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Kinetics of flowing plasma around two dust grains

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Abstract. The characteristics of plasma particle kinetics in the presence of ions flowing around two stationary dust grains aligned in the direction of the flow are studied using a three-dimensional molecular dynamics simulation code. The dynamics of plasma electrons and ions as well as the charging process of the dust grain are simulated self-consistently. Distributions of electron and ion number densities, and the electrostatic plasma potential are obtained for various intergrain distances, including those much less, of the order of, and more than the plasma electron Debye length.

The fundamental question of importance for the understanding of processes involving the formation and evolution of various self-organized structures such as colloidal crystals [1] in a complex “dusty" plasma, is the interaction of dust grains with themselves and the surrounding plasma. Since in a typical laboratory discharge dust particles are negatively charged and levitate in the sheath or pre-sheath region under the balance of gravitational, electrostatic (due to the sheath electric field) and plasma (such as the ion drag) forces, these interactions involve collective processes associated with the flowing plasma. The ion flow, providing a direct dragging influence, is also responsible for the generation of associated collective plasma processes such as the formation of the plasma wake [2, 3, 4]. The latter can strongly modify the interactions of dust grains between themselves and with the plasma; in particular, supporting a Cooper-pairing-like attraction of grains of the same sign of the charge [2, 5].

The modeling of the plasma response to the presence of colloidal dust particles in the presence of plasma flows is usually performed by particle-in-cell methods [6, 7]. The first report on the self-consistent three-dimensional molecular dynamics simulation [8] of plasma kinetics around one stationary dust grain demonstrated strong ion focusing, with the ion density in the focus exceeding the ion density in the flow by a factor of 5-6. Thus the charging of the second dust grain located behind the first one, will be strongly affected by this (highly nonlinear) effect. Here, we present the results of a self-consistent molecular dynamics (MD) three-dimensional (3D) simulation of the kinetics of plasma electrons and ions around two aligned (in the direction of the flow) dust grains, taking into account the dust charging and the supersonic ion flow.

The details of the technique used for the numerical integration of the equations of multi-particle dynamics are described in [8, 9]. The numerical method used involves simulation of the time evolution of the fully ionized ($Z_i = 1$, i.e. the ions are single charged) argon plasma consisting of N_i positively (ions) and N_e negatively (electrons) charged particles confined in a simulation box $0 < x < L_x$, $0 < y < L_y$, $0 < z < L_z$, together with two macroscopic absorbing grains (dust particles), each of radius R, with infinite masses and initial (negative) charges $Q_{1,2} = Z_{d1,2}e$, where e is the electron charge. The ions are introduced in the system at the plane $x = 0$ as a uniform flow in the x-direction with the Mach number $M = V_0/V_s$ ($V_0 > 0$) and the temperature T_i, where $V_s = (T_e/m_i)^{1/2}$ is the speed of the collisionless sound waves, T_e is the temperature of plasma electrons (all temperatures are in energy units, i.e., Boltzmann's constant is unity), and m_i is the ion mass; at $x = L_x$ the ions are removed from the system. The walls bounding the simulation region are elastic for electrons; for ions, they are elastic in the y and z directions, i.e. at $y = (0, L_y)$ and $z = (0, L_z)$. The dust grains are placed at $x = x_0 = L_x/4$ and $x = x_0 + D$, such that D is the distance between the grains, with the other coordinates being $y = y_0 = L_y/2$ and $z = z_0 = L_z/2$; thus the grains are aligned in the direction parallel to the ion flow. The equations of motion are solved by the Runge-Kutta method of the fourth order with an automatically chosen time step.

For the characteristic lengths we have (for most calculations unless otherwise specified) $L_x/2 = L_y = L_z = 20 \cdot h_x$, with the characteristic grid step in the presented results $h_x = 2h_y = 2h_z = 0.5375\mu$m. For the given values, the characteristic lengths in the plasma are: electron Debye length $\lambda_{De} = 5.256\mu$m and ion Debye length $r_{Di} = 0.831\mu$m. The ion number density is $n_i = 2 \times 10^{12}$ cm^{-3}, and hence the ion Debye length in term of the average ion-ion distance $r_{Di} n_i^{1/3} = 1.06$; the number of ions in the ion Debye sphere is approximately 5, and we can consider the system as an ideal plasma. The simulated time of the physical processes is 9.2×10^{-9}s which should be compared with the inverse ion plasma frequency $\tau_{pi} = 1/\omega_{pi} = 3.4 \times 10^{-9}$s. The speed of the ion flow corresponds to the Mach number $M = 2$. The Landau length for scattering of the ions on the dust particle by the angle $\pi/2$ is $r_L \equiv Z_d e^2/m_i V_0^2$; for our parameters $r_L \approx 0.5\mu$m (for the dimensionless charge $Z_d = 1400$).

TABLE 1. The charges on the dust grains depending on the distance between them.

Distance D	Charge Q_1	Charge Q_2
$0.06L_x = 0.25\lambda_{De}$	1390	840
$0.10L_x = 0.41\lambda_{De}$	1420	860
$0.15L_x = 0.62\lambda_{De}$	1390	840
$0.20L_x = 0.82\lambda_{De}$	1430	1010
$0.25L_x = 1.03\lambda_{De}$	1470	1040
$0.35L_x = 1.45\lambda_{De}$	1500	1080
$0.40L_x = 1.64\lambda_{De}$	1410	1020
$0.50L_x = 2.05\lambda_{De}$	1480	1130
$0.60L_x = 2.46\lambda_{De}$	1450	1230
$0.65L_x = 2.67\lambda_{De}$	1430	1180
$1.00L_x = 4.10\lambda_{De}$	1460	1200
∞	1450	n/a

Table 1 demonstrates the dependence of the charges accumulated on the dust grains as functions of the intergrain distance. We see that when the particles are very close to each other, their charges are influenced by the presence of the other particle. This influence is especially strong for the second (i.e., downstream) particle; its charge is significantly (typically, 40%) less than the charge of an isolated particle (see the last line of the table). As soon as the distance between the particles is increased, the second charge exhibits a noticeable increase; it is interesting to note that the first charge is increased, too, although by a lesser value. We also see that when the interparticle separation becomes of the order of the electron Debye length, the increase of the charge of the first particle stops; on the other hand, the increase of the charge accumulated on the second particle located downstream continues to grow until the distance is of the order of two electron Debye lengths. We can attribute this phenomenon to the fact that the ion wake of the first particle is spreading at distances significantly exceeding the electron Debye length; on the other hand, the influence of the second (i.e., downstream) particle on the charge of the first one in the simplest approximation is limited to distances of the order of the electron Debye length. Note that other charge variations express fluctuations always present in the particle charges as well as the plasma parameters, see also [7]. The charge of the second particle, at the considered distances (up to four electron Debye lengths), is always less than the charge of the first particle.

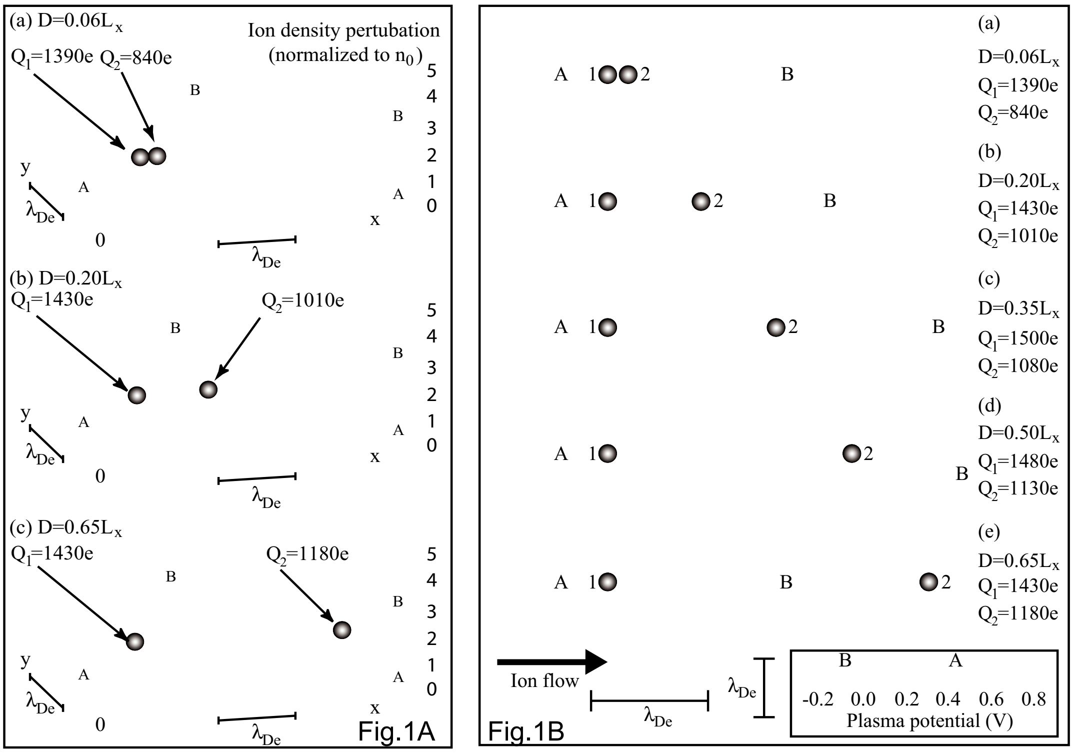

FIGURE 1. Surface plot of the normalized ion density, showing ion focusing, for three different separations D between two dust grains (Fig. 1A) and contour plot of the plasma potential (Fig. 1B) for five different distances between the grains. The plots are presented in the greyscale topograph style; in Fig. 1A regions A correspond to the normalized (to the unperturbed ion density n_{i0}) ion densities below 1, and regions B correspond to the normalized ion densities above 1; in Fig. 1B regions A correspond to the repulsive potential, and regions B - to the attractive potential for the negative particles. The distances are given in the units of the total length of the simulation box in the direction of the ion flow $L_x \approx 4.1\lambda_{De}$ used in the calculation; the physical distance corresponding to the electron Debye length λ_{De} is also presented. Note that the potential well (Fig. 1B, region B) is formed behind the dust grain and starts to form between the grains when the separation exceeds the electron Debye length.

In Fig. 1A, we present surface plots of the ion density n_i normalized to $n_{i0} = N_i/L_xL_yL_z$, for three different distances between the charged colloidal particles: the first one (Fig. 1A(a)) corresponds to the short distance of $D = 0.25\lambda_{De}$, the second one

(Fig. 1A(b)) is of order the electron Debye length: $D = 0.82\lambda_{De}$, and the third one (Fig. 1A(c)) corresponds to the relatively large distance exceeding the electron Debye length: $D = 2.7\lambda_{De}$. For better visualization, parts of the simulation volume where $n_i/n_{i0} < 1$ and $n_i/n_{i0} > 1$, respectively, are presented in the (greyscale) topograph style, i.e. part A is for $n_i/n_{i0} < 1$ and part B is for $n_i/n_{i0} > 1$, so that the change from lower (with respect to n_{i0}) to higher densities is clearly seen. A strong ion focus is formed at the distance of a fraction of the electron Debye length behind the first dust grain; depending on the position of the second grain, the wake maximums are either combined, see Fig. 1A(a), or clearly separated, see Fig. 1A(c).

Fig. 1B gives the contour plot of the plasma potential (in V) for five different distances between the grains: (a) corresponds to a short distance which is much less than the electron Debye length, $D = 0.25\lambda_{De}$, (b) is for the increased distance $D = 0.82\lambda_{De}$, (c) is for $D = 1.43\lambda_{De}$, (d) is for $D = 2.1\lambda_{De}$, and (e) is for a distance relatively large with respect to the electron Debye length $D = 2.7\lambda_{De}$. We see that for short distances (Figs. 1B(a) and 1B(b)), the wake is practically corresponding to that of one combined particle; on the other hand, for distances of the order of, Fig. 1B(d), or more than, Fig. 1B(e), the electron Debye length, the formation the wake can be seen after the first grain, i.e. before the second one. The characteristic distance for the region of the attractive potential to appear in the x-direction is of the order of the electron Debye length.

To conclude, we have self-consistently simulated from first principles by MD calculations the plasma kinetics around two charged macroscopic bodies (dust grains) in the presence of an ion flow. We have demonstrated that the ion wake strongly influences the charge of the second grain located downstream with respect to the first particle. The influence of the downstream particle on the charge of the particle located upstream is limited to distances of the order of the electron Debye length. The charge of the second particle, for the distances considered (up to four electron Debye lengths), is always less than the charge of the first particle, and this is attributed to the long-range influence of the plasma wake.

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