Confinement of dust particles in a double layer

A. Barkan and R. L. Merlino
Department of Physics and Astronomy, The University of Iowa, Iowa City, Iowa 52242

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Negatively charged, micron-sized dust grains have been electrostatically confined in the high-potential region of an anode double layer formed in a single-ended Q-machine plasma. The levitated dust grains are large enough to be visually observed in the scattered light from the plasma source. The various forces on a dust grain in a plasma, i.e., gravitational, electric, ion drag, and neutral drag are estimated based on the measured plasma and dust parameters. The possibility of observing a Coulomb lattice in such a setup is discussed. © *1995 American Institute of Physics.*

I. INTRODUCTION

A dusty plasma is an ionized gas which contains charged dust particles. These multicomponent plasmas are relatively common throughout the universe, since most of the solid matter in the universe is in the form of dust grains, often embedded in an ionized gas. The role of dusty plasmas has been discussed in connection with the radial structure of Saturn's rings, as observed by the Voyager spacecraft, the narrow rings of Uranus, and the incomplete rings of Neptune.[1] Dusty plasmas are also being studied in connection with the manufacture of microelectronic components. Dust particles which are grown in the plasmas used for etching and deposition are a major source of contamination which reduces manufacturing yield.[2]

If dust particles are introduced into a typical laboratory plasma, they become charged by the collection of ions and electrons. Electrons are initially collected by a dust grain, due to their higher thermal velocity relative to the ions. Since a grain is electrically floating, it charges to a negative surface potential, V_s, in order to repel further electron collection and enhance ion collection. The balance of electron and ion currents leads to the following equation for V_s:

$$\sqrt{\frac{kT_e}{m_e}}\exp\left(\frac{eV_s}{kT_e}\right)=\sqrt{\frac{kT_i}{m_i}}\left(1-\frac{eV_s}{kT_i}\right), \quad (1)$$

where $T_{e(i)}$ is the electron (ion) temperature and $m_{e(i)}$ is the electron (ion) mass.[1,3]

The grain charge, Q, is related to its surface potential, V_s, by the grain capacitance, C, which for spherical grains of radius a (usually much smaller than the Debye length, λ_D) is simply $4\pi\epsilon_0 a$, and thus,

$$Q=4\pi\epsilon_0 aV_s. \quad (2)$$

This model for the grain charge applies to the case where the grains are sufficiently far apart (compared to the Debye length, λ_D). Complications from this simple picture arise when the density of dust grains, n_d, is large enough so that the intergrain spacing, $d(\sim n_d^{-1/3})$, becomes comparable to λ_D.[3,4]

Usually, the confinement time of a dust grain in a laboratory plasma is limited by the time it takes to fall through the plasma under the influence of gravity. However, since the grains are charged (typically with ~ thousands of elementary charges), it is possible to suspend them against gravity with electric fields. The ability to confine a dust cloud in a plasma opens up the possibility for studying new aspects of dusty plasma behavior such as dust dynamics, dust transport, dusty plasma waves and instabilities, and other collective effects. Such a configuration also allows the possibility of studying grain coagulation which may be an important process in the early stages of planet formation.[5]

Electrostatic trapping of dust particles has been observed in parallel plate radio frequency (RF) plasma-processing devices.[6] In such devices the negatively charged dust grains were trapped within a region where the plasma potential is positive with respect to the surrounding plasma. The electric fields required to levitate and confine the particles were provided by sheaths near the plasma boundaries. It has also recently become apparent that charged dust grains may become trapped in regions of locally enhanced ionization within plasma-processing devices due to the higher plasma potential in these regions. The presence of these "hot spots" can also perturb the ion trajectories adversely affecting process uniformity.[7]

If the kinetic energy of the suspended dust grains is small compared to their Coulomb energy, Ikezi[8] has argued that a "Coulomb lattice" may be formed in which the dust grains are arranged in a regular spatial array, similar to the crystal structure of a solid. Recently a number of observations of these Coulomb crystals formed in RF discharge plasmas have been reported.[9] These dust "crystals" are visually observable with the unaided eye and their lattice properties have been analyzed by illuminating them with laser light.

In this report we present observations of the trapping and confinement of dust grains in a plasma, performed under somewhat different conditions than those previously reported. Our experiments were performed in a single-ended Q-machine which provides a magnetized plasma consisting of electrons and singly charged potassium ions. The dust grains were levitated by the radial electric field of an anode double layer formed within the plasma column. The experimental setup is described in Sec. II and the results presented in Sec. III. A discussion of the results is given in Sec. IV.

II. EXPERIMENTAL SETUP

A schematic diagram of the device is shown in Fig. 1. The plasma is formed by surface ionization of potassium atoms on the hot tantalum plate ($T \sim 2500$ K) which also

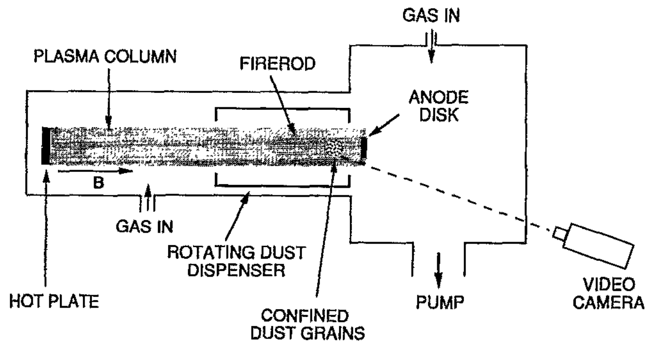

FIG. 1. Schematic diagram of the Q-machine, including the rotating drum dust dispenser. A firerod (shaded) is shown with levitated dust grains.

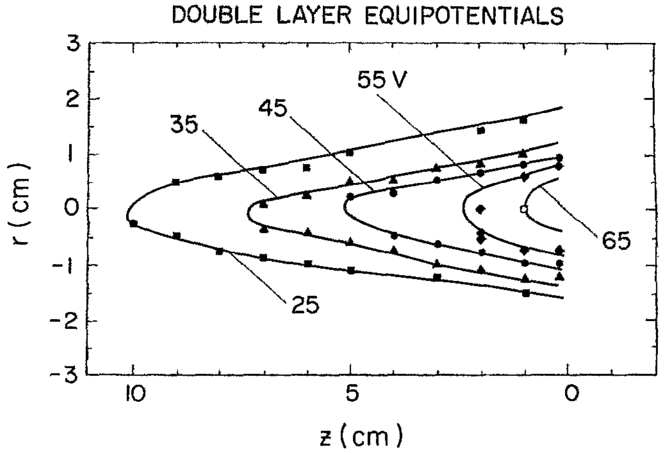

FIG. 2. Equipotential profiles in the r-z plane of a typical firerod. The anode was located at $z=0$ and biased at $V_D=240$ V. The neutral (N_2) pressure was 10 mTorr.

provides neutralizing electrons. The plasma column (~4 cm diameter and 1 m long) is confined by a longitudinal magnetic field ~3–4 kG. The electrons and K^+ ions have approximately equal temperatures, $T_e \approx T_i \approx 0.2$ eV, and densities in the range of $\sim 10^7-10^9$ cm^{-3}. To disperse dust grains into the plasma, the column is surrounded, over a portion of its length by the rotating dust dispenser (see Ref. 4 for further details). The dust material was kaolin (hydrated aluminum silicate), and a typical dust sample contained grains of various shapes and sizes (most of the grains were in the 1–15 μm range with an average "size" $a \sim 5$ μm).

The dust grains which are introduced into the plasma column acquire a negative charge, and under normal operating conditions, simply fall through the plasma column. To suspend the negatively charged particles, an appropriate electric field configuration must be established within the plasma column. This "electrostatic trap" was provided by forming an *anode double layer* near the end of the plasma column. A double layer was formed in the Q-machine by establishing a glow discharge to a small anode disk (16 mm diameter) located at the end of the plasma column. Neutral gas (N_2 or Ar) was leaked into the chamber using either (or both) of the two gas inlets shown in Fig. 1. Typically the neutral pressure was in the range of 1–10 mTorr. When the anode disk is biased to a positive potential, electrons from the ambient plasma are accelerated to the anode. If the potential somewhere in the anode sheath exceeds the ionization potential of the neutral gas, the accelerated electrons can ionize the gas. When the density of ions in the sheath becomes comparable to the electron density, the sheath detaches from the anode with the potential drop now occurring in a double layer at the boundary between the ambient (K^+) plasma and the glow discharge plasma (ion species determined by the neutral gas used) at the anode.[10] These anode glow plasmas were usually visible (we refer to them as "firerods") due to the emission of light from the excited atoms. The plasma parameters within the double layers can be quite different from those in the ambient plasma. Typically, within the firerods, $T_e \sim 2-4$ eV, $T_i \sim 0.2$ eV, and the plasma density $\sim 10^8-10^9$ cm^{-3}.

III. EXPERIMENTAL RESULTS

The experiments consisted in first producing an anode double layer (firerod) within the plasma column and then dispersing dust into it. To establish the firerod within the Q-machine plasma column, the anode disk was biased at ~200 V and the neutral gas (N_2) pressure was set to ~10 mTorr. The disk current was ≈10 mA. The electric potential structure of the firerod was determined from measurements of the floating potential of an emissive probe. Equipotentials of a typical firerod, formed on a disk located at $z=0$, are shown in Fig. 2. The geometry of the equipotential lines reflects the diverging magnetic field configuration in the region where the anode disk is located. The radial (outward) electric field of the double layer is ~20–40 V/cm. The axial electric field which is directed away from the disk has a magnitude ~2–5 V/cm. The magnetic flux tube subtended by the disk is a high-potential region with respect to the background plasma, and thus acts as a trap for negatively charged dust grains. Grains that become trapped in the high-potential region upstream of the disk are pulled back toward the disk by the axial electric field. The downward component of the electric field in the region $r<0$ provides the upward force to levitate the dust grains. Grains which are levitated by the electric fields near the bottom on the firerod ($r \approx -1$ cm) then provide vertical support for grains above them due to their mutual Coulomb repulsion.

A sequence of images illustrating the trapping and confinement of dust in the firerod are shown in Fig. 3. When the dust dispenser is turned on, a cylindrical dust cloud becomes trapped along the axis of the device and remains trapped after the dispenser is turned off. This elongated cloud is optically dense and rotates about the axis with a spiral-like motion which gradually advances axially toward the disk, as shown in Fig. 3(a). Over a period of a few seconds this spiraling cloud slows down and collapses to a spherical-like structure located about 5 cm in front of the disk [Fig. 3(b)]. This "dust ball" continues to rotate about the axis and gradually relaxes to the point at which individual dust grains can be observed at an interparticle spacing $d \approx 0.5-1$ mm. The relaxation process can be promoted by briefly increasing the neutral gas pressure. Although the individual dust grains never achieve a totally stationary state, the overall structure

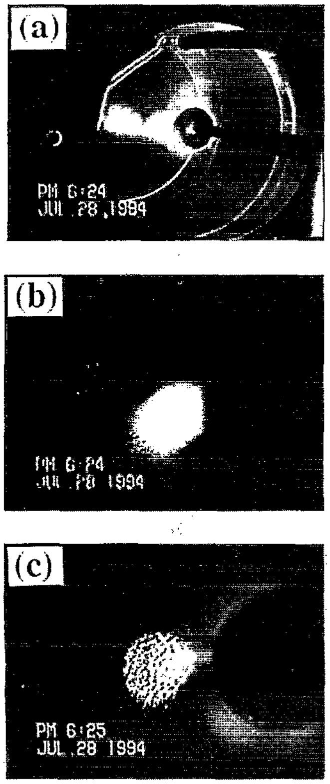

FIG. 3. A sequence (a)–(c) of video images showing the trapping and confinement of dust grains in a firerod. The final relaxed state, dust ball, is shown in (c).

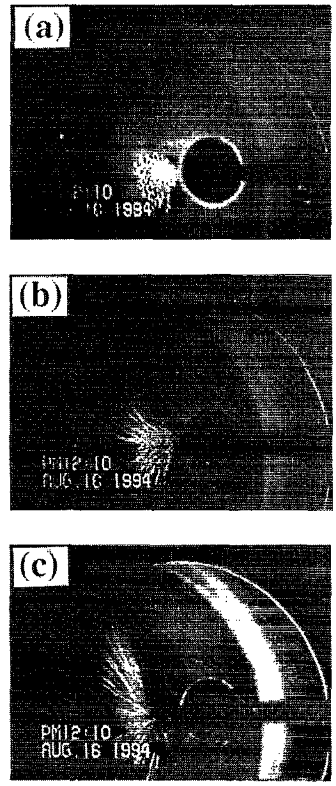

FIG. 4. A dust ball explosion. (a) Dust ball confined in a firerod, (b) and (c) successive (single-frame) video images immediately after the firerod was turned off, showing the radial explosion of grains due to the repulsive Coulomb forces.

of this dust ball remains intact even as the dust ball continues its rigid body-like rotation. It is interesting to note that the observed rotation is in the **E**×**B** direction, where **E** is the radial electric field of the double layer. This point will be considered further in Sec. IV.

The individual dust grains in the images appear larger than their actual average size of about 5 μm. If the dust ball is left undisturbed the grains grow in size, presumably due to coagulation. After falling out of the firerod, some of these grain aggregates were collected for *ex situ* examination. These were typically in the form of elongated branch-like structures of several hundred microns up to millimeters in length. The growth of these structures is favored by a reduction in the gas pressure, since the grains tend to be more agitated at low pressures.

The effect of neutral gas drag on the dust particles was directly observed. This effect was probably also important in confining the dust grains axially since, from the equipotential profiles of Fig. 2, it is apparent that the electrostatic trap is open on the right side. We were not able to confine the dust particles if the gas flow was directed toward the disk. The dust grains could be moved toward the disk by increasing the gas flow at the upstream inlet. By inserting a gas nozzle under the dust ball and blowing the gas upward we could push the grains into the upper half of the firerod. In this region ($r>0$) the grains were "levitated" against the upward gas dynamic force by a combination of gravity and the downward electric force.

The effect of the strong intergrain repulsive potential is illustrated in Fig. 4 which shows three successive single frame video images just before [Fig. 4(a)] and immediately after [Figs. 4(b) and 4(c)] the firerod was suddenly turned off. The removal of the confining electric field results in a radial "explosion" of the dust ball. By measuring a typical grain's displacement, $\Delta r \approx 1$ cm, over a single frame ($\Delta t = 1/60$ s), the average acceleration of a grain was estimated to be $\Delta r/(\Delta t)^2 \approx 3$ g.

IV. DISCUSSION

A. Grain levitation

We have shown that negatively charged dust grains can be levitated by the electric field of an anode double layer produced in a magnetized plasma column. From the condition of force balance the grain potential V_s can be calculated and compared with the solution of Eq. (1). Using Eq. (2) for Q and writing the grain mass in terms of a and the mass density ρ, the force balance $QE=mg$, can be written as

$$[4\pi\epsilon_0 a V_s]E=[(4\pi/3)a^3\rho]g. \tag{3}$$

Using $a\approx 5$ μm, $\rho \approx 2000$ kg/m^3, $E\approx 2500$ V/m in Eq. (3) we get $V_s \approx 7$ V. This compares well with the theoretical value $|V_s|=10$ V obtained from Eq. (1) with $T_e=4$ eV and $T_i=0.2$ eV.

B. Neutral and ion drag forces on a dust grain

In addition to the gravitational and electrostatic forces on a dust grain, the observations indicate that forces due to collisions with neutrals (neutral drag) and ions (ion drag) may also be significant. Rough estimates of these forces were made using expressions given in Winske and Jones.[11]

1. Neutral drag force

The neutral drag force F_n was estimated from

$$F_n = N v_n m_n \pi a^2, \tag{4}$$

where N is the neutral gas density, v_n the relative velocity between the neutrals and dust grains, and m_n the neutral mass. From the measured gas flow rate we estimate that $v_n \simeq 10$ m/s. Then for a typical pressure of 10 mTorr we find from Eq. (4), $F_n \approx 2\times10^{-13}$ N. This F_n is comparable to the electric force on a dust grain in the direction of the disk due to the axial component of the electric field of the double layer.

2. Ion drag force

The ion drag force, F_i, can be computed from Eq. (12) of Winske and Jones

$$F_i \cong n_i m_i v_i^2 4\pi b_{\pi/2}^2 \Lambda, \tag{5}$$

where n_i is the ion density, m_i the ion mass, v_i is the relative velocity between ions and dust grains, $b_{\pi/2} = eQ/4\pi\epsilon_0 m_i v_i^2$ is the impact radius corresponding to a 90° deflection and $\Lambda = \ln(b_{\max}/b_{\min})$ is the Coulomb logarithm, with $b_{\max}$ and $b_{\min}$ the maximum and minimum impact parameters, which are taken to be λ_{De} and the grain radius a, respectively.[12] Using Eq. (5) we find $F_i \sim 10^{-12}$ N for $n_i \sim 10^9$ cm^{-3}, $Q \approx 4\times10^4$ e, $a = 5$ μm, and $v_i \approx 10^4$ m/s. This ion velocity corresponds to the $\mathbf{E}\times\mathbf{B}$ drift of the ions in the double layer, $v_i \approx v_{\mathbf{E}\times\mathbf{B}} \approx E/B \approx (2500\text{ V/m})/0.25\text{ T} = 10^4$ m/s. An ion drag force of this magnitude is sufficient to spin up the dust grains to the observed rotation rate and, as noted in Sec. III, the dust grains do rotate in the $\mathbf{E}\times\mathbf{B}$ direction.

C. Analysis of the dust ball "explosion"

As shown in Fig. 4 the dust grains on the surface of the dust ball acquire a substantial (few g's) acceleration when the confining electric field is suddenly removed. This relatively large acceleration cannot be accounted for solely by the interaction of a grain with its nearest neighbor, which gives rise to an acceleration $\approx Q^2/4\pi\epsilon_0 d^2 m \approx 1.5$ m/s^2, using $Q = 4\times10^4$ e, $d \approx 0.5$ mm, and $m = 10^{-12}$ kg. A better estimate can be obtained if we assume that a grain at the surface is acted upon by the electrostatic force, F_Q, due to a spherical charge distribution of total charge $N_T Q$, where N_T is the total number of grains within the sphere. The acceleration is then given by $F_Q/m \approx N_T Q^2/4\pi\epsilon_0 R^2 m$; N_T can be estimated by using the measured values for the intergrain distance d and dust ball radius R, since $N_T \approx (4\pi/3)R^3 n_d$, and $n_d \approx [(4\pi/3)d^3]^{-1}$, where n_d is the density of dust grains. With $d \approx 0.5$ mm and $R \approx 0.5$ cm, we get that $F_Q/m \approx 15$ m/s^2, which is comparable to the measured acceleration of ~ 3 g.

D. On the possibility of forming a Coulomb solid

The question arises as to whether or not the type of grain structures that we have observed [Fig. 3(c)] can be classified as "Coulomb solids." From the visual observations it seems clear that these structures do not display the high degree of regularity as in the two-dimensional lattice arrays reported by others.[9] This observation is in line with estimates of the Coulomb coupling parameter Γ which is below the critical value of 170 required for the formation of Coulomb solid.[8,13] To estimate Γ we use the expression given by Ikezi[8]

$$\Gamma = \frac{Q^2 \exp(-d/\lambda_D)}{4\pi\epsilon_0 d k T_d}, \tag{6}$$

although one needs to bear in mind that there is a lack of theoretical work on the nature of Coulomb solids with Debye shielding and the values of Γ necessary to form a "solid" may be different from expectations when Debye shielding is properly taken into account. Following Ikezi,[8] we take $\lambda_D = \lambda_{Di}$, since the shielding distance should be determined by lower temperature species. With $n_i \approx 5\times10^8$ cm^{-3} and $T_i \approx 0.2$ eV, we have $\lambda_{Di} \approx 0.2$ mm and using $Q \approx 4\times10^4$ e, and d (intergrain spacing) ≈ 0.5 mm, we obtain $\Gamma \approx 6\times10^{-17}/kT_d$. From an analysis of the video we estimate dust grain velocities up to ≈ 1 cm/s, or $kT_d \approx (1/2)mv^2 \approx 5\times10^{-17}$ J, so that $\Gamma \approx 1$. Since Γ depends exponentially on d/λ_D, there are large uncertainties in the estimated Γ values, so that a range $0.1 < \Gamma < 10$ cannot be excluded. These relatively low Γ values would be consistent with the fact that a very regular (lattice) structure of the dust grains was not observed. On the other hand, Γ values $\gtrsim 1$ indicate that the grains would exhibit some degree of "strong coupling" behavior which was observed in the experiment.

If the grains were cooled to the thermal temperature of the neutrals (i.e., ≈ 300 K), then the value of Γ would be in the range $10^3 - 10^4$, and a Coulomb solid should be possible. There are a number of reasons why the dust grains in our system have not relaxed to the point necessary to form a Coulomb solid. Shear in the gas flow and plasma rotation may "melt" the crystal even through the Γ value may be large. Fluctuations may be produced by instabilities due to the relative motion of the dust grains and plasma ions. Finally, it is not clear if a regular lattice structure can be produced in a system with grains having a distribution of sizes. Since the grain charge depends on its size, such a system is not likely to be characterized by a unique lattice constant (interparticle spacing).

In summary, we have shown that dust grains can be confined in the high-potential region of an anode double layer formed in a magnetized plasma. Three-dimensional structures of negatively charged grains have been produced and the effects of neutral and ion drag forces have been observed. Many of the experimental observations seem to be accounted for by the simple theoretical models.

ACKNOWLEDGMENT

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