Probe-Induced Particle Circulation in a Plasma Crystal

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A biased probe placed in an argon plasma near the sheath edge has been found to alter significantly the structure and properties of a plasma crystal, inducing particle circulation around a stable crystalline island. The origin of the island and the circulation are attributed to the formation of a nonuniform electric field in the crystal region by the probe. Variation in the space-charge flux due to the ion wake associated with the probe is also considered important, as it may alter the grain charge and the transfer of momentum to the dust particles. [S0031-9007(98)06086-4]

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Colloidal particles become charged when placed in a low-temperature radio frequency plasma, and, under certain conditions, group together in the form of stable hexagonal lattices several layers thick, with well defined intergrain separations [1–4]. This phenomenon is presently of interest due to its utility for studying basic plasma-physical processes [5,6] and solid-liquid-gas phase transitions [7–9], as the necessary experimental conditions for their existence fall within the plasma processing range, and, as such collections of dust are likely present in space plasmas [10] including the mesosphere, ionosphere, planetary rings, and nebulae. "Plasma crystals," compared with traditional colloidal suspensions, are easily modified and reach a state of equilibrium within fractions of a second. This equilibrium occurs primarily within a plasma sheath, where the electric field has strength enough to overcome the force of gravity on heavier particles. We have found that placing a positively biased electrostatic probe above a plasma crystal disrupts the crystal lattice stability, inducing an amassment of particles below the probe and initiating a convective circulation within the suspension around an exceedingly stable crystalline island—somewhat like the "eye" of a hurricane [11]. The higher the probe voltage above the local plasma potential, the smaller and more bound is the "eye" and the more violent the circulation; below the plasma potential, the particles are repelled from beneath the probe (see Fig. 1). If the probe is moved, the particles follow.

The structure that colloidal particles assume in a plasma sheath is determined by several factors: grain charge (Coulomb forces), neutral gas cooling, the number density of dust particles, and also the distribution and motion of the ions and electrons between grains [12]. Grain charge, Q, is dependent upon the local temperatures and densities of electrons and ions, T_e, T_i, n_e, and n_i, as they determine the balance of charged fluxes to the surface of a grain. These parameters vary through the sheath from the plasma to the electrode surface, as does the strength of the electric field. In general, a negative equilibrium charge of several thousand e is set up and maintained on the grains [13], which suspend just millimeters below the plasma-sheath edge. In this region, a charged particle's Coulomb field is modified by the rearrangement of space-charge around it, effectively screening its potential, for the most part over a characteristic distance, λ_D, called the Debye distance. The Debye distance is dependent both on the plasma temperatures, T_e and T_i, and on the plasma density, n_0. Although it was derived for shielding in an isotropic plasma, it may be loosely applied to shielding in a nonisotropic sheath (for lack of a comprehensive sheath-specific theory), where the ions move directionally with velocity greater than v_B, the Bohm velocity, and where the electrons stream back and forth at the driving frequency, ω. Coulomb forces between grains as such are mainly important when the intergrain separation, a, is less than a few λ_D. Other forces, some of which might be attractive, are also possible [14–16].

A probe placed within the plasma above a plasma crystal perturbs the directional flow of ions into the sheath, and modifies the local electric field [17] by

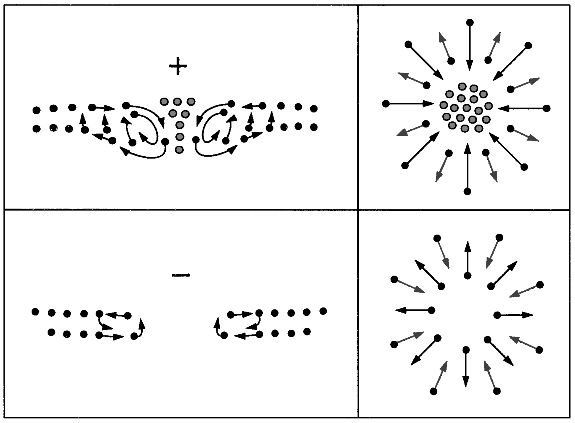

FIG. 1. General effect of a positively biased probe (top) and negatively biased probe (bottom), looking from the side (left) and from the top (right). Particle motion is indicated by the arrows, with particles in the "eye" drawn in gray. For the side views, the "+" and "−" represent the position and sign of the probe. For the top views, black arrows represent the motion of particles in the upper layers, and gray arrows describe motion in the lower layers.

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altering the time-averaged ion and electron densities in the region. The modified field induces the colloidal motion while the nonuniformity in ion flux may alter the grain charge, as well as the transfer of momentum to the grains.

In our experiments, a plasma of argon was maintained between two parallel stainless steel electrodes, 25 mm apart. The pressure was held at 0.5 torr, and the lower 16 cm diameter electrode was driven with a peak-to-peak voltage of 90 V at 13.56 MHz. Spherical 14.9 μm melamine formaldehyde (mf) particles were dropped through a 3 cm diameter hole in the 18 cm diameter grounded top electrode, into the plasma. The crystal was illuminated using a laser (HeNe 633 nm) from the side, spread into a fan by an arrangement of lenses to illuminate one or more layers of the crystal at a time. A CCD video camera fitted with a (633 nm) filter was used to view the crystal from above or from the side. The fan of laser-radiation could be tilted so that the camera was always normal to the illuminated plane.

Upon injection, the mf particles fell downward under the influence of gravity, and quickly settled from ~1–4 mm below the plasma-sheath boundary, within the sheath, where they arranged themselves into a crystalline-lattice [see Figs. 2(a) and 2(c)]. Particles were forbidden from dispersing laterally because they were confined to a potential well produced by a 2 mm thick, 40 mm diameter copper ring, placed on the lower electrode. With a particle mass of 2.65×10^{-12} kg, the force of gravity on each particle was 2.56×10^{-11} N; and with an ion density of 5×10^{15} m^{-3}, and an electron temperature of 3 eV we estimate the ion drag force to have been 3.89×10^{-12} N—a small force in comparison. Given a plasma potential of 20 V, and a sheath thickness of 6 mm, the electric field was likely less than 3000 V/m where the particles settled (if the electric field were curved), and thus the charge on each particle must have been around $50\,000e$ to balance the gravitational and ion drag forces (a value comparable to that which one may derive assuming a vacuum capacitance, $C = 4\pi\varepsilon_0 r$, and a floating potential comparable to kT_e/e in an isotropic plasma). Intergrain forces were estimated in the basic crystal first by considering a Debye-Hückel potential, $\Phi(r) = \Phi_0 \exp^{-r/\lambda_D}$. With an average intergrain separation of $r = 337$ μm, this force could have been anywhere between $F_d \approx 7.9 \times 10^{-13}$ N, where we consider only the electron Debye length, $\lambda_{De} = 180$ μm, to $F_d \approx 1.6 \times 10^{-20}$ N, when we adopt the

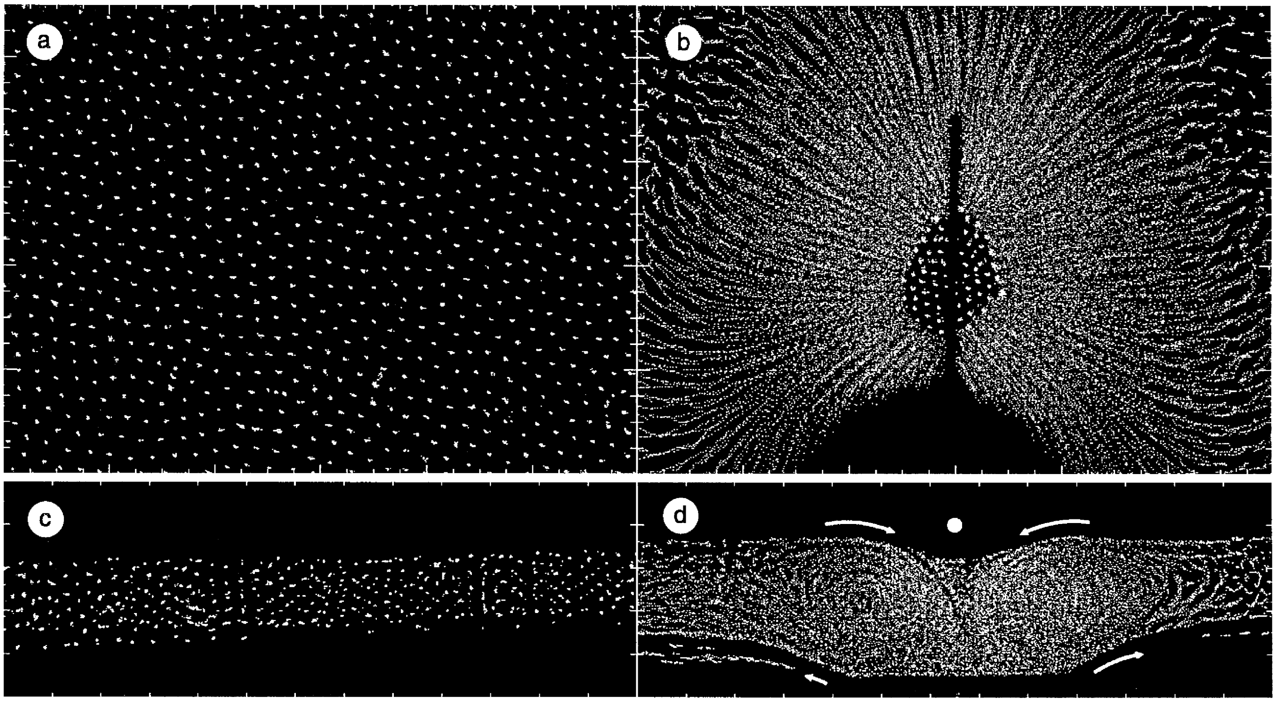

FIG. 2. One second of overlapping successive video frames of the plasma crystal (a) without a probe, viewed from above: an ordinary homogeneous plasma crystal with uniform particle separation. (b) With a probe (held at 25 V to ground, seen as a linear shadow above the "eye"), viewed from above: isotropy is broken, particles stream towards the probe, where they compress a small crystalline "eye," then fall to a lower layer and stream back the other way. [*Note:* The conditions of the plasma are identical for (a) and (b)—the only difference is the introduction of the probe. The "pressure" associated with the particles in the "eye" is clearly higher than in the ordinary plasma crystal.] (c) Without a probe, side view: a uniform thin crystal of ~6 layers. (d) With a probe (white circle), side view: the density of particles below the probe is increased, and the vortices associated with the circulation are clearly visible, as is the "eye." Circulation is such that the particles stream towards the probe in the top layers, and away in the bottom layers (see arrows). The sharp horizontal line at the base of the colloidal suspension is due to the confining ring, which extends to 2 mm above the driven electrode. The collection of particles actually extends below 2 mm, but is obscured. For the views from above, 1 major tick = 2 mm. For the side views, 1 major tick = 1 mm.

ion Debye length, $\lambda_{Di} = 17\ \mu\text{m}$, which is closer to the linearized Debye length often used in the plasma [18]. It is not certain what shielding length should apply in the sheath, and the relative contribution due to attractive forces is also unknown.

A 5 mm long tantalum probe, 0.25 mm diameter, placed $\sim$1 mm above the top layer of the plasma crystal, altered the structure drastically. Below the probe the grains gathered together densely, forming a rigid elliptical crystalline "eye," with average interparticle separation 40% smaller than in the situation without a probe, toward which the surrounding colloidal particles continually streamed. Looking from the side, the streaming particles clearly circulated down the edges of the "eye" toward the lower layers, retaining, to a large extent, their relative lattice positions as they did so, where they then moved away from the probe, counterstreaming. The vortices associated with this circulation could easily be seen—in some cases extending to the edge of the crystal; in certain other cases, countervortices appeared near the edges.

Four parameters of the experiment were varied independently to provide insights into the cause and properties of the circulation and "eye" [see Fig. 3]. Probe height, voltage, discharge power (electrode voltage), and discharge pressure were adjusted. Of these parameters, it became evident that the effective potential of the probe was the factor that most closely determined the resulting structure. Merely moving the probe closer to the crystal increased the particle amassment and circulation [see Fig. 3(a)], in accordance with the accompanied increase in the shielded field. With a fixed probe height and variable potential, the structure was the most significantly altered—the more

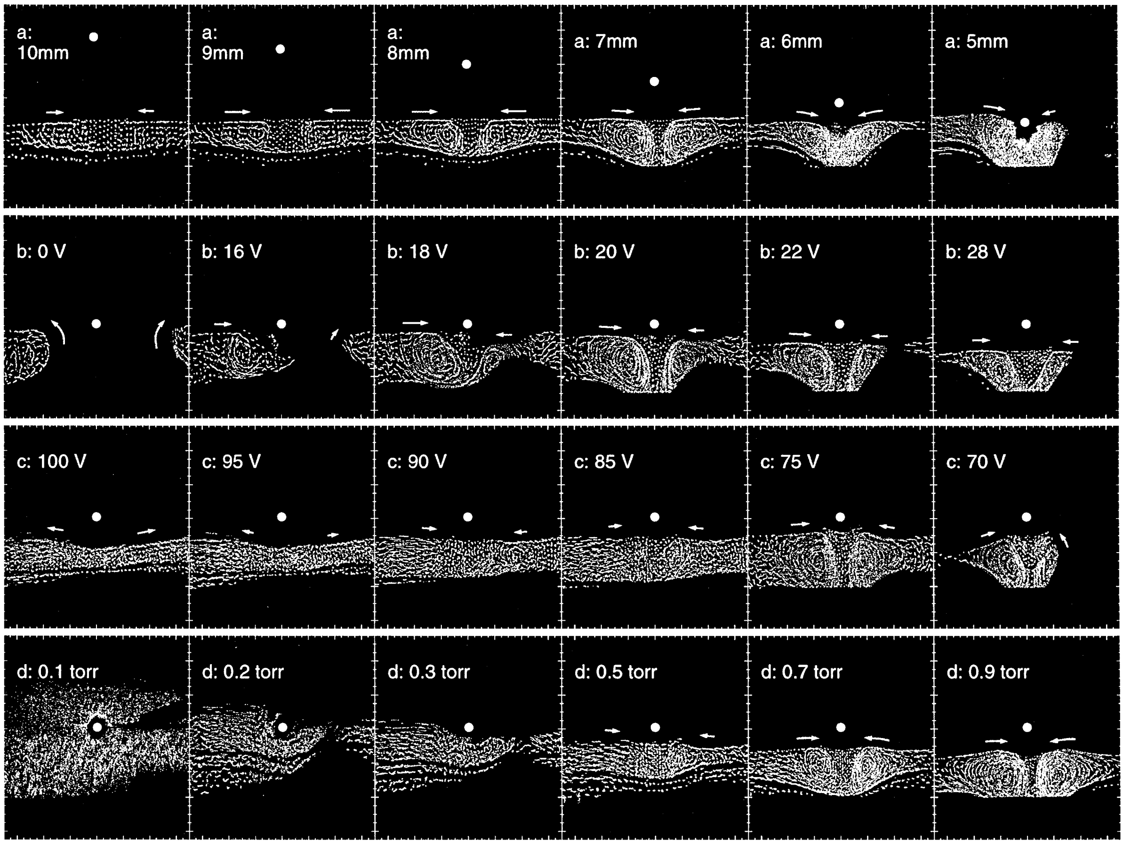

FIG. 3. 18 overlapping video frames ($\sim\frac{3}{4}$ sec), side views, major ticks = 2 mm. Experimental conditions: probe height, 6 mm; probe voltage, 30 V (to ground); electrode voltage, 90 V (peak-to-peak); pressure, 0.5 torr. For each of (a)–(d), one of the above parameters is varied, with all others kept constant: (a) Probe height: as the probe (white circle) is lowered from 10 to 5 mm, the circulation (see arrows) and amassment of particles become more prominent. (b) Probe voltage: as the probe voltage is increased, the particles change from being repelled (when the probe is below the local plasma potential) to being attracted—amassing and circulating. This occurs at $\sim$16–18 V. (c) Electrode voltage: as the power is lowered, the local plasma potential is reduced, adjusting the effective potential of the probe. At the lowest power the probe is the most positive with respect to the local plasma potential and the circulation is, accordingly, the most pronounced. (d) Pressure: pressure does not significantly affect the circulation, it mainly alters the Coulomb coupling parameter, Γ, which determines the "state" of the crystal. At 0.1 torr the particles are in an energetic gas-like state. As the pressure is raised the colloidal suspension moves lower, due to the change in sheath thickness, and the structure solidifies with ordinary circulation resuming. In all of the above plots, the horizontal asymmetry is due to the ceramic probe-casing extending towards the illuminated plane, inclined 30° to the right from the normal to this page. The shadow of the casing is visible in the lower-lefthand plot. Variation in the total number of particles between cases (a)–(d), and standard diagnostic error, account for the discrepancies between different experiments with identical experimental parameters.

positive the probe, the smaller and more tightly bound the crystalline "eye" became, with the surrounding particles streaming more quickly [see Fig. 3(b)]. Power variation, or variation in electrode voltage, had a similar effect, altering the local plasma potential, making the probe with fixed voltage to ground become effectively more positive as the power was lowered, and causing the circulation and amassment to become more pronounced [see Fig. 3(c)]. Variation in pressure was seen to have little effect on the circulation, altering more the state of the crystal, and the sheath thickness [crystal height; see Fig. 3(d)].

When the probe is positive with respect to the local plasma potential, the electric field is modified in such a way that the particles in the upper layers of the crystal experience an attractive force towards the probe, possibly by a slightly curved plasma-sheath boundary—though, given that these layers remained essentially flat in the experiments with height virtually unchanged, only the horizontal component of the electric field appears to be important. This attraction compresses the central region, forcing the particles to become more tightly bound, due, at least in part, to the inwardly directed momentum of the streaming particles in the upper layers, transmitted by electrical repulsion between grains. With 750 grains striking the "eye" every second with an average velocity of 8 mm/s in the general regime, the maximum momentum transferred per second is equivalent to a total force of 1.6×10^{-11} N. Accordingly, we can associate with the crystal a rough bulk modulus, $K = 3.5 \times 10^{-5}\ \mathrm{N/m}^2$, where $K = -\frac{\Delta P}{\Delta V/V_0}$, with height considered unchanged and ΔP equal to the force per unit area on the circumference of the "eye." This (very compressible) modulus allows us to make a rough estimate of the sound speed in our crystal, $v_s \simeq \sqrt{K/\rho} = 0.019$ m/sec, a value comparable to other measurements published [19,20]. Also, the amount by which the streaming particles reduce the intergrain distances within the "eye" suggests that the appropriate screening length in the sheath is closer to λ_{De} than to λ_{Di}, or perhaps that λ_{Di} is significantly modified in the sheath region.

The ion-wake associated with the probe and the probe sheath may also play a significant role in the formation of the "eye" and the circulation. A positive probe repels ions, producing a region below the probe with ion density slightly lower than the surrounding area, perhaps altering the local "state" of the crystal by altering the grain charge, making particles more negative. The boundary between these regions, which may appear as a phase discontinuity, might then dictate the location of any initial instability, as some particles would be unable to sustain their charge and thus would fall to lower layers where the electric field of the sheath is stronger.

When the probe is negative with respect to the plasma potential, particles are repelled from beneath the probe, and there is slight circulation in the opposite direction. This is consistent with the above conjecture that the electric field below a probe may be nonuniform with the horizontal component varying in the vertical direction.

In conclusion, we have shown that a biased probe alters the structure and properties of a plasma crystal, inducing particle amassment and circulation around a stable crystalline island. The size of the solid "eye," and the resulting circulation are attributed to a nonuniform "attraction" of the colloidal particles to the biased probe, and to an initial local instability; as well as to variations in the space-charge density due to the ion wake associated with the probe.

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