in the measurements, there was no appreciable shift in either layer when the two layers were placed in the cell simultaneously, as shown in Figure 6. The distances between layers for this pressure, as well as the distance from the top layer to the predicted location of the first potential maximum, are shown in Figure 7. As before, the distances between the two layers was in all cases significantly less than this distance from the top layer to the first potential maximum.

IV. DISCUSSION

As figure 8 shows, the only appreciable shift of layer heights due to bilayer interactions was in the opposite direction as the force due to the ion wake field effects, as predicted by the combined fluid model and wake field model. The vertical component of the wake field effect, then, is relatively weak, and is dominated by other forces between the dust layers.

If a method of eliminating error were developed, then perhaps a shift would also be seen in the upper layer at 150 mTorr. However, without such a method, to suggest that this shift is significant would be unreasonable. The error bars as they appear in this paper are the result of the assumption that each of three measurements taken for each datum is accurate to within ± 2 pixels, for a total effective error of roughly ± 10 pixels. With the current methods of analysis, a significantly higher degree of accuracy cannot be assumed.

V. FUTURE WORKS

A study of the horizontal component of the ion wake field effect is ongoing. Once more progress has been made, perhaps new light will be shed upon the vertical component of this effect. These two components are indeed one single effect, and are best understood in light of each other.

There are several improvements to the wake field model that are desired. Currently, the model does not take into account that the potential depends upon the lower layer in addition to the upper layer. Also, it is hoped that the model

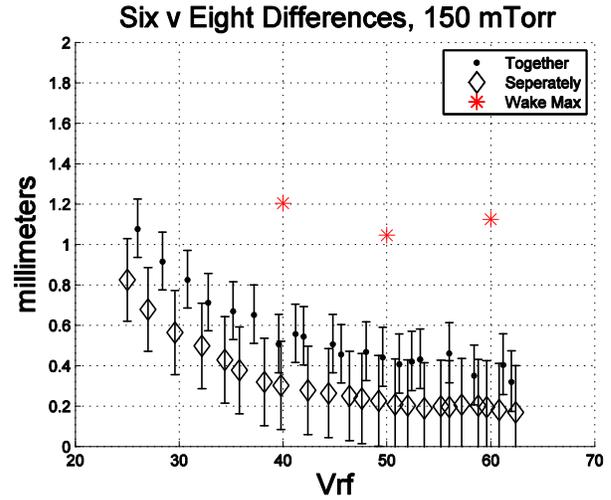


Figure 7: Height differences between layers vs. distance from top layer to predicted wake field maximum potential at 150 mTorr

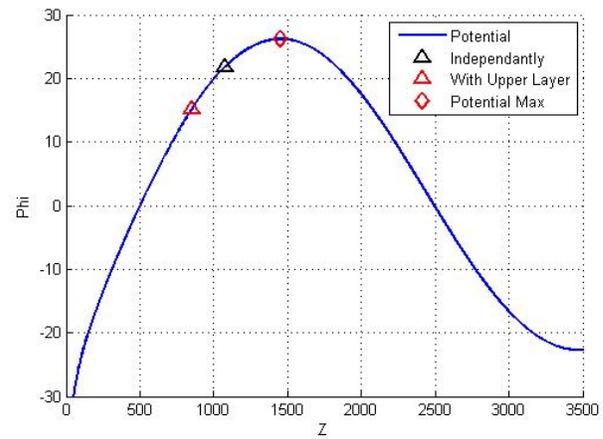


Figure 8: A typical example of lower layer height as compared to first potential maximum

can be expanded to predict the wake field force on the lower layer in addition to the shape of the potential curve.

And finally, this research showed that the vertical component of the wake field effect is relatively weak, and is dominated by other interlayer forces. A better understanding of these forces is desired.

VI. ACKNOWLEDGEMENTS

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