The Attractive Force between Dust Particles in a Vertical Two-Particle Chain

Martin J. Iwanicki, Mudi Chen, Jei Kong, Victor Zhang, Lorin Matthews, Truell W. Hyde

***Abstract*—In a complex dusty plasma, an ion flow creates an attractive force between two dust particles in a vertical chain. Helical structures can also be formed when the radio frequency power is adjusted. By using a glass box inside a GEC radio frequency cell, the attraction between dust particles in a vertical chain is observed. The attractive force is found to be asymmetrical. The anisotropy parameter, the ratio of the radial and vertical confinement forces, decreases as the system power of the cell increases.**

***Index Terms*—Anisotropy parameter, complex dusty plasma, helical structure, ion wake.**

I. INTRODUCTION

THE study of complex plasmas is a growing field within the study of plasma physics. Complex dusty plasmas are partially ionized low-temperature gases, comprised of electrons, ions, neutral gas molecules, and dust grains. The micron-sized dust grains can attain a negative charge at a magnitude of 10^3 to 10^4 electron charges through the absorption of electrons and ions within the plasma. The nature of interacting forces between dust particles will be analyzed.

In dusty plasma, dust grains are surrounded by electrons and ions, creating a Debye sphere. Interactions between dust grains can be characterized by the Debye-Hückel or Yukawa potential as being repulsive and short range. However, many theories and experiments have predicted and shown that attractive forces exist between these particles. An attractive force due to overlapping Debye spheres (ODS) has been found in simulations [1], also showing that a combined Yukawa-ODS potential better models experimental data over pure Debye-Hückel/Yukawa potential, especially when the Coulomb screening parameter is at κ = 2.3 or higher [2]. Experimental studies have further identified attractive forces between dust grains; an asymmetrical attractive force between two dust grains caused by an ion cloud at low pressures has been investigated [3]. Short range repulsive forces and long range attractive forces also were investigated between a negatively biased wire and a monolayer of dust particles, where particle interactions were determined to be a sum of the repulsive electrostatic forces at short ranges and the attractive ion drag forces at long ranges [4]. The attractive ion wake force due to the ion wake has been confirmed in simulations and in experiments [5]. A further explanation of forces and phenomena in complex dusty plasma can be found in Ref. 5 and 6.

Dust particles in a glass box can form vertical chains and helical structures. By adjusting the radio frequency power, the horizontal and vertical confinement forces acting on the particles change. Single chains, double chains, three-, and four-fold helical structures form at specific system powers. The location of the particle systems inside the glass box is crucial in understanding the transitions between structures. The anisotropy parameter is also an important factor in understanding the transitions between helical structures. The ratio of the confinement forces can be determined through the manipulation of a particle by the radiation pressure force of a laser.

Reported here will be the interactions between two dust grains in a vertical chain. Forces of attraction can be determined by investigating the reaction of one particle caused by the movement of another. By analyzing the trajectories of particles in motion, the positions, velocities, and accelerations can be determined, which can be used in order to explore the dynamics of dust particle interactions.

II. METHOD

The experiments are conducted in a Gaseous Electronics Conference (GEC) radio frequency reference cell, depicted in Fig. 1. The lower electrode is driven at 13.56 MHz, while the upper electrode is grounded. A glass box with dimensions of 12.5mm x 10.5mm (height x width) with a wall thickness of 2mm is placed in the center of the lower electrode, which is facilitated to create and contain dust particle chains. Two sets of laser systems are used. Melamine formaldehyde dust particles of size 8.89μm in the Argon plasma are illuminated by an expanded laser beam. The radiation pressure of a second laser is used to manipulate particles within the plasma.

This work was supported in part by the National Science Foundation through the grant PHY-1002637.

M. Iwanicki is with Saint Joseph's University, Philadelphia, PA 19131 USA and the Center for Astrophysics, Space Physics & Engineering Research, Waco, TX 76798. (email: martin.iwanicki@sju.edu).

M. Chen is with Baylor University, Waco, TX 76798 USA. (email: Mudi_Chen@baylor.edu).

J. Kong is with Baylor University, Waco, TX 76798 USA. (email: J_Kong@baylor.edu).

V. Zhang is with Baylor University, Waco, TX 76798 USA. (email: Victor_Zhang@baylor.edu)

L. Matthews is with Baylor University, Waco, TX 76798 USA. (email: Lorin_Matthews@baylor.edu).

T. Hyde is with the Center for Astrophysics, Space Physics & Engineering Research at Baylor University, Waco, TX 76798 USA. (email: Truell_Hyde@baylor.edu)

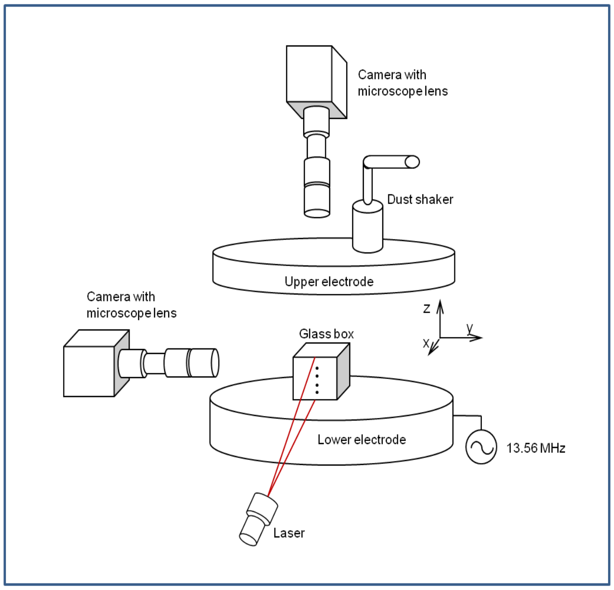


Figure 1: An illustration of the GEC RF reference cell used in the experiment.

Dust particles are dropped into the chamber. The confinement forces due to the glass box act on the dust particles, which create vertical chains as opposed to crystalline structures. By changing the system power, chains and layers of dust particles form. A single chain, two chain, three chain, four chain, and two layer system of particles are created, and the system power for each system is recorded. The system powers set for this experiment through the creation of these structures include 594, 620, 648, 675, and 764 mV, respectively. A chain comprised of two dust particles is produced inside the glass box at a specified system power and pressure of 100 mTorr. Once the two particle chain is created, the Verdi laser is turned on and focused on the top particle for a few seconds. Once the laser is turned off and the system stabilizes, the laser is then focused onto the bottom particle for a few seconds. The movements of the particles are captured by a side-view CCD camera on the side of the GEC reference cell. Particle positions are later identified in order to reproduce the trajectories for analysis.

III. Results

In Fig. 2, position vs. time graphs show when the laser perturbs a particle at a system power of 648mV. Fig. 2a is when the laser power is set to 0.01W, and Fig 2b. is when the laser power is set to 0.05W. The first graph shows the x-position trajectories of the top and bottom particle while the top particle is being perturbed (increasing positive values indicate particle moving to the left). As the top particle oscillates left and right, the bottom particle seems to mimic its x-position trajectory. The top particle displaces to the left, the bottom particle also moves left, in a delayed fashion. When the laser power is increased to 0.05W, the top particle moves to the left, while the bottom particle remains at the x-position origin. Fig. 2c presents the x-position trajectories of both particles as the bottom particle is manipulated by a laser with a laser power of 0.01W. As the bottom particle initially moves to the left, the top particle remains in its equilibrium position.

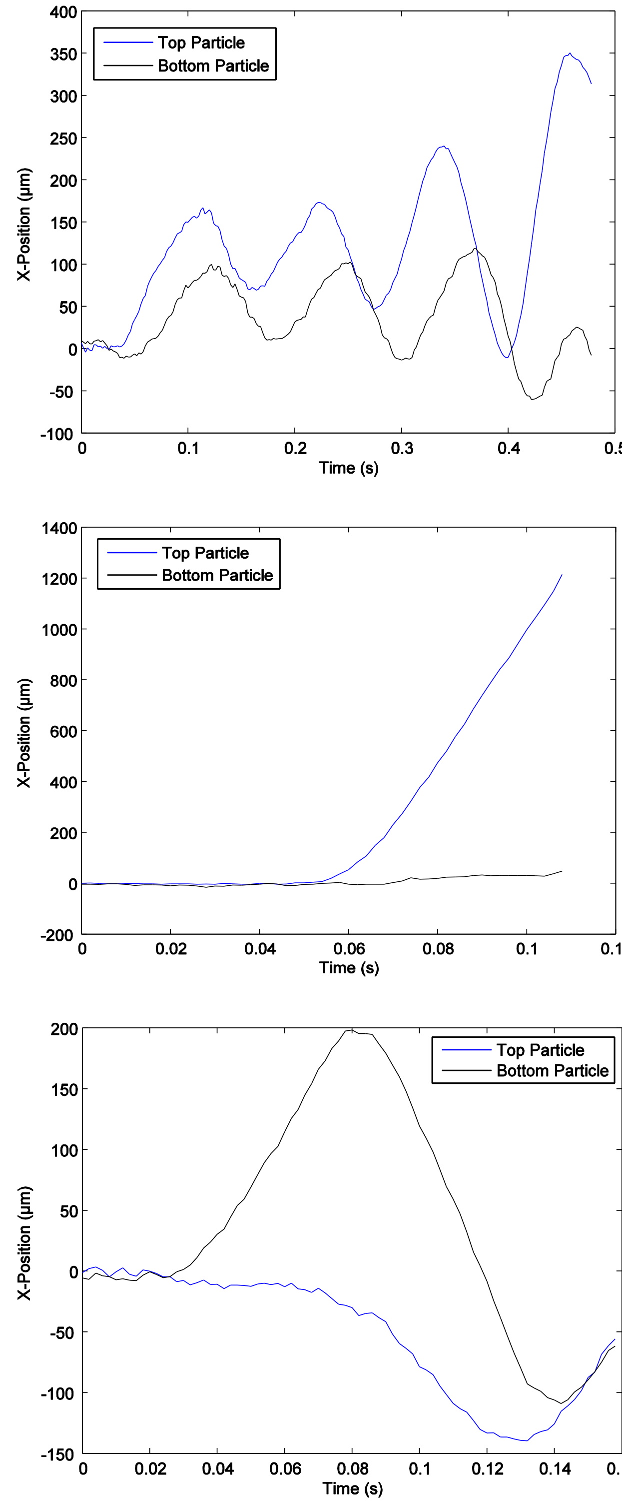


Figure 2a: The x-position vs. time graph of a two particle system when the top particle is pushed by a Verdi laser at a power of 0.01W. Figure 2b: The x-position vs. time graph of a two particle system when the top particle is pushed by a Verdi laser at a power of 0.05W. Figure 2c: The x-position vs. time graph of a two particle system when the bottom particle is pushed by a Verdi laser at a power of 0.01W.

The x-acceleration values of the bottom particle are plotted with respect to the x-position of the top particle in Fig. 3. These values are taken from when the laser focuses on the top particle at a laser power of 0.01W and a system power of 648mV. The graph represents the accelerations and positions of the particles the first time the top particle moves to the left, as can be seen in Fig. 2a. A cubic fit is added to the graph in order to better understand the relationship between the acceleration of the bottom particle and the position of the top particle. A near-constant nonzero acceleration can be found from position values 20μm to 120μm, while most of the fit plotted within the values of the data points is positive.

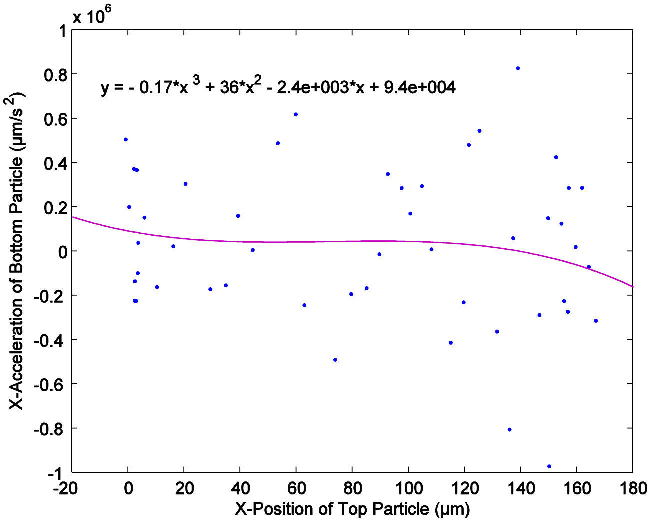


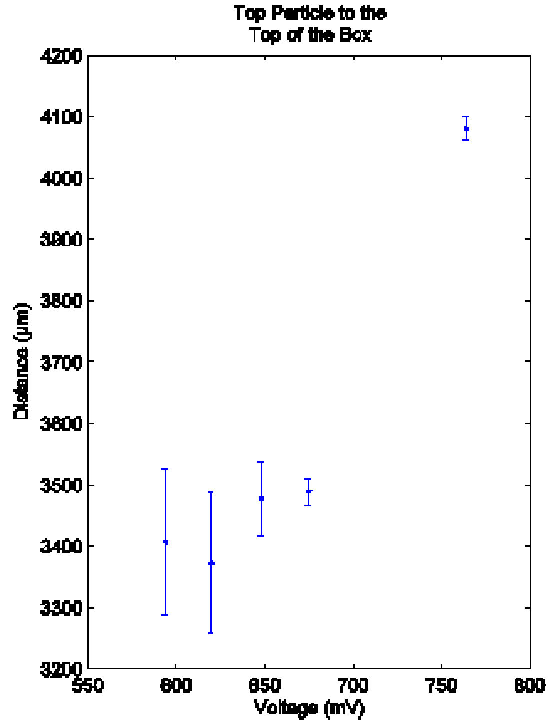
Figure 3: The x-acceleration of the bottom particle vs. the x-position of the top particle as the top particle moves left due to the radiation pressure force of the Verdi laser with a cubic fit.

The distance between the top particle and the top of the box and the distance between particles at every system power can be seen in Fig. 4. The distance between the top particle and the top of the box, shown in Fig. 4a, range between 3300-3600μm for the first four system powers. When the system power is increased to 764mV, where two layers of dust particles are formed, the distance between the top of the box and the top particle increases to a distance of 4000-4100μm. In Fig. 4b, the distance between particles decrease as the system power increases.

The anisotropic parameters for three system powers were plotted (594, 620, and 648 mV) in Fig. 5. The parameter was found by

$$\alpha = \left(\frac{\omega_{horizontal}}{\omega_{vertical}}\right)^2 \quad (1)$$

where $\omega_{horizontal}$ is the horizontal frequency of a particle, and $\omega_{vertical}$ is the vertical frequency of the particle. A linear fit shows that as the system power increases in magnitude, the anisotropy parameter decreases.



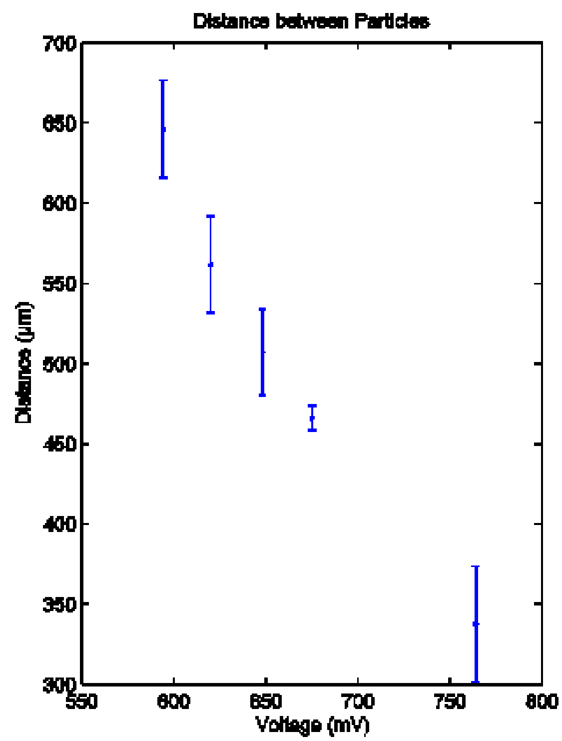


Figure 4a: The distance between the top particle in a vertical chain and the top of the glass box inside the GEC cell. The first four system powers are the system powers in which chains and helical structures exist. Figure 4b: The distance between two particles in a vertical chain at different system powers. Both show the one standard deviation from the median value.

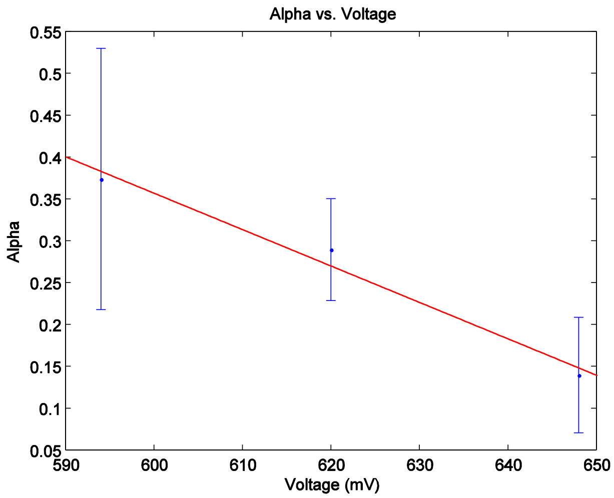


Figure 5: The anisotropy parameter vs. the system power graph for three system powers. As the system power increases, the anisotropy of the system tends to decrease.

IV. Discussion

In Fig. 2a, the x-trajectories of two particles as the top particle is manipulated by a laser are plotted over time. As the top particle oscillates left and right, the bottom particle mimics the motion of the top particle. The bottom particle tends to lag behind or have a delay in its motion. This delay can be attributed to the ion drag force. The ion drag force acts on a dust particle when ions collide with the dust particle as it is in motion [5]. This explains the lagging the bottom particle has. However, an attractive force must be acting on the bottom particle in order to cause it to move, since besides an ion drag force, the bottom particle has no other external force acting upon it. In Fig. 2c, when the bottom particle is pushed by the laser at a power of 0.01W, the top particle does not ever mimic the motion of the bottom particle. This absence of motion shows that there is no force acting on the particle at any point. In Fig. 2b, there is no mimicking of the top particle's motion by the bottom particle when a laser power of 0.05W is used, meaning no attraction between the two particles. The attractive force seen in Fig. 2a can be explained by the ion wake force. The ion wake force occurs due to the ion flow around a dust particle creating a positive potential beneath the dust particle, which is a source of attraction [5]. When the bottom particle is manipulated by the laser, there is no attraction seen between the two particles, suggesting that this attraction is asymmetrical. Since higher powers lead to no noticeable attraction between the particles, this attractive force or wake must have some time dependency or a reaction time in order for the bottom particle in order to react to the motion of the top particle. This asymmetrical force can be attributed to the ion wake force.

In Fig. 3, the cubic fit plotted against the data shows an almost constant nonzero acceleration of the bottom particle for a great portion of the time as the top particle moves to the left. Due to the direct relationship of acceleration and force, there is a constant nonzero force acting upon the bottom particle at some point, which can be attributed to the ion wake force. As the particle continues moving to either the left or the right, the acceleration of the bottom particle tends to also be constant and nonzero. At higher powers or when the bottom particle is manipulated, there is force acting between the two particles. This once again, points again to the existence of an ion wake field between the two particles that produces attractive force.

The distance between the top particle of a vertical chain and the top of the glass box tends to be similar distances at system powers where a single chain or multiple chains can exist. When increased to a system power where a double layer occurs, the top particles drop further into the box. Since transitions between these structures can be understood by these distances, it is probable that the transition between vertical chains and helical structures is not as great as the transition between vertical chains and double layer systems. In a double layer system, the particles in the top layer seem to not affect the particles in the bottom layer, whereas the particles in a vertical chain or in helical structures tend to affect other particles in the system greater. The distance between the particles in a two-particle vertical chain also decreases as the system power increases. In multiple chains or double layer systems, particles might be able to be at equilibrium points closer to each other than at a system power where a single vertical chain can exist.

The anisotropy parameter was found through the Fourier transform of position vs. time graphs and finding the maximum values for the radial and vertical frequencies. For the first three power systems, the anisotropy parameters were found to be decreasing as the system power increases. The anisotropy parameter is very important in understanding transitions between chains and helical structures. The anisotropy parameter is a measurement of the confinement forces acting on the particle inside the glass box. In a glass box, particles experience vertical forces, the electrostatic force and the force due to gravity, and radial or horizontal forces, the forces due to the confinement forces from the walls of the glass box. As the system power increases inside the chamber, the ratio of the confinement forces changes, showing a decrease in the anisotropy parameter. This decrease allows the particles to be able to transition from multiple chains to helical structures, and from helical structures to double layers. More experiments need to be done in order to understand these transitions better and be able to see more important factors in the transitions between structures.

V. Conclusion

Two particles in a vertical chain are able to help understand the dynamics of complex dusty plasma. An asymmetrical attractive force can be seen between a top particle placed into motion and a bottom particle with no other force acting upon it. This attractive force is generally constant as the top particle moves towards a direction. The ion wake force can be identified as the attractive force between the two particles, since the ion wake force is asymmetrical in nature. Distances between the top particle of a chain and the top of the box tend to be near the same value for single and multiple chains, while the distance between two particles tend to decrease as the system power increases. The anisotropy parameter also decreases as the system power increases.

Acknowledgment

Martin J. Iwanicki thanks the member and personnel at the Center for Astrophysics, Space Physics, & Engineering Research, Baylor University, and the National Science Foundation.

References

[1] L. J. Hou, P. K. Shukla and A. Piel, "Effect of overlapping Debye spheres on structures of 2D Dusty Plasmas", *Phys. Rev. A*, 373 (2009) pp. 458-461.

[2] S. Baruah and N. Das, "Formation of Coulomb crystal in presence of attractive overlapping Debye sphere potential", *Physics of Plasma*, 18, (2011).

[3] A. Melzer, V. A. Schweigert, and A. Piel, "Transition from Attractive to Repulsive Forces between Dust Molecules in a Plasma Sheath", *Physical Review Letter*, 83(1999) pp. 3194-97.

[4] D. Samsonov, A. V. Ivlev, G. E. Morfill, and J. Goree, "Long-range attractive and repulsive forces in a 2-D complex dusty plasma", *Physical Review E*, 63 025401 (2001) pp. 1-4.

[5] P.K. Shukla, B. Eliasson, "Fundamentals of dust-plasma interactions", *Rev. Mod. Phys.* (81) 2009.

[6] P. K. Shukla and A. A. Mamun *Introduction to Dusty Plasma Physics (Series in Plasma Physics)* Chapter 1: Introduction pp. 1-35.