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Long-range attractive and repulsive forces in a two-dimensional complex (dusty) plasma

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An interaction of a negatively biased wire with a monolayer lattice of negatively charged particles has been studied experimentally. The particles levitated at the height of the wire in a sheath of an rf discharge. It was found that the particles close to the wire were repelled from it electrostatically, while the far particles were attracted due to the drag of the ion flow deflected toward the wire. The ion drag force prevails far from the wire, whereas the electrostatic force is stronger close to the wire. The range of the forces is one to two orders of magnitude greater than the screening length.

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The possible existence of attractive forces in a complex (dusty) plasma has been widely discussed recently. The particles immersed in a plasma charge negatively and thus repel each other electrostatically. However, it was shown both experimentally and theoretically that an attractive contribution to the interaction might also exist. Several mechanisms can provide attraction: ion focusing in the wake behind the particle [1–3], mutual ''shadowing'' of the electron and ion fluxes between the particles [4], collective interaction via ion oscillations in the plasma sheath [5], and charge-dipole interaction of polarized grains [6,7]. Here we report on an experimental study of an attraction force between the particles of a monolayer plasma crystal and a negatively biased wire.

The experiments were performed in a capacitively coupled rf discharge (Fig. 1) similar to that of Ref. [8]. The discharge chamber had a lower disk electrode and an upper ring electrode. The upper electrode and the chamber were grounded. A rf power of 4 W (measured as forward minus reverse) was applied to the lower electrode, creating a dc self-bias of -50 V. A krypton gas flow at a rate of 1 sccm maintained the working gas pressure in the chamber. Monodisperse plastic microspheres 8.9 ± 0.1 μm in diameter were levitated in the sheath above the lower electrode, forming a monolayer hexagonal lattice. They were confined radially in a bowl shaped potential formed by a rim on the outer edge of the electrode. The monolayer particle cloud was about 12 cm in diameter with a number density of 4–5 mm^{-2} and levitated at a height of $\simeq 3.5$ mm above the lower electrode. The particles were illuminated by a horizontal thin (0.2–0.3 mm) sheet of He-Ne laser light and imaged by a top view digital video camera at 160 frames/s.

A horizontal tungsten wire 0.1 mm in diameter was placed exactly at the height of the particles roughly half way between the center and the edge of the electrode. A similar wire configuration was previously used in a different apparatus in the experiments of Refs. [9,10]. The wire was biased negatively so that it repelled the particles electrostatically. The distance between the wire and the first row of the grains was $\simeq 6$ mm, as seen in Fig. 2(a). When the bias voltage was made more negative, the rows of particles close to the wire were repelled as expected. What was unexpected was the observation that the particles far from the wire (at a distance of about 16–20 mm) moved toward the wire, indicating an attractive force. The particle levitation height always remained the same within ± 50 μm or better.

A sinusoidal (10 V peak-to-peak) voltage at 1 Hz frequency was then applied to the wire in addition to the bias. Since the plasma potential was $\simeq +11$ V, the wire was always negative with respect to the plasma.

The particle positions were identified and traced from one frame to another in order to reconstruct the particle trajectories. Then the trajectories were averaged in 46 narrow bins

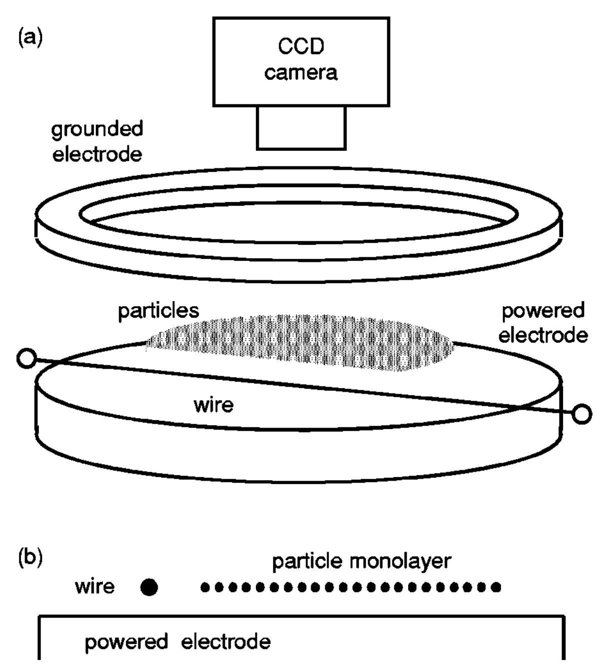

FIG. 1. Sketch of the apparatus. (a) Oblique view. Spherical particles charge negatively and form a monolayer levitating in the plasma sheath above the lower electrode. (b) Side view. The wire is placed at the same height as the particles.

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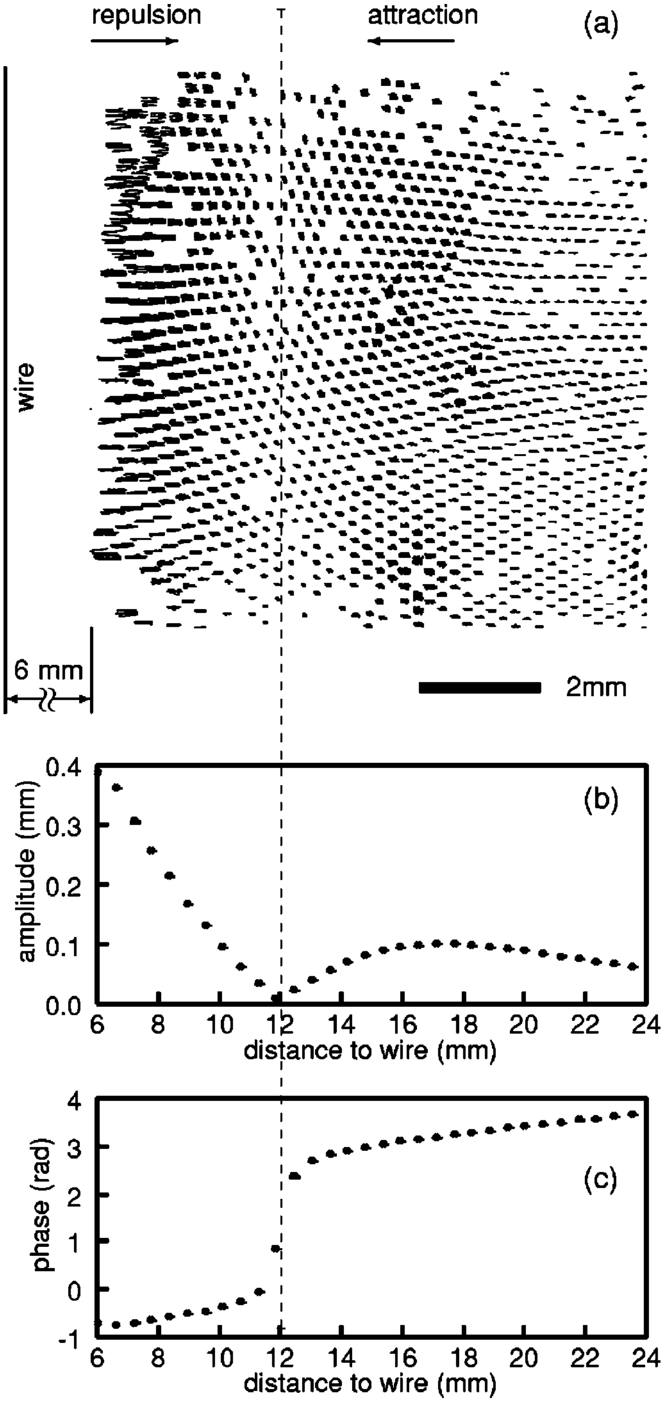

FIG. 2. (a) Top view of the particle cloud interacting with a negatively biased wire. When the far particles are attracted by the deflected ion drag, the near particles are repelled by the electrostatic force that prevails over the saturated ion drag. The gas pressure is 6.5 Pa, the dc wire bias is -40 V, the peak-to-peak excitation voltage is 10 V, and the excitation frequency is 1 Hz. (b) Amplitude of the particle oscillations. The amplitude has a minimum at $\simeq 12$ mm. (c) Phase of the particle oscillations. At $\simeq 12$ mm, the phase of the motion abruptly changes by $\simeq \pi$.

parallel to the wire and Fourier analyzed to get the amplitude and phase of the first harmonic of the grain oscillations [see Figs. 2(b) and 2(c)]. The second and higher harmonics had

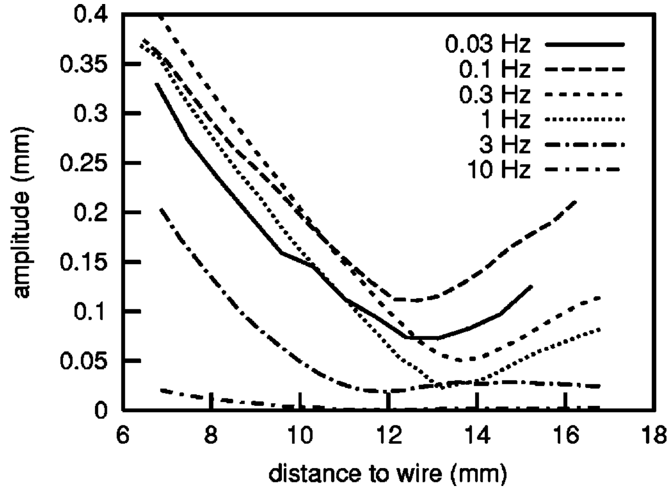

FIG. 3. Amplitude of the particle oscillations for different excitation frequencies taken at 7 Pa gas pressure, -20 V dc wire bias, and 10 V peak-to-peak excitation voltage. The amplitude has a minimum at 12.5 mm$\pm 10\%$ from the wire, which is the same for all frequencies. At the frequencies greater than approximately 3 Hz, the motion amplitude rapidly decreases.

negligible amplitude. This procedure was the same as in Refs. [8,10]. The amplitude, shown in Fig. 2(b) is the largest in the first row of particles and decreases as the distance from the wire increases. It reaches a minimum at $\simeq 12$ mm and rises again while the phase changes abruptly by $\simeq \pi$ [Fig. 2(c)], indicating oscillations with opposite phase at distances $\gtrsim 12$ mm. The amplitude finally decays to zero at $\gtrsim 30$ cm.

In order to check how the observed effect depends on the excitation frequency and the wire dc bias, we varied these two parameters. Figure 3 shows that the position of the minimum is the same at all frequencies, 12.5 mm$\pm 10\%$. At low frequencies (0.03–1 Hz), the amplitude of the particle motion is practically independent of the frequency. At higher frequencies (3 and 10 Hz), the amplitude decreases rapidly. If the dc bias is more negative (Fig. 4), the position of the amplitude minimum shifts farther away from the wire and becomes less distinct, finally vanishing at $\simeq -80$ V. We also found that the amplitude minimum shifts closer to the wire at higher pressures (20 Pa) and moves away at lower pressures (2.5 Pa). Also, there is practically no dependence on rf power.

The total excitation force acting on the particles was derived from the wave equation for a one-dimensional inhomogeneous particle lattice. Assuming all the time dependent variables to be proportional to $e^{i\omega t}$ and omitting this factor, we get

$$\omega^2 u - 2i\gamma\omega u + \Delta \frac{d}{dx}\left(\frac{Q^2 e^{-\Delta/\lambda}}{M\Delta^2}\left[1+\left(1+\frac{\Delta}{\lambda}\right)^2\right]\frac{du}{dx}\right) = -\frac{F_{\rm tot}}{M}, \qquad (1)$$

where ω is the excitation frequency, γ is the damping due to neutral drag, x is the distance from the wire, $u(x)$

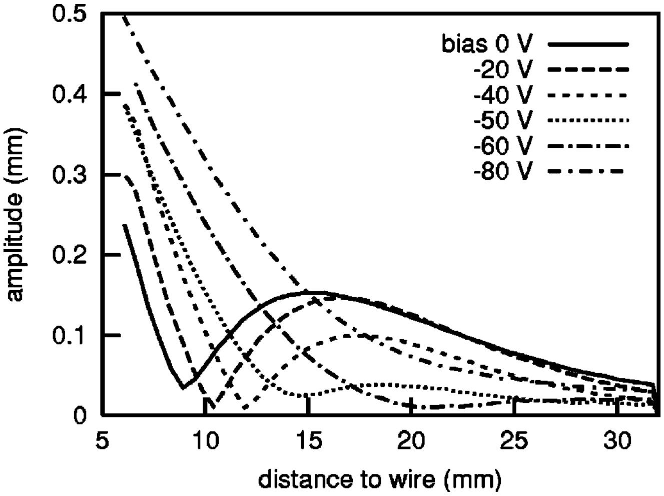

FIG. 4. Amplitude of the particle oscillations for different dc wire biases taken at 6.5 Pa gas pressure, 1 Hz excitation frequency, and 10 V peak-to-peak excitation voltage. As the negative bias increases, the amplitude minimum moves farther from the wire and vanishes.

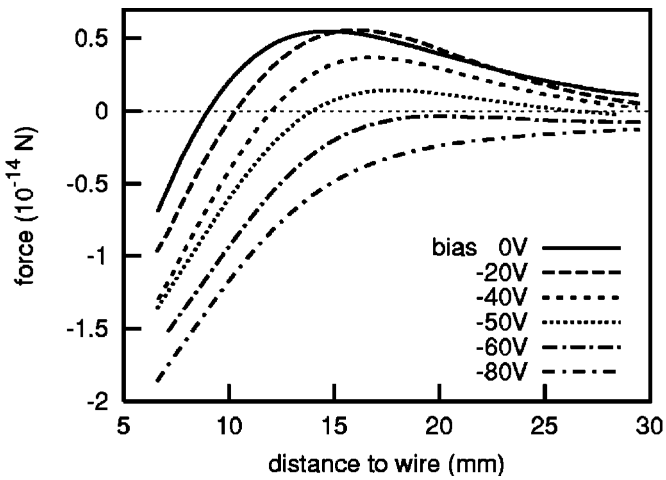

FIG. 5. Total force acting on the particles in the direction away from the wire. It changes from repulsive (negative) to attractive and then decays as the distance to the wire increases. It was calculated using Eq. (1) and the amplitude and phase data for the conditions of Fig. 4. The repulsion is due to the electrostatic force and the attraction is due to the drag of the ion flow deflected in the wire field.

$=u_0(x)e^{i\varphi(x)}$ is the particle displacement in the x direction with an amplitude u_0 and phase φ, $F_{\rm tot}(x)$ is the horizontal component of the total excitation force from the wire, $\Delta(x)$ is the time average particle separation in the lattice, M and $Q=eZ$ are the particle mass and charge, respectively, and λ is the screening length (which is of the order of the electron Debye length).

In order to calculate the excitation force, we used the amplitude u_0 and the phase φ measured for different experimental parameters. We approximated the phase dependence with a straight line and changed the sign of the amplitude where the phase jumped by π. This eliminates the phase error near the jump due to the small amplitude of the particle motion. (This error could produce a sharp peak in a narrow region around the amplitude minimum). Substituting u_0 and φ for the experimental conditions of Fig. 2 into Eq. (1), we obtain the total force on a particle, $F_{\rm tot}(x)$, shown in Fig. 5. The force is repulsive close to the wire and attractive far from it. For the conditions of our experiment ($\omega/2\pi=1$ Hz, $\gamma=5\ \ {\rm s}^{-1}$), the first two terms in Eq. (1) are of similar magnitude and the third term is negligible (less than the amplitude measurement error). This makes our result insensitive to the exact charge of the particles, which is difficult to measure anyway. It is worth mentioning that the force has a surprisingly long range (10–30 cm), which is much longer than the screening length (less than 1 mm).

We attribute the attractive component of the force acting on the particles to the drag of the ion flow deflected in the field of the wire. In our experiment, the ions normally flow downward perpendicular to the (horizontal) particle monolayer. When the wire is biased negatively, it also attracts ions and their trajectories curve toward it. The horizontal component of the ion flow drags the vertically confined particles toward the wire, resulting in an ‘‘attractive’’ force on the particles. The total force is the sum of the electrostatic (repulsive) and ion drag (attractive) forces, $F_{\rm tot}=F_E-F_{id}$. The electrostatic force is $F_E=eZE_x$, where E_x is the horizontal electric field of the wire. The ion drag force in the horizontal direction is [11]

$$F_{id}=m_in_iu_xu_\Sigma\pi a^2\left[1+\frac{2\alpha}{M_\Sigma^2}+\frac{4\alpha^2}{M_\Sigma^4}\Gamma\right], \qquad (2)$$

where m_i and n_i are the ion mass and number density, respectively, a is the particle radius, $\alpha=e^2Z/aT_e$ is the normalized particle charge (usually about a few), and T_e is the electron temperature. The total ion velocity is $u_\Sigma=\sqrt{u_x^2+u_z^2}$, where u_x and u_z are the horizontal and vertical components of the ion velocity, respectively, and $M_\Sigma^2=u_\Sigma^2/c_s^2\equiv M_x^2+M_z^2$ is the corresponding ion Mach number normalized to the ion acoustic velocity $c_s=\sqrt{T_e/m_i}$. The ion drag force (2) is a sum of the collection and orbital parts [the last term in Eq. (2)] that is determined by the Coulomb logarithm for the ion-dust elastic collisions, Γ, integrated over the interval from the ion collection impact parameter, $b_{\rm c}=a\sqrt{1+2\alpha/M_\Sigma^2}$, to the screening length λ. The Coulomb logarithm is

$$\Gamma(M_\Sigma)=\frac{1}{2}\ln\left[\frac{(\lambda/a)^2+4\alpha^2/M_\Sigma^4}{1+2\gamma/M_\Sigma^2+4\alpha^2/M_\Sigma^4}\right].$$

If $b_{\rm c}$ exceeds λ, the orbital force equals zero ($\Gamma=0$).

Let us evaluate the ratio of the ion drag to the electrostatic force. For our experimental conditions the ion mean free path is $\simeq 0.3$ mm, much less than the system dimensions. Therefore, the ion drift velocity (or ambipolar diffusion speed) far away from the wire is given approximately by $eE_x\sim m_i\nu_{in}(u_\Sigma)u_x$. The ion-neutral collision frequency is $\nu_{in}=\sigma_{in}(u_\Sigma)n_nu_\Sigma$, where σ_{in} is the ion-neutral collision cross section and n_n is the number density of the neutrals. Substituting for E_x, we obtain for the electrostatic force

$F_E = eZE_x \sim Zmn_n u_x u_\Sigma \sigma_{in}(u_\Sigma)$, and thus the ratio of the ion drag to the electrostatic force is

$$\frac{F_{id}}{F_E} \sim \frac{q}{Z} \frac{\pi a^2}{\sigma_{in}} \left[1 + \frac{2\alpha}{M_\Sigma^2} + \frac{4\alpha^2}{M_\Sigma^4} \Gamma \right], \qquad (3)$$

where $q = n_i / n_n$ is the ionization fraction. Unfortunately, the spatial distribution of the wire electric field E_x in the sheath [and therefore the dependence $M_\Sigma(E_x)$] is unknown, but a qualitative conclusion can be made. Far from the wire its electric field is weak and the ion velocity is mostly determined by the (vertical) sheath electric field. Thus, $u_z \gg u_x$ and $M_\Sigma \simeq M_z$ is constant at a large distance. However, if the horizontal distance to the wire (which has its own sheath) is sufficiently small, the ions drifting to the lower electrode are affected by the strong long-range electric field of the wire and could gain rather high velocity towards it. Assuming the vertical drift velocity to be relatively small $M_z \lesssim 1$, we can have $u_z \lesssim u_x$ and thus $M_\Sigma \simeq M_x \gtrsim M_z$ close to the wire. For our conditions, one can evaluate $Z \sim 10^4$, $q \sim 10^{-6}$, $\alpha \sim 6$, and $\sigma_{in} \sim 3 \times 10^{-15}$ cm^2. Let us suppose that $M_x \sim 1$ close to the wire and $M_z \sim 0.3$. Therefore, $\Gamma \sim 3$ and we finally get from Eq. (3) $F_{id}/F_E \sim 0.1$ at small distances, and $F_{id}/F_E \sim 10$ far from the wire. Hence, the ion drag might significantly exceed the electrostatic force at large distances, which results in the attraction of the particles (see Fig. 5). Close to the wire the electrostatic interaction is stronger, so that the total force F_{tot} is repulsive. As the bias voltage on the wire becomes more negative, the point where the total force is zero shifts away from the wire as well as the minimum of the motion amplitude seen in Fig. 4.

In this paper we reported an experimental study of the interaction of a biased wire with a monolayer hexagonal dust lattice. It was found that the interaction has a long range (one to two orders of magnitude longer than a screening length). The interaction is a sum of two forces: the electrostatic force and the ion drag of the deflected ion flow. The repulsive electrostatic force prevails at short distances, while the attractive ion drag force prevails far from the wire.

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