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Probe induced voids in a dusty plasma

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An experimental study of the formation of voids (dust-free regions) around negatively biased probes in a dusty plasma is described. Stable voids are maintained by the balance of electric and ion drag forces on the dust particles. A theoretical model is proposed to explain how the size of the void scales with the probe bias potential.
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I. INTRODUCTION

Dusty plasmas are susceptible to the formation of a "void," a centimeter-size region within the plasma that is free of dust particles. The boundary between the dust-free plasma (void) and the dusty plasma is typically quite sharp. Praburam and Goree[1] first reported the appearance of a spoke-shaped, dust-free region in a cloud of 100-nm carbon particles in a radio-frequency discharge formed between parallel-plate graphite electrodes. This dust-free region (called the great void) rotated azimuthally in the discharge and only appeared when the dust particles had grown to a sufficiently large size.

Voids have also been an unexpected occurrence in dusty plasmas produced under microgravity conditions. In laboratory devices, dust particles must be levitated against gravity by the relatively strong electric fields at the sheath above the electrodes. This precludes the formation of large three-dimensional (3D) crystal structures, since the particles are relegated to relatively thin layers just above the lower electrode. Voids formed in dusty plasmas under microgravity conditions were observed in the PlasmaKristall experiments (PKE-Nefedov) onboard a sounding rocket[2] and recently on the International Space Station.[3] Recent ground-based experiments have simulated these microgravity observations by applying a temperature gradient across the plasma volume of an rf glow discharge plasma. This creates an upward thermophoretic force that counteracts the role of the gravitational force, allowing the size of the cloud to increase and also facilitating the formation of a large oval-shaped void.[4]

The spontaneous formation of voids has been attributed to an instability that develops if a local depletion of negatively charged dust particles occurs within a spatially uniform dusty plasma.[5] The dust density perturbation produces a positive potential with respect to the surrounding plasma and thus an electric field that points outward from the region of the dust depression. This electric field has two effects: it produces an inward electric force F_E on the negative dust, and an outward ion drift. The ion drift causes an outward ion drag force on the dust particles F_D that tends to expel them from the region. If $F_D > F_E$, the initial density depression grows into a void. Thermophoretic forces have also been invoked to explain void formation,[2,6] although recent work[7,8] suggests that the ion drag force is more likely the mechanism responsible for the formation of voids in dusty plasmas under microgravity conditions.

Voids in dusty plasmas have also been produced by inserting a probe that is negatively biased with respect to the surrounding plasma into a dusty plasma. A cylindrical void with a diameter of ~ 1 cm was produced when an electrically floating tungsten rod of 1.6 mm diameter was inserted into a dusty plasma formed in a nitrogen discharge plasma.[9] Observations were also made of the effect of moving the floating rod through the dusty plasma at speeds either below or above the dust acoustic speed. When the rod was moved through the dust cloud on a time scale long compared to the time for a dust-acoustic perturbation to move across the cloud, a moving void was formed.

The present paper describes the results of a similar experiment in which a void was formed in an argon glow discharge plasma by inserting a negatively biased probe into the dusty plasma. Unlike the previous experiment, however, we were now able to study the effect that changing the probe bias has on the size of the void. The experimental results are compared to a model in which a stable void is maintained by the balance of the outward electrostatic force on the negative dust by the electric field of the probe and the inward ion drag force due to ions that are drawn into the void and collected by the probe. It is important to note that in the voids generated by a negatively biased probe described here, the roles of the electric and ion drag forces are *reversed* compared to voids formed under microgravity conditions (Refs. 2 and 3). Thus the present study provides a complimentary view of void formation in dusty plasmas. The first experiment where the balance of ion drag and electric force was proposed to explain the confinement of particles in the field of a negatively biased wire (in 2D particle clouds) was reported by Samsonov *et al.*[10]

The experimental setup and methods are described in Sec. II and the results are given in Sec. III. The theoretical

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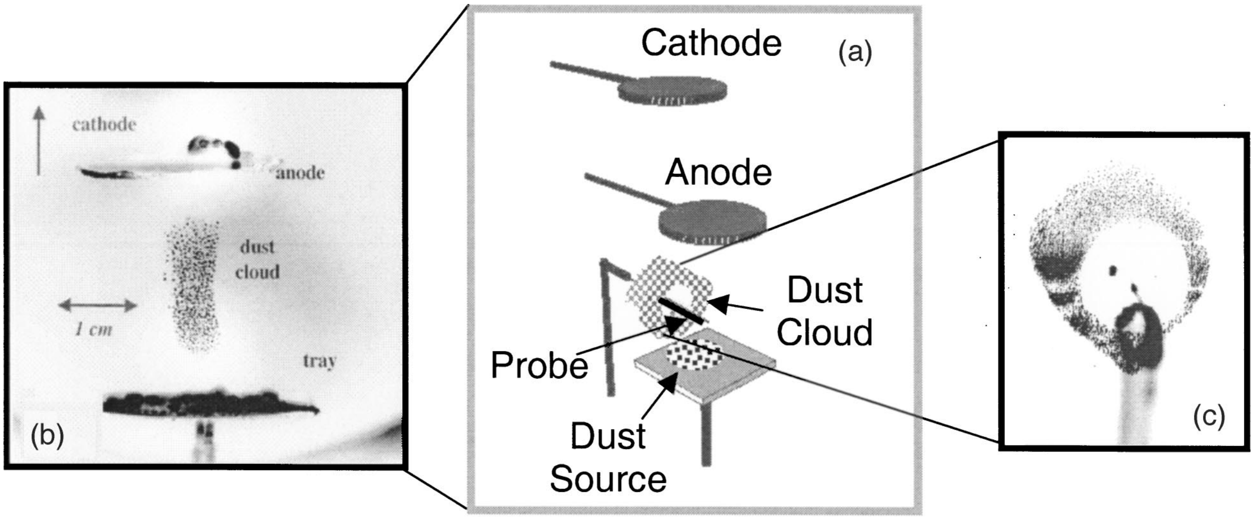

FIG. 1. (a) Schematic of the experimental apparatus. (b) Photograph of the experimental device and confined dust cloud. (c) Dust cloud with void surrounding the probe.

model and a discussion of the results is presented in Sec. IV. Summary and conclusions are given in Sec. V.

II. EXPERIMENTAL SETUP AND METHODS

Dc glow discharge plasmas were generated in the DPX (dusty plasma experiment) device using both a biased cathode and a biased anode, as shown schematically in Fig. 1(a). The cathode is a 2.5-cm-diameter brass disk. Approximately 5 cm below the cathode is the anode which is a rectangular stainless steel plate, 9 mm wide and 37 mm long. An electrically floating brass tray containing 2.9-μm diameter silica powder is used as the source of dust particles. This tray can be moved vertically in the vacuum chamber and for these experiments was located roughly 3 cm below the anode. When the discharge is initiated, some of the dust particles on the tray, which are in contact with the plasma, become charged, leave the tray and become trapped within the anode spot that is attached to the underside of the anode. Dust clouds having well-defined boundaries are electrostatically levitated within this anode glow plasma. Further details of the experimental setup have been described elsewhere.[11]

The dust particles suspended in the plasma are illuminated using a Nd:YAG laser. The beam is expanded into a sheet using a cylindrical lens and images of the illuminated particles are recorded on a video camera. Single frame images of the particle cloud are then captured for analysis. A typical example of one of the confined dust clouds is shown in Fig. 1(b). From images of this type, estimates of the dust grain density can be made. Measurements of the plasma parameters were made using Langmuir probes. A summary of the experimental parameters is given in Table I.

III. EXPERIMENTAL RESULTS

The void was produced by inserting a negatively biased (with respect to the plasma) wire (0.2 mm diameter) into the dust cloud. An example of a void formed by the probe is shown in Fig. 1(c). This void is on the order of a centimeter in size, and is centered on the probe although appears to be off center which is an artifact of the viewing angle. By moving the laser sheet in the vertical direction we were able to see that the void was cylindrical in shape. (The image also shows the presence of dust acoustic waves, which appear of the left side of the image as dark striations. The dust acoustic waves, which were present before the void was formed, continued to propagate around the void after it was formed.)

The main result of this experiment was the observation of the effect of the probe bias on the size of the void. Figure 2 is a series of images of the void taken at various values of the probe bias voltage. The probe bias, ranging from 160 to 196 V, is indicated on each image. The probe I-V characteristic is shown in Fig. 3, where the ion current is positive. Although the net probe current is negative for $V_b > 200$ V, the probe continues to collect ion current up to the plasma potential. The plasma potential in a glow discharge generally

TABLE I. Summary of experimental parameters.

Discharge parameters	
Neutral gas	argon
Neutral pressure	120–130 mTorr
Anode voltage	200–215 V
Cathode voltage	-100–-130 V
Plasma parameters	
Ion density	$2-4\times10^{15}$ m^{-3}
Electron temperature	2–4 eV
Debye length	~ 300 μm
Dust parameters	
Material	silica (SiO_2)
Size	2.9 μm$\pm$1.5 μm
Mass density	2200 kg/m^3
Mass	2.8×10^{-14} kg
Charge (OML)	$\sim 5000\ e$
Interparticle spacing	2×10^{-4} m
Dust density	$\sim 10^{10}-10^{11}$ m^{-3}
Video measurements	
Laser	Nd-YAG at 532 nm
Video resolution	16 μm/pixel
Uncertainty	0.43 mm

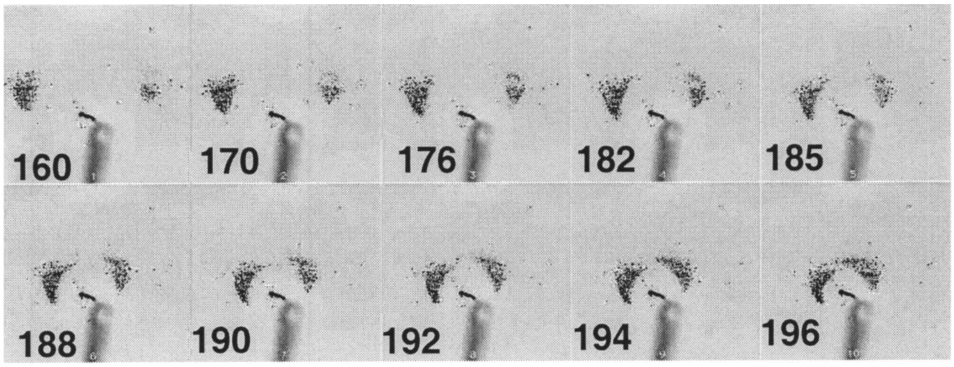

FIG. 2. Sequence of single frame video images of dust cloud with voids of various size sepending on the probe bias potential listed in the lower left corner.

follows the anode potential (213 V in this case) and is typically a few volts more positive than the anode. Thus for all of the images shown in Fig. 3 the probe is negative with respect to the plasma. As the probe voltage (relative to the plasma) is decreased from 196 to 160 V, the size of the void increases, as shown in Fig. 4.

IV. PHYSICAL MODEL AND DISCUSSION

Basic model. A model was developed to account for the dependence of the void size on probe voltage. The basis of the model is shown schematically in Fig. 5. The probe, biased at φ_b, is located at $x=0$ and the void boundary at $x=x_o$. The void is maintained by a balance of the outward Coulomb force on the dust and the inward ion drag force due to the ions that are accelerated inward by the electric field of the negative probe. As we will show, inside the void the electric force exceeds the ion drag force, i.e., $F_E > F_D$, and at the void boundary $F_E = F_D$. The electric force on the dust is given by $F_E = Q_d\, E$, where E is the inward electric field due to the probe. The ions are assumed to be mobility limited, so for the ion flow velocity we have

$$u_i = \mu_i E, \tag{1}$$

where the ion mobility is given by $\mu_i = e/m_i \nu_{in}$, $\nu_{in} = N\sigma_{in}\, v_{T,i}$ is the ion neutral collision frequency (N is the neutral density and σ_{in} is the ion neutral collision cross section). We also assume that the ions obey the continuity equation $\partial(n_i u_i)/\partial x = 0$, so that

$$n_i u_i = n_{io} u_{io} = \text{const} = \frac{I_o}{eA_p}, \tag{2}$$

where I_o is the ion current collected by the probe and A_p is the effective collecting area of the probe. The electrons are taken to be in Boltzmann equilibrium,

$$n_e = n_{eo} e^{e\varphi(x)/kT_e}, \tag{3}$$

where n_{eo} is the electron density at the edge of the void. Within the void, the dust density is zero, $n_d = 0$, so Poisson's equation for the potential φ reads

$$\varphi''(x) = -\frac{e}{\varepsilon_o}(n_i - n_e), \tag{4}$$

where $\varphi''(x) = d^2\varphi/dx^2$. If we denote the electric field at the void edge as E_o, and taking $\vec{E} = -|E|\hat{x} = -|\varphi'(x)|\hat{x}$, where $\varphi'(x) = d\varphi/dx$, then combining Eqs. (1) and (2) we have

$$\frac{n_i}{n_{io}} = \frac{E_o}{|\varphi'(x)|}. \tag{5}$$

Using Eqs. (3) and (5) in Eq. (4) we obtain the following differential equation for the potential within the void:

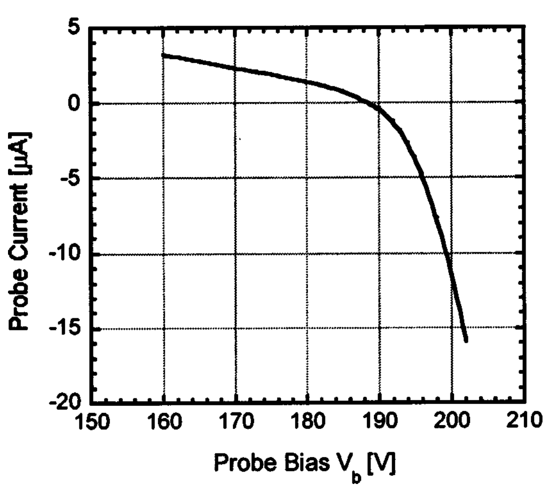

FIG. 3. Probe current-voltage characteristic. Ion current is positive.

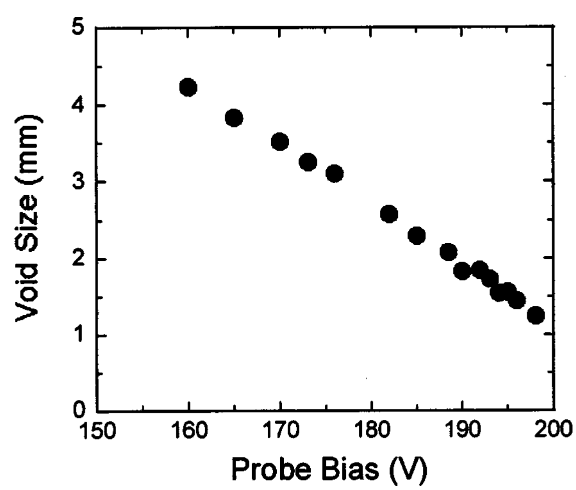

FIG. 4. Experimental measurements of the void size dependence on probe bias potential.

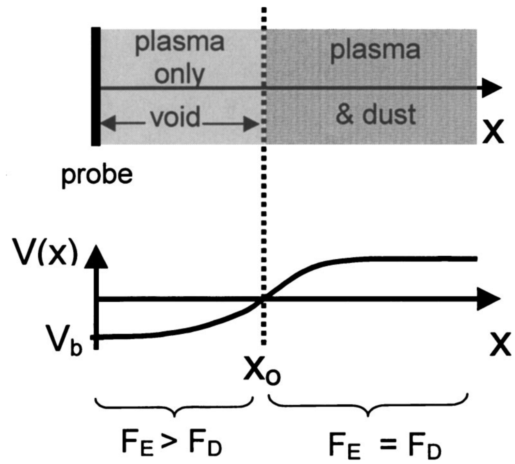

FIG. 5. Schematic of the theoretical model. The probe is located at $x=0$ and x_o denotes the void boundary. The bottom is a schematic potential distribution.

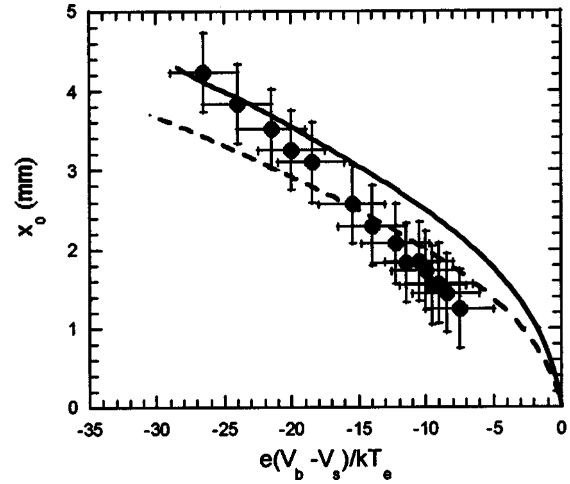

FIG. 6. Void size vs normalized probe potential relative to plasma potential. Solid dots are data taken from Fig. 5. Curves are theoretical values for $E_o=1700$ V/m (solid) and 2500 V/m (dashed). $T_e=2.0$ eV.

$$\varphi''(x)+\frac{en_{io}}{\varepsilon_o}\left(\frac{E_o}{|\varphi'(x)|}-p_o e^{e\varphi(x)/kT_e}\right)=0, \tag{6}$$

where $p_o=n_{eo}/n_{io}$.

Ion drag force. To solve Eq. (6), the value of the electric field, $E_o=|\varphi'(x_o)|$, at the void boundary is required. This is obtained from the force balance condition, $Q_dE_o(x_o)=F_D(x_o)$, where $F_D(x_o)$ is the ion drag force at the boundary. The ion drag force is usually expressed as $F_D=F_{coll}+F_{orb}$, where F_{coll} is the contribution due to momentum transfer from the ions that are collected by the particle and F_{orb} is the contribution due to ions that transfer momentum due to Coulomb scattering. When the ion flow is superthermal, $u_i\gtrsim v_{Ti}$, as we show below, the formula of Barnes *et al.*[12] can be used to calculate the ion drag force. (The ion drag force for the case of subthermal ion flow is the subject of ongoing discussion in the literature.[13]) We estimate the ion flow speed at the boundary using Eq. (2). For probe currents in the range of 1–3 μA, an effective probe area of $A_p\approx 4.4\times10^{-6}$ m^2, and an ion density of $n_{io}\approx 3\times10^{15}$ m^{-3}, we obtain a $u_{io}\approx(500-1500)$ m/s, on the order of or larger than the ion thermal velocity, $v_{Ti}=250$ m/s, so that the ions can be considered as superthermal. This is reasonable since the ions are accelerated by the relatively large electric field of the probe. The dust charge is estimated using $Q_d=4\pi\varepsilon_o a\varphi_f$, where in an argon plasma with $T_e/T_i=2$ eV/0.025 eV$=80$, the balance of electron and ion currents yields a dust floating potential $\varphi_f=-2.5\,kT_e/e$, so that with $T_e=2$ eV and a dust radius $a=1.5\,\mu$m, $|\varphi_f|=5$ V and the dust charge magnitude is $Q_d=8.3\times10^{-16}$ C $(Z\approx5200)$. From the video measurements of the interparticle spacing $d\approx2\times10^{-4}$ m, the dust density, n_d can be estimated using $n_{do}\approx(4\pi d^3/3)^{-1}$, giving $n_d\approx3\times10^{10}$ m^{-3}. From the quasineutrality condition $n_{io}=n_{eo}+Zn_{do}$, the ratio $p_o=n_{eo}/n_{io}$ is estimated to be ~0.9.

The ''Barnes formula'' for the ion drag force is

$$F_{coll}=\pi n_i m_i u_i v_s b_c^2, \tag{7}$$

where

$$b_c^2=a^2\left(1-\frac{2e\varphi_f}{m_i v_s^2}\right) \tag{8}$$

and

$$F_{orb}=4\pi n_i m_i u_i v_s b_{\pi/2}^2\Gamma, \tag{9}$$

where $v_s=(v_{Ti}^2+u_i^2)^{1/2}$ is the mean speed of the ions, v_{Ti} being the ion thermal speed, and

$$b_{\pi/2}=\frac{eQ_d}{4\pi\varepsilon_o m_i v_s^2},\quad \Gamma=\frac{1}{2}\ln\left(\frac{\lambda_{De}^2+b_{\pi/2}^2}{b_c^2+b_{\pi/2}^2}\right), \tag{10}$$

where λ_{De} is the electron Debye length, and φ_f is the floating potential of the dust particle relative to the plasma. With $T_e=2$ eV and $n_e\sim3\times10^{15}$ m^{-3}, the electron Debye length is $\lambda_{De}=2\times10^{-4}$ m. Using Eq. (8) in Eq. (7) and Eq. (10) in Eq. (9), we obtain values for the ion drag force in the range $F_D\sim(2.8-1.1)\times10^{-11}$ N for $u_i=(500-1500)$ m/s. The corresponding values for $E_o=F_D/Q_d$ are then in the range of (3400–1200) V/m. As a check on the consistency of this estimate, we compute u_i from Eq. (1) and find that $u_i\sim1000$ m/s, in reasonable agreement with values estimated from the probe current.

Comparison of theory and experiment. Equation (6) was solved numerically to determine how the void size x_o depends on the probe bias φ_b. To perform this calculation a value for $E_o[=\varphi'(x_o)]$ is chosen as one boundary condition at $x=x_o$, and the potential $\varphi(x_o)=0$ is the other boundary condition. The potential is continuous between the probe and the boundary and that the electric field is finite everywhere. Good agreement is achieved if the computed potential at $x=0$ matches the probe bias φ_b. Figure 6 is a plot of the void size vs the probe bias relative to the plasma potential normalized to the electron temperature, i.e., $e\varphi_b/kT_e=e(V_b-V_s)/kT_e$ for $kT_e=2$ eV, $P_o=0.9$ and two values of E_o. The solid dots are the experimental points taken from Fig. 5.

Our first goal in presenting the model was to account for the dependence of void size on probe bias, and the model seems to work well in this regard. A secondary goal was to

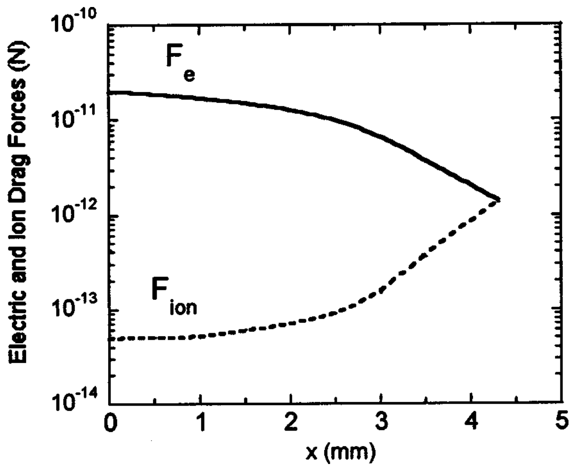

FIG. 7. Theoretical plots of the electric and ion drag forces on dust particles in the void for a void boundary at $x=4.3$ mm.

show that the balance of electric and ion drag forces could account *quantitatively* for the void size and within the uncertainties in the experimental parameters, a reasonable agreement was achieved.

Equation (6) also provides values for the electric field within the void from which the electric force and ion drag forces can be computed as functions of x inside the void. As shown in Fig. 7 the electric force increases in the direction of the probe whereas the ion drag force decreases, the two forces being equal at the void boundary.

V. SUMMARY AND CONCLUSIONS

Results of an experimental investigation of voids (dust-free regions) formed around negatively biased probes in a dusty plasma produced within a dc glow discharge have been presented. The size of the void was controlled by varying the bias on the probe. A theoretical model was developed in which a stable void is maintained by the balance of the outward Coulomb force on the dust due to the electric field of the probe and the inward ion drag force exerted on dust particles that are accelerated inward to the negatively biased probe. This model is able to account quantitatively for the dependence of the void size on probe bias. It is worthwhile to note once again in closing that the voids studied here are maintained in a stable configuration by the same forces, which, in the opposite direction, are also able to account for stable voids formed under microgravity.

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