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Nature of the force field in plasma wakes

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Plasma wakes are relevant in a number of applications. Here the attention is focused on complex plasmas formed by dust particles suspended in partially inonized plasmas. Two forces are observed to contribute significantly in a wake created by a suspended particle immersed in a plasma with supersonic flowing ions. First, the well-known electrostatic force caused by the macroscopic electric field produced by charge accumulation in the wake. Second, the ion flow field is distorted in the wake and creates a flow-induced force caused by the momentum transfer from ion particles. The first force (electrostatic) has been proposed to cause the alignment of dust particles observed in experimental conditions in complex plasmas. The present article provides evidence that actually the second force (ion flow), not previously considered, is a more likely candidate that can explain the alignment observed in experiments.

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I. INTRODUCTION

Wake fields are a classic topic in plasma physics. Their relevance range from fusion applications to satellite technology. Recently, however, a large number of studies on wakes have been published for application to the area of complex plasmas.

Complex plasmas are systems composed of suspended solid particles (often called dust particles, therefore giving to the overall system the name *dusty plasma*) immersed in a plasma. One remarkable feature of such systems is that the suspended dust particles tend to be located in regions where the ions flow at near-sonic or supersonic speed.

It is expected that under such experimental conditions the ion flow creates wake fields downstream of each dust particle reached by it. It has been suggested that the presence of wakes can produce aligning forces among suspended particles so that a particle upstream can align a particle located downstream (but not vice versa) [1–6]. The wake effect is to date the only possible explanation for such an asymmetric behavior observed in experiments [7].

So if experiments strongly support the presence of plasma wakes in complex plasmas, the exact nature of the force within plasma wakes requires further investigation.

Previous works [1–6] have focused on the effect of electrostatic fields. It is well known that plasma wakes have a potential structure characterized by a Mach cone, inside which the potential has an oscillatory nature in space which includes the presence of attractive electrostatic potential energy wells.

However, in the present article, I propose that, besides the electrostatic wake force, another relevant effect of the wake field is the creation of a ion flow field that produces forces by means of momentum transfer by charging collisions and by Coulomb scattering (i.e., the ion drag force). Such a flow field includes horizontal components that are responsible for a horizontal force that can act to align dust particles in complex plasmas. I will show that the strength of such ion flow force is greater than that of the electrostatic force.

The mechanism proposed here can be explained in simple fluid terms. A negatively charged dust particle immersed in flowing ions acts as an electrostatic lens, creating a downstream converging ion flow field by virtue of the focusing effect. As a consequence, the ion wind downstream includes a horizontal component directed toward the ideal axis emerging from the center of the dust particle creating the wake and aligned with the flow. A second dust particle located downstream would be at rest only directly below the first particle, if it were to be located off axis, the ion wind would push it towards the axis.

Note that the vertical distance between the particles along the ion flow is set, instead, by the equilibrium of a number of forces [8–10]; in the present paper the attention is focused solely on the horizontal alignment.

The relevance of the ion drag force to dust motion in complex plasmas has long been recognized [9,11]. In a recent experimental study, it has been also suggested that ion drag forces can effectively become attractive [12]. However, to my knowledge, the present article is the first instance where it is proposed that plasma wakes can distort the flow, in turn creating a horizontal ion drag force that can align dust particles in complex plasmas.

II. PLASMA WAKES

The goal of the present article is to investigate the force field generated by the wake produced when a ion flow engulfs a particle with size much smaller than the electron Debye length (i.e., a dust particle).

To investigate the issue, I shall consider a dust particle immersed in a plasma with flowing ions, for conditions typical of the sheath region of glow discharges where complex plasmas form.

To study this configuration, I shall make no approximations and investigate it fully with the PIC simulation package described in Ref. [13]. The simulation package uses computational particles to solve the Vlasov-Poisson model for each

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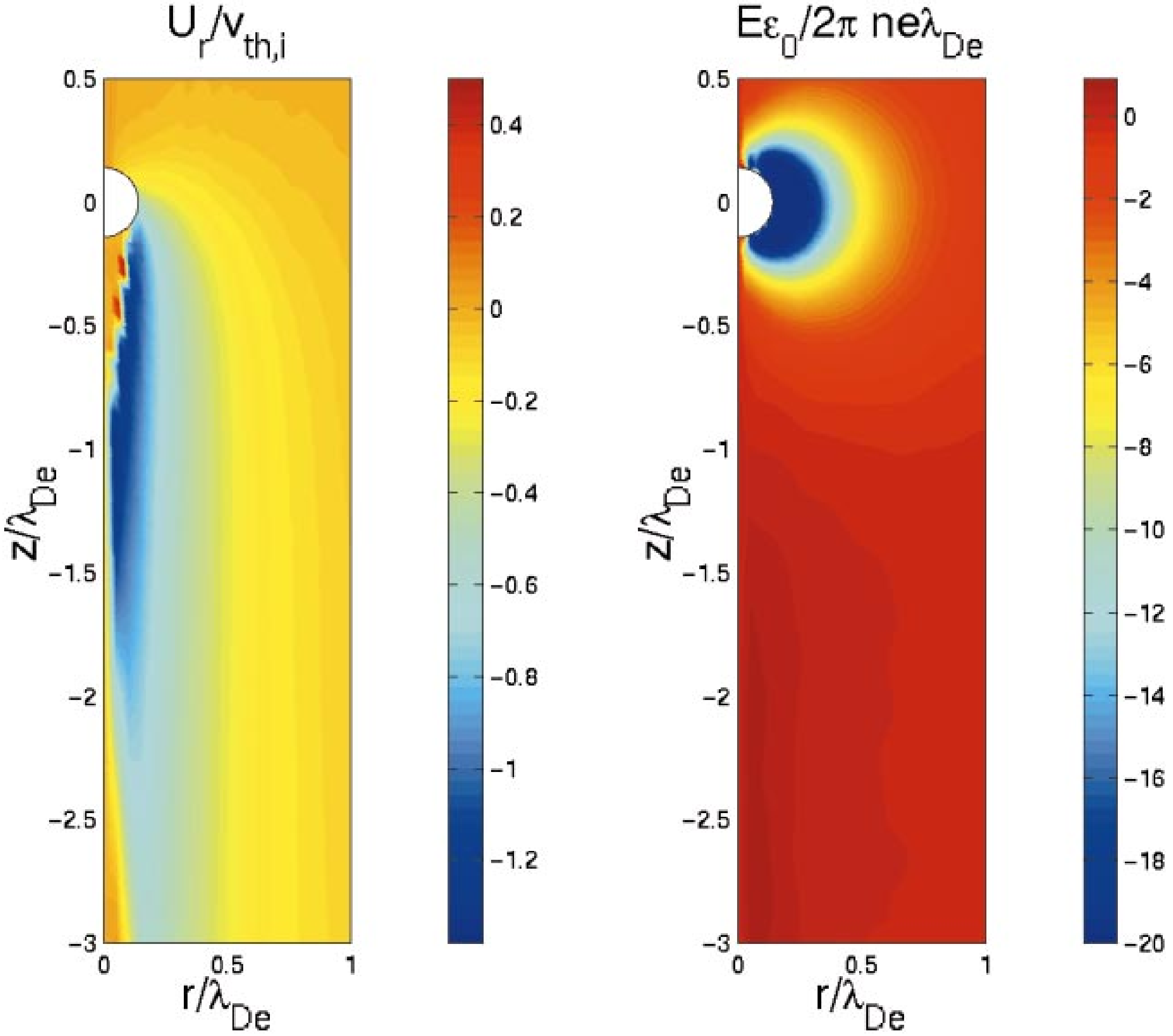

FIG. 1. (Color) Horizontal (radial, using a cylindrical coordinate system) velocity field and horizontal electric field downstream of a dust particle immersed in a plasma with an ion flow having upstream Mach number $M = 1.5$, directed downward.

species. The dust particle charging is treated self-consistently, exactly as it would happen physically in a real experiment. Initially the dust particle is neutral and charges up as the plasma particles hit its surface and are captured. As the dust particle charges, the surrounding plasma adjusts itself self-consistently. The results below are relative to the end of the simulation, when the system has reached equilibrium and the dust particle is fully charged ($\omega_{pi}t = 300$).

The initial configuration is characterized by a hydrogen plasma with the following parameters: electron temperature, $T_e = 2\text{eV}$; temperature ratio in the sheath $T_i/T_e = 0.1$; plasma density $n = 10^{16}\,\text{m}^{-3}$. Furthermore, the ions are assumed to have an upstream unperturbed velocity with a Mach number $M = U/v_B = 1.5$ (where U is the unperturbed upstream ion flow velocity and v_B is the Bohm velocity) directed downward in the figures below.

The dust particle is spherical with radius $r_d = 0.13\lambda_{\text{De}}$ and with mass density: $\rho_d = 2.2\times 10^3\ \ \text{kg/m}^3$. The geometry used is fully 3D, but the assumption is made of azimuthal symmetry.

At equilibrium the charge on the dust reaches a value of $q/e = -2.8\times 10^4$. For comparison, the orbital motion limited (OML) theory would predict a charge of $q/e = -3.9\times 10^4$ for the same conditions considered above and including the effect of the ion flow [14]. The agreement is good considering the limitations of the OML theory regarding the large size of the dust particle considered here [15,16].

The simulation results, besides charging, present the full description of the plasma field in the wake. Figure 1 shows the horizontal (i.e., radial, given the assumption of azimuthal symmetry) component of the ion flow velocity and of the electrostatic field in the wake produced by the dust particle. The wake is clearly characterized by an electric field as discussed in several previous works [1–6] but also by a distorted ion flow field, not previously considered. Note that the typical oscillatory nature of the wake is present on longer

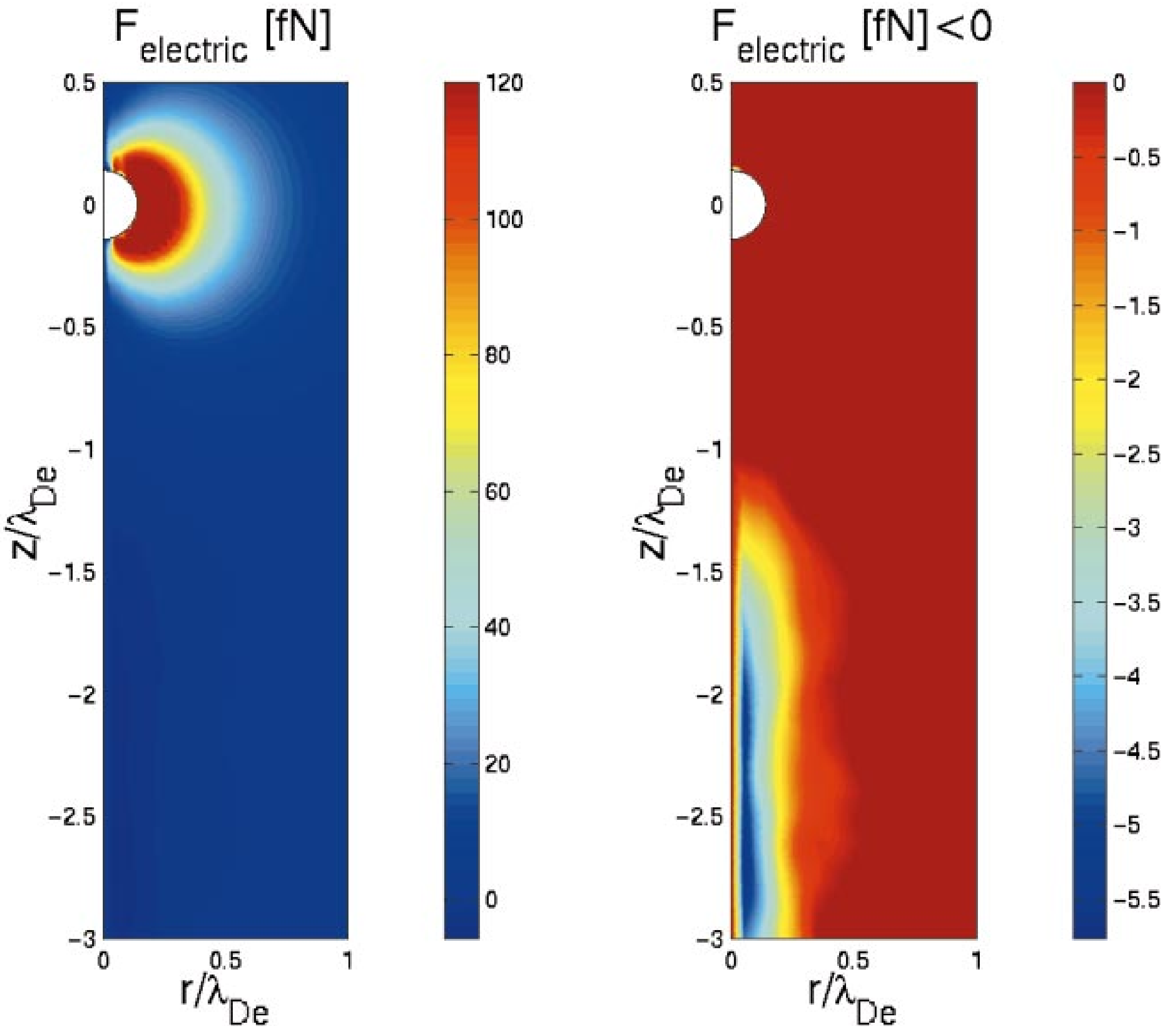

FIG. 2. (Color) Horizontal component of the electrostatic force, expressed in femtonewton (fN), downstream of a dust particle immersed in a plasma with an ion flow having upstream Mach number $M=1.5$, directed downward. The left panel shows the complete force field, the right panel shows only negative values (all positive values are cut off at zero).

length scale than shown in Fig. 1. However, the typical interparticle distance in the systems of interest here is about $d\sim\lambda_{\rm De}$; it is, therefore, of no interest here to consider longer length scales. A further detail observed in Fig. 1 is the jagged separation between the negatively directed horizontal flow just below the particle and the inner region devoid of plasma just downstream of the particle. The effect is due to the limited resolution of the simulation. It should be noted that a convergence study has been conducted to show that the jagged separation does not affect the solution. The present simulation is already relatively expensive, requiring several days of CPU time on a dual Xeon 1.7 GHz workstation. The cost is primarily due to the requirement to use the physical mass ratio $m_i/m_e=1836$ and to use a realistic size of the dust particle (small relative to the electron Debye length).

III. FORCE FIELDS

As discussed above, the plasma wake shown in Fig. 1 gives rise to two very different force fields. Such fields, of course, depend on the wake but also on the object upon which they exert themselves. To fix the ideas, I shall assume that the object experiencing the force fields is another dust particle with the same geometry, mass, and charge as the dust particle originating the force fields. Such assumption constitute a rough approximation of reality, where the dust particles in a typical complex plasma can be assumed to have approximately the same properties if located nearby. More accurate calculations that correctly represent the mutual modifications of the particle properties induced among the particles are beyond the scope of the present work.

The two force fields are the electrostatic force and the ion flow force. I shall consider them in turn.

First, the electric field is directly responsible for the electrostatic force. The computation of this force field is straightforward. The electrostatic force is simply

$$\mathbf{F}_e=q_t\mathbf{E}, \tag{1}$$

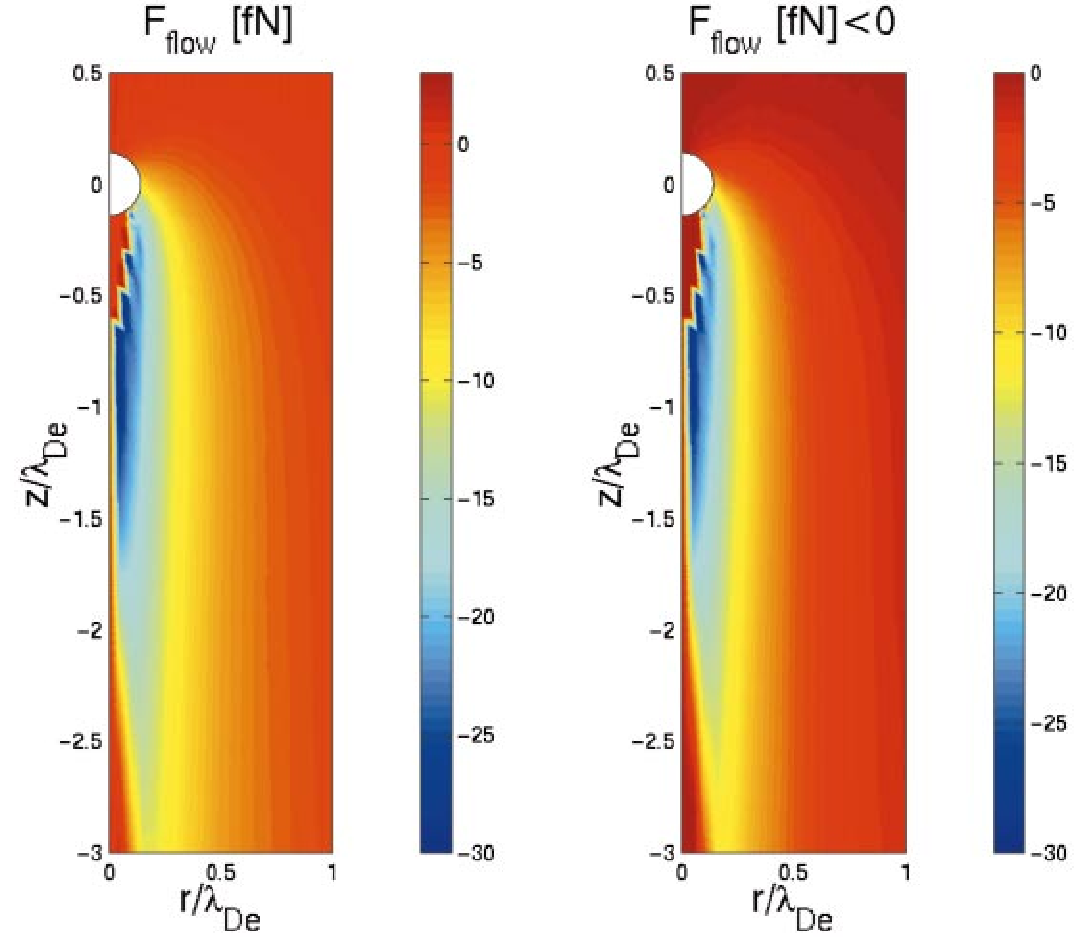

FIG. 3. (Color) Horizontal component of the ion flow force (drag force), expressed in fN, downstream of a dust particle immersed in a plasma with an ion flow having upstream Mach number $M=1.5$, directed downward. The left panel shows the complete force field, the right panel shows only negative values (all positive values are cut off at zero).

where the test charge q_t is assumed in the computations below to equal the charge of the dust particle creating the field. Figure 2 shows the electrostatic force field obtained from the simulations using Eq. (1). The result presented in Fig. 2 is in qualitative agreement with the linear theories [1–3,5,6]. However, the linear theories are quantitatively inapplicable in the present case as they would predict a potential beyond their range of applicability, namely, they would predict a huge wake potential $e\phi \gg kT_e$. Linear theories by definition can only be valid in the limit of small potentials; only the nonlinear kinetic simulations presented here can be trusted quantitatively.

Second, the ion flow exerts a force on any object it encounters: the ion drag force. The ion drag force is a well-known force that has attracted considerable research efforts and an established theory is available in the literature [11]. It has long been known that the ion drag force exerts a vertical force on dust particles [9,10] that contributes to determine the location of dust particles in glow discharge reactors. However, to my knowledge, never has it been suggested that plasma wakes induce disturbances of the ion flow that can produce *horizontal* components of the force. Below such horizontal force component is computed starting from the horizontal ion flow speed obtained from the simulations and displayed in Fig. 1. The ion drag force is calculated considering the momentum transfer from two sources: the collection force (i.e., momentum transferred by ions collected by the dust particle) and the orbit force (i.e., Coulomb scattering of ions by the dust particle) [9].

The *orbit force* is calculated as [11]

$$\mathbf{F}_{i,\text{orbit}} = \frac{\Lambda}{m_i} 8\pi \frac{(e q_t)^2 n_i}{(4\pi\epsilon_0)^2 v_{th,i}^2} \Psi(U_i / v_{th,i}) \frac{\mathbf{U}_i}{U_i}, \tag{2}$$

where $\Lambda = \log(1+\lambda_{\text{De}}^2/r_t^2)/2$ is the Coulomb logarithm (r_t being the radius of the test particle assumed equal to r_d as noted above) and Ψ is the Chandrasekhar function,

$$\Psi(x) = \frac{1}{2x^2}\left(\operatorname{erf} x - \frac{2x}{\sqrt{\pi}} e^{-x^2} \right). \tag{3}$$

The *collection force* is calculated as [9]

$$\mathbf{F}_{i,\text{collection}} = n_i m_i \mathbf{U}_i v_s \pi b_c^2, \tag{4}$$

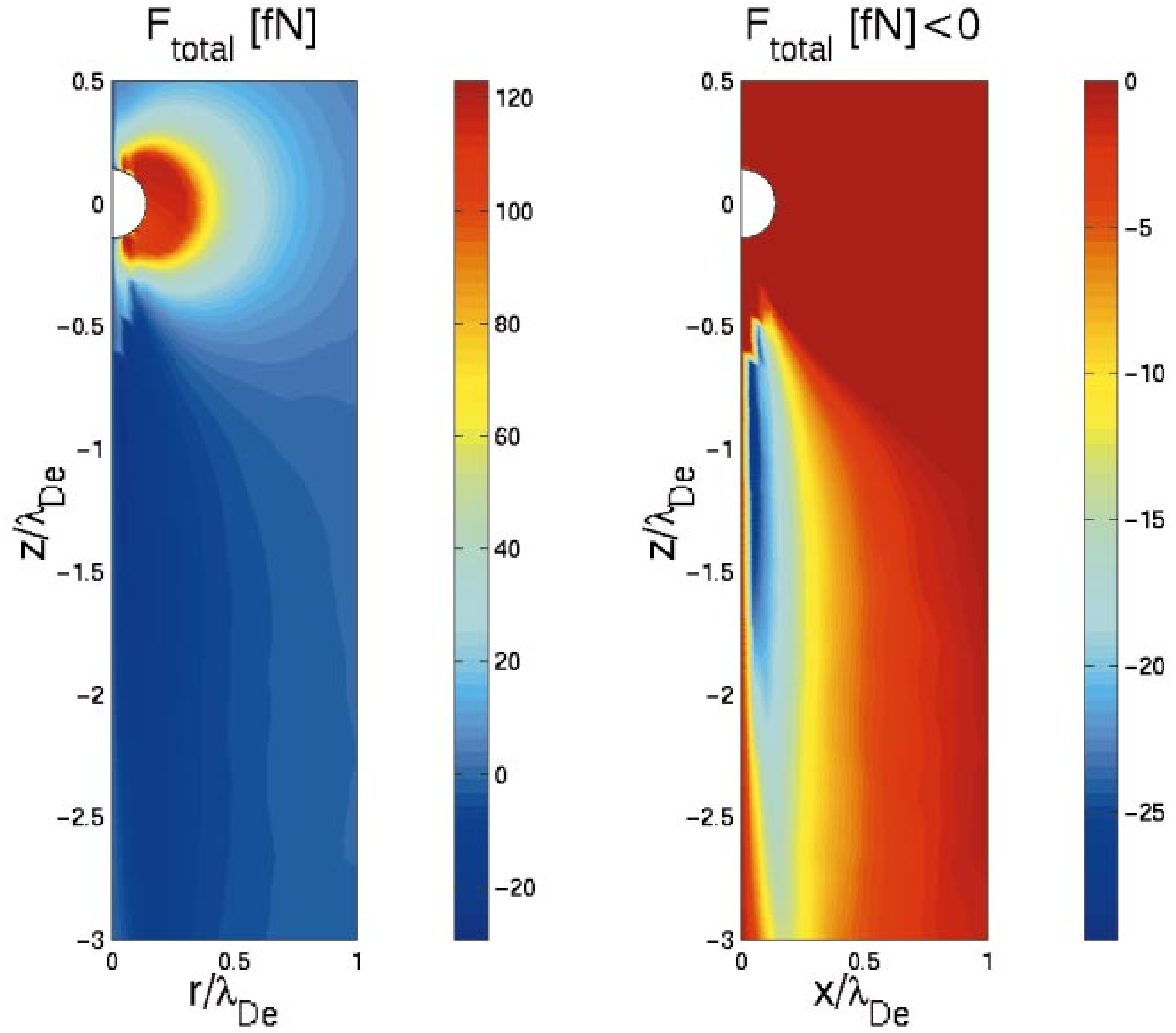

FIG. 4. (Color) Total horizontal force in fN, obtained by summing the electrostatic force (in Fig. 3) and the ion flow force (in Fig. 4). The left panel shows the complete force field, the right panel shows only negative values (all positive values are cut off at zero).

where the mean speed is $v_s=(8v_{th,i}^2/\pi+U_i^2)^{1/2}$ and the collection impact parameter is $b_c^2=r_t^2[1-eq_tm_i/(4\pi\epsilon_0 r_t m_i v_s^2)]$.

The ion flow in Fig. 1 creates a force field $\mathbf{F}_{flow}$ determined by Eqs. (2), (4). Figure 3 shows the force field obtained for the plasma parameters described above. Clearly, the horizontal force created by the ion flow is not negligible. Indeed, it exceeds the electrostatic force by almost an order of magnitude. When the total force is computed by simply summing the electrostatic and flow forces (see Fig. 4), it is easily observed that the ion flow force dominates everywhere in the downstream wake region, the electrostatic force being eminently negligible, playing a noticeable role only very close to the dust particle, upstream of the flow.

The horizontal forces shown in Figs. 2–4 can be repsonsible for the aligning forces observed in complex plasma experiments [7]: A negative radial component would tend to move objects towards the axis, resulting in an alignment.

The active region where the ion-flow-induced alignment force is present is closer to the dust particle generating the force than it is the aligning force due to the electrostatic force. The alignment due to the ion flow force starts to be present right at the dust particle and continues downstream up to about 3 $\lambda_{\rm de}$. The alignment due to the electrostatic force, instead, starts only at about 1.5 $\lambda_{\rm De}$ downstream. Experiments have consistently shown interparticle distances of the order of $d\sim\lambda_{\rm De}$. The electrostatic force acts too far away from the dust particle generating it to be able to explain most of the experiments. The ion flow force acts right were the experiments observe the alignment.

IV. CONCLUSIONS

We have simulated directly the conditions observed in complex plasma experiments. The simulations follow the physics exactly with no assumptions or approximations.

The plasma environment and particularly the plasma wake created around a dust particle immersed in flowing ions has been calculated.

Two horizontal forces have been observed and computed. First, the electrostatic force due to the presence of the wake electric field. Second, the ion flow force due to the distortion of the ion trajectories.

The two wake mechanisms should not be confused. Electrostatic wake forces are due to the self-consistent (Vlasov) macroscopic field caused by charge accumulation in the wake. Ion drag forces, instead, are due to the microscopic fluctuations caused by the momentum exchange between plasma particles and dust particles (Lenard-Balescu collision integral).

The comparison shows that in this case the ion-flow-induced force is dominant over the electrostatic wake force.

This conclusion is relevant to all laboratory experiments where dusty plasma crystals are formed: the present force can be the dominant aligning effect. But the present work is also relevant to the ongoing micorgravity experiments on the International Space Station ALPHA, where the ion drag force is even more important due to the absence of gravity. It should be noted that the ion drag force is most effective at $U/v_{th,i}=2$ corresponding typically to $M \ll 1$ as expected in the regions where the dust forms crystals in microgravity experiments. On the ISS ALPHA the effect considered here is even more relevant than on Earth.

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