

# The interaction of stationary and moving objects with dusty plasmas

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The interaction of an electrically floating metal object with a dusty plasma formed in a dc discharge was investigated experimentally. Three cases were studied in which (a) the object was at rest in the dusty plasma, or was moved through the dusty plasma with a speed that was either (b) on the order of the dust-acoustic speed or (c) much faster than the dust-acoustic speed. When the object was at rest, a dust-free cavity with a boundary with a sharp dust density gradient was formed around the object. The size of the cavity was largely determined by shielding of the object by the plasma ions. A similar (although dynamic) behavior was observed in the moderate speed case (case b). When the object was moved very rapidly (case c) the dust grains did not have time to respond, and the object mechanically removed the grains, leaving behind a narrow channel which quickly filled in.

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## I. INTRODUCTION

During the last few years several aspects of dusty plasmas have been investigated, such as the charging of dust grains by collection of plasma ions and electrons,<sup>1,2</sup> the effects of dust on various plasma waves and instabilities,<sup>3</sup> the very-low-frequency mode known as the dust-acoustic<sup>4,5</sup> wave, and the nature of strongly coupled plasmas and dust crystals.<sup>6</sup>

Recently we have considered one more aspect of the behavior of dusty plasmas, namely the interaction of such plasmas with a metallic object which is either at rest in the plasma or moving through it at various speeds. The present paper describes our experiments. The results we have obtained shed some light on the mechanisms through which the plasma is shielded from the potential of the metallic body. A study of the effect of a biased probe on the properties of plasma crystals, in particular, probe-induced particle circulation, has also been performed.<sup>7</sup> In Sec. II of the paper we describe the experimental arrangement, in Sec. III we describe the experimental results, and Sec. IV contains a discussion of these results.

## II. EXPERIMENTAL SETUP

The experimental setup is shown schematically in Fig. 1. A discharge plasma is produced in nitrogen gas at a pressure of 25–30 mTorr, in a stainless steel vacuum vessel 2 m long and 30 cm in diameter. The vessel is surrounded by a set of ten magnet coils (not shown) which can produce an axial magnetic field of magnitude up to 0.6 T and spatial uniformity of ~1%. For the experiments described here only a modest magnetic field of 100 G was applied to provide some radial confinement of the plasma. The discharge is maintained between a hot spiral cathode (FC) 5 cm in diameter, located at one end of the vacuum vessel, and a 6 cm diameter anode (D/A) biased at +300 V located at the opposite end. Typically the discharge current was  $\approx 5$  mA.

The values of the various plasma parameters in this experiment are expected to be very similar to those obtained in

our previous work<sup>5</sup> on dusty plasmas in a dc discharge, with a plasma density in the  $10^7$ – $10^8$  cm<sup>-3</sup> range, an electron temperature  $T_e \approx 2$ –3 eV, and an ion temperature close to that of the neutral gas,  $T_+ \approx 0.02$ –0.03 eV.

Dust is provided to the discharge by shaping the aluminum anode (D/A) in the form of a shallow cup which is filled with dust-embedded steel wool held in place by thin stainless steel wires. The steel wool faces the plasma column and the dust consists of grains of aluminum oxide Al<sub>2</sub>O<sub>3</sub> ranging in size from  $\sim 0.05$  to  $\sim 1$   $\mu$ m.

Dust grains ejected from the anode were charged up negatively by the plasma (P) and were levitated within a cylindrical double layer that forms adjacent to the anode. The trapped dust cloud is approximately 20–30 cm long and has a transverse size of about 3 cm. The “object” (O), whose interaction with the dusty plasma (D) is investigated, is an electrically floating tungsten wire of 1.6 mm diameter that can be manually swept through the plasma. This is easily accomplished since the wire is mechanically attached to a rod, parallel to the axis of the vacuum vessel and located several cm off axis, which can be turned from outside the vessel at various angular speeds.

The region of the dusty plasma through which the “object” moves is monitored by a video camera (VC) at a rate of 30 frames/sec. The relative positions of camera and “object” are shown in Fig. 1.

## III. EXPERIMENTAL RESULTS

The results of our observations can be conveniently divided into three groups, namely, (a) those for which the tungsten wire (the “object”) was at rest within the dusty plasma, (b) those for which it was moving at “moderate” speed and, finally, (c) those for which it was moving at “high” speed. The terms “moderate” and “high” indicate how the speed of the object compares with the dust acoustic speed in our plasma,  $C_{DA}$ , which is typically in the range 10–15 cm/sec. (Dust acoustic waves are often present in the dusty plasma and their speed can be easily measured by ana-

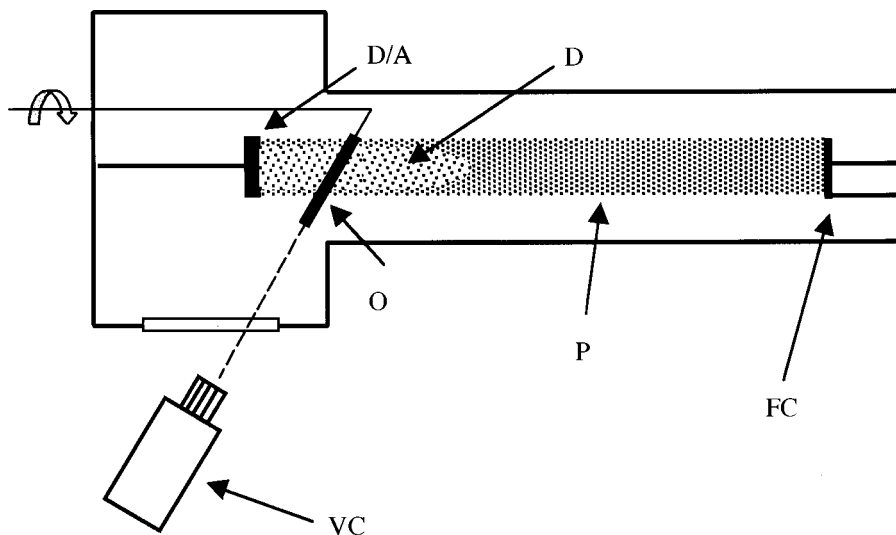


FIG. 1. Schematic of the experimental setup. D/A—dust dispenser/anode, FC—filament cathode, D—dust, P—plasma, O—object, and VC—video camera.

lyzing successive video frames.) Thus, a “moderate” speed was, generally, one of some 6–8 cm/sec, while a “high” speed was on the order of 30–50 cm/sec. The division into moderate and high speed results is reasonable, since the dust-acoustic speed is a natural speed in a dusty plasma.

#### A. “Object” at rest

The result of placing a stationary electrically floating object in the dusty plasma is shown in Fig. 2. A nearly circular region of  $\sim 12$  mm diameter centered on the “object”



FIG. 2. Single frame video image of the “object” at rest in the dusty plasma.

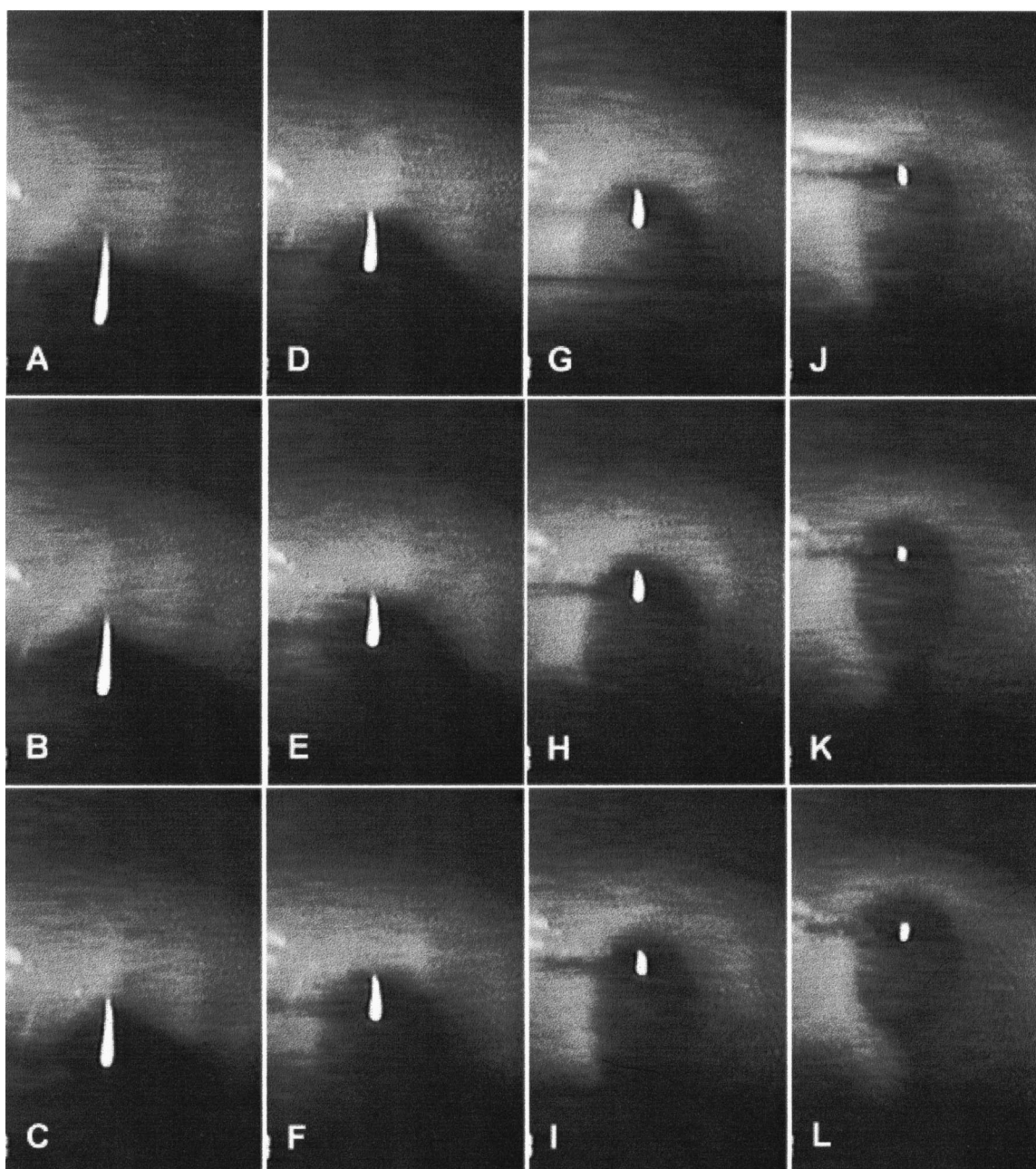


FIG. 3. Sequence of single frame video images ( $\frac{1}{30}$  sec intervals) of the "object" moving at a "moderate" speed through the dusty plasma.

appears to be devoid of dust grains. Furthermore, the edge of this region is rather sharply defined, the transition from dust to no dust occurring over a distance of  $\sim 1$  mm or less, as determined from a video image intensity profile taken through the midplane of the dust-free cavity.

### B. "Object" moving at "moderate" speed

Figure 3 consists of a series of pictures of the dust cloud and of the "object," which is moving at a speed of  $\sim 8$  cm/sec. The time interval between successive frames is  $\frac{1}{30}$  sec. As the "object" moves upward through the cloud one notices the development of a cavity similar in size to that observed Sec. III A ("object" at rest), but no longer of a circular shape. Rather, the dust-free cavity is elongated in the

direction of motion of the "object" and assumes a tear-drop shape. The cavity appears to refill over several consecutive single frame images. This process of refilling can be analyzed by plotting the distance between the two edges of the evolving drop versus the frame number (see Fig. 4). The edges approach each other at a speed of  $\sim 6$  cm/sec. Thus, each edge moves inward at a speed of  $\sim 3$  cm/sec, smaller than the dust-acoustic speed.

### C. "Object" moving at "high" speed

A sequence of frames for the "high" speed situation is shown in Fig. 5. Each frame is separated from the successive one by  $\frac{1}{30}$  sec. The "object" is moving here from bottom to top at a speed of  $\sim 40$  cm/sec.

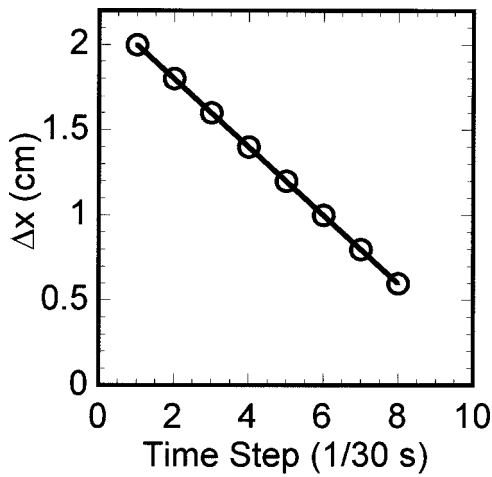


FIG. 4. Separation of the two edges of the evolving "tear drop" (shown in Fig. 3) versus time.

Two main features of the object-dust interaction are easily noticed. First, as the "object" approaches the dust cloud, the cloud boundary is deformed. The appearance of the cloud is that of some kind of plastic bag filled with marbles, which is hit by a high-speed stick. Second, there is no longer a circular or tear-drop dust-free cavity as in Sec. III A or B; rather, only a very narrow track is left by the mechanical removal of dust by the moving object, the thickness of the track being about the same as the diameter of the "object." As will be discussed in Sec. IV, this is probably a consequence of the fact that the "object" crosses the cloud in a time short compared to the cloud reaction time.

#### IV. DISCUSSION OF THE EXPERIMENTAL RESULTS

Some of the dusty plasma parameters are relatively well known, while others can be derived in a more indirect way from the observations and are, therefore, somewhat less certain. The density,  $n$ , of the plasma is obtained by using the relation  $I_{\text{anode}} \approx eAnv_{e,th}$ , where  $A$  is the anode area and  $v_{e,th}$  is the electron thermal speed. With  $A = 28 \text{ cm}^2$  and  $v_{e,th} \approx 5 \times 10^7 \text{ cm/sec}$  (corresponding to an electron temperature  $T_e \approx 2 \text{ eV}$ ) we obtain  $n \approx 2 \times 10^7 \text{ cm}^{-3}$ . This together with a  $T_e \approx 2 \text{ eV}$  and an ion temperature  $T_+ \approx 0.02\text{--}0.03 \text{ eV}$  results in a plasma Debye length,  $\lambda_p \approx 0.03 \text{ cm}$ . An important parameter of the dust grains is their size which, in part, determines their charge and mass. The aluminum oxide dust loaded into the anode has grains ranging in size from  $\sim 0.05$  to  $\sim 1 \mu\text{m}$ . There is no assurance, however, that this same range of sizes will be present within the dust clouds of our experiments, where the size distribution will be affected, among other things, by the not-well-understood mechanism of dust injection from the steel wool of the anode or by the efficiency of any process of aggregation of small-sized grains into grains of larger size. One way of estimating an upper limit to the size of the grains is by requiring that the electric fields of the cylindrical double layer be capable of levitating the grains. In our previous experiments in dc discharges<sup>5</sup> the electric fields in the double layer were measured with emissive Langmuir probes and were found to be in the range  $E$

$\approx 1\text{--}5 \text{ V/cm}$ . Thus balancing the gravitational force,  $f_g$ , on a (spherical) dust grain of radius  $a$  and density  $\rho$  ( $f_g = 4\pi a^3 \rho g/3$ ) with the electrical force  $f_E = QE$  on the grain of charge  $Q$ , computed from the relation  $Q = 4\pi\epsilon_0 a V_s$ , with  $V_s \approx 4kT_e/e$ , provides an upper limit to  $a$  of  $1\text{--}2 \mu\text{m}$ .

A better way of estimating the grain size is by making use of the measured value of the dust-acoustic speed,  $C_{\text{DA}} \approx 10 \text{ cm/sec}$  in our plasma, and of the dispersion relation for dust-acoustic waves

$$C_{\text{DA}} \approx \left( \frac{kT_d}{m_d} \epsilon Z^2 \right)^{1/2}, \quad (1)$$

where  $m_d$  is the mass of the grains,  $eZ = Q$  is their charge, and  $\epsilon = n_d/n$  is the ratio between the dust grain density and the plasma density. The quantity  $\epsilon Z$  (the fraction of negative charge on the dust grains) is typically<sup>5</sup> in the range of  $0.3\text{--}0.9$ ; thus  $\epsilon Z \approx 1$ , and the relation above can also be written as

$$C_{\text{DA}} \approx \left( \frac{kT_d}{m_d} Z \right)^{1/2}, \quad (2)$$

which, since  $Z \propto a$ , and  $m_d \propto a^3$ , provides a value for  $a$ . We obtain  $a \approx 0.5 \mu\text{m}$ . It then follows the  $Z \approx 3000$ ,  $m_d \approx 1 \times 10^{-15} \text{ kg}$ , and  $\epsilon \approx 1/Z \sim 3.3 \times 10^{-4}$ . The dust density  $n_d = \epsilon n$  is then  $\approx 7 \times 10^3 \text{ cm}^{-3}$ , while the intergrain distance  $d \sim (n_d)^{-1/3} \approx 0.05 \text{ cm}$ , comparable to the plasma Debye length. Another quantity of interest is the dust plasma frequency

$$\omega_{pd} = \left( \frac{n_d e^2 Z^2}{\epsilon_0 m_d} \right)^{1/2}, \quad (3)$$

which, with the values of  $n_d$ ,  $Z$  and  $m_d$  derived above, is  $\approx 380 \text{ sec}^{-1}$ . The dust plasma period  $T_{pd} = 2\pi/\omega_{pd} \approx 0.02 \text{ sec}$ .

Finally, we estimate the dust Debye length,  $\lambda_d$ , given by

$$\lambda_d = \left( \frac{\epsilon_0 k T_d}{n_d e^2 Z^2} \right)^{1/2}. \quad (4)$$

If  $T_d$  is the same as the temperature of the neutral gas and of the positive ions, we have  $\lambda_d \approx 5 \times 10^{-4} \text{ cm}$ , nearly two orders of magnitude smaller than the plasma Debye length,  $\lambda_p$ . Table I summarizes the above discussion of the various plasma/dust parameters.

Next we turn to a discussion of the results obtained in the three cases of Sec. III A, "object" at rest, Sec. III B "object" moving at "moderate" speed and Sec. III C "object" moving at "high" speed.

#### A. Object at rest

When the stationary object is placed in the dusty plasma a dust-free void extending out to a radius of  $5\text{--}6 \text{ mm}$  from the object is observed around the object. The radius of this void corresponds to about  $10\text{--}20$  times the plasma Debye length and more than  $10^3$  times the dust Debye length, indicating that the shielding of the object's electric field is due to the plasma. A rough estimate of the size of the void can be obtained if we assume that the dust density  $n_d$  follows the Boltzmann relation,  $n_d = n_{d0} \exp(-eZV/kT_d)$ , where  $Z$  is the

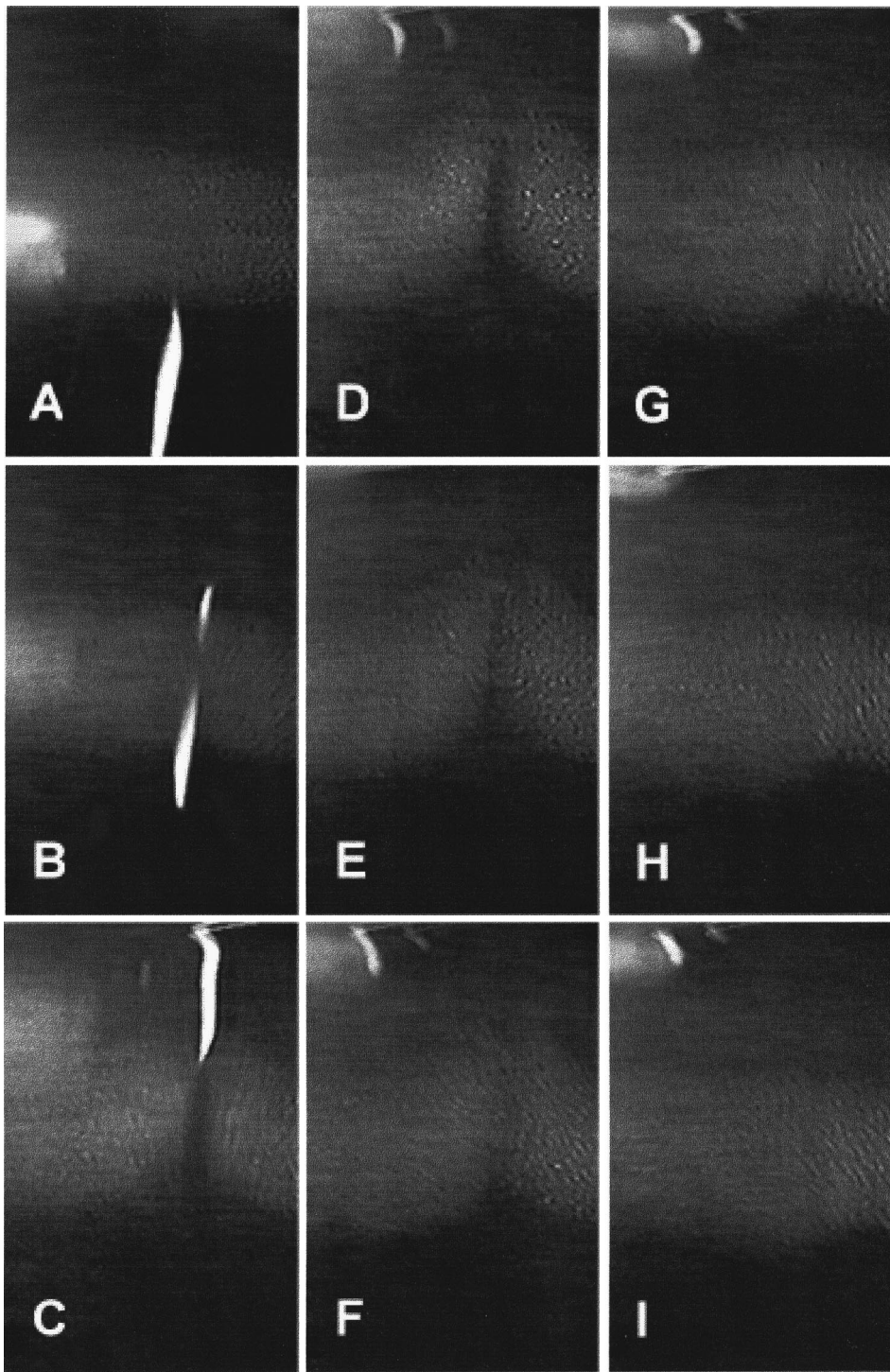


FIG. 5. Sequence of single frame video images ( $\frac{1}{30}$  sec intervals) of the “object” moving at “high” speed through the dusty plasma.

grain charge number,  $V$  is the absolute value of the potential due to the floating object, and  $T_d$  is the dust temperature. From the linearized Boltzmann relation for  $n_d$  we see that the space around the stationary rod will be devoid of dust out to a radius where the potential  $V(r)$  has fallen from the rod floating potential  $V_f$  to the  $kT_d/eZ$  of the dust. Assuming that the potential falls off as  $V(r) = V_f \exp(-r/\lambda_p)$ , the dust density will be zero out to a radius  $r$  given approximately by  $r \approx -\lambda_p \ln(kT_d/eZV_f)$ . Using  $kT_d = 0.025$  eV,  $Z = 3000$  and  $V_f = 8$  V, we obtain an  $r \approx 14\lambda_p$ , which is close to what the

images indicate (Fig. 2). Note also that, due to the logarithmic dependence,  $r$  is relatively insensitive to the dust charge and temperature.

The experimental results presented are also in general agreement with a theoretical analysis of the electrostatic shielding of dust grains near the boundary of a plasma by Luo and Yu.<sup>8</sup> By solving the nonlinear Poisson equation with Boltzmann density distributions for the ions, electrons and dust grains, they showed that a dust “density sheath” (DS), which is much narrower than the plasma sheath (PS), forms

TABLE I. Plasma/dust parameters.

Plasma density	$2 \times 10^{13} \text{ m}^{-3}$
Electron temperature, $T_e$	2–3 eV
Ion temperature, $T_+$	0.02–0.03 eV
Neutral gas temperature, $T_n$	0.02–0.03
Dust temperature, $T_d$	0.02–0.03 eV
Dust density, $n_d$	$7 \times 10^9 \text{ m}^{-3}$
Intergrain spacing, $d \sim (1/n_d)^{1/3}$	$5 \times 10^{-4} \text{ m}$
Plasma Debye length, $\lambda_p$	$3 \times 10^{-4} \text{ m}$
Dust Debye length, $\lambda_d$	$5 \times 10^{-6} \text{ m}$
Dust plasma frequency, $\omega_{pd}$	$380 \text{ sec}^{-1}$
Dust grain "radius"	$5 \times 10^{-7} \text{ m}$
Dust grain mass	$1 \times 10^{-15} \text{ kg}$
Dust grain $Z=Q/e$	3000

near the plasma/wall boundary. In the DS, the dust density drops sharply, since the relatively highly charged dust grains are strongly affected by the potential.

An interesting feature of the observations described in Sec. III A is that they provide a clear *visual* illustration of Debye shielding.

### B. Object moving at "moderate" speed

In the "moderate" speed case, instead of a nearly circular hole in the dust grain distribution, we observe a tear-drop shape for the region devoid of dust and surrounding the "object." The region is elongated in the direction of motion of the "object," with a pronounced tail. The general size of the hole is the same as in Sec. IV A.

An interesting observation is the refilling of the dust in the tail portion of the tear drop, which takes place at a speed of 3 cm/sec. Thus, the refilling appears to take place at a speed intermediate between the dust-thermal speed and the dust-acoustic speed.

### C. Object moving at "high" speed

Of the two main features noted when the object is moving at "high" speed, the first, namely the deformation of the cloud boundary occurring as the "object" approaches the

cloud can, perhaps, be best understood in terms of an "erosion" of the high potential region, where the grains are trapped, by the negative potential of the "object." The second feature, namely the absence of the circular or of the tear-drop dust-free cavity, and the appearance of a narrow track due to a simple mechanical removal of the grains, can be understood by the fact that the time it takes the "object" to move across the dust cloud is not much longer than the time required by the cloud to respond to the action of the "object." For a cloud of 3 cm transverse size and a velocity of the "object" of  $\sim 40$  cm/sec, the transit time is  $\sim 0.08$  sec. The response time of the cloud could perhaps be measured either by the quantity  $T_{pd} = 2\pi/\omega_{pd} \approx 0.02$  sec or, better still, by the time required by a dust-acoustic perturbation to move across the cloud, which is  $t_{DA} \sim 3 \text{ cm}/(10 \text{ cm/sec}) = 0.3$  sec.

### ACKNOWLEDGMENTS

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<sup>1</sup>S. Robertson, Phys. Plasmas **2**, 2200 (1995).

<sup>2</sup>A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Rev. Lett. **73**, 3093 (1994).

<sup>3</sup>R. L. Merlino, A. Barkan, C. Thompson, and N. D'Angelo, Phys. Plasmas **5**, 1607 (1998).

<sup>4</sup>A. Barkan, R. L. Merlino, and N. D'Angelo, Phys. Plasmas **2**, 3563 (1995).

<sup>5</sup>C. Thompson, A. Barkan, N. D'Angelo, and R. L. Merlino, Phys. Plasmas **4**, 2331 (1997).

<sup>6</sup>J. H. Chu, J.-B. Du, and L. I, Phys. Rev. Lett. **72**, 4009 (1994); Y. Hayashi and K. Ichibana, Jpn. J. Appl. Phys., Part 2 **33**, L804 (1994); H. Thomas, G. E. Morfill, V. Demmel, J. Goree, B. Feuerbacher, and D. Möhlmann, Phys. Rev. Lett. **73**, 652 (1994); A. Melzer, T. Trottenberg, and A. Piel, Phys. Lett. A **191**, 301 (1994).

<sup>7</sup>D. A. Law, W. H. Steel, B. M. Annaratone, and J. E. Allen, Phys. Rev. Lett. **80**, 4189 (1998).

<sup>8</sup>H. Luo and M. Y. Yu, Phys. Rev. E **56**, 1270 (1997).