Electrical interactions between positively charged particles in highly collisional plasmas: effect of ionization/recombination processes

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The shape of the interparticle interaction potential is a very important factor which determines various physical phenomena in complex (dusty) plasmas (as well as in other interacting particle systems). Different mechanisms of attraction and repulsion between the charged particles immersed in plasmas have been discussed in the literature[1, 2]. It is shown that as long as collective effects relevant to dense dust clouds are neglected, two negatively charged particles repel each other electrically at any distance. However, two positively charged particles can attract each other at long distances. The possibility of attraction between individual positively charged emitting particles in collisionless plasmas was pointed out by Delzanno *et al* [3, 4]. Later on, an analytical approach to calculate the attractive part of the potential between positively charged emitting particles was developed for the highly collisional plasma regime [5] and it was suggested there that attraction can explain the formation of ordered structures in the "dusty combustion experiment" [6]. However, an important effect – ionization and recombination in the background plasma – was neglected in this theoretical study. The focus of this paper is to investigate the effect of ionization and recombination processes on the attractive branch of the interaction potential between a pair of small positively charged particles in plasmas.

We consider a small individual charged spherical grain in a highly collisional, weakly ionized isotropic plasma. The plasma sources and sinks are present in the vicinity of the grain which itself acts both as plasma source (by emitting electrons) and plasma sink (by absorbing ions and electrons). Ion and electron temperatures are uniform but not necessary equal to each other. In the highly collisional regime ($\ell_{i(e)} \ll \lambda_{\rm D}$, where $\ell_{i(e)}$ denotes the mean free path for ions (electrons) and $\lambda_{\rm D}$ is the plasma screening length) both the ion and electron components are mobility controlled and are suitably described by the hydrodynamic equations:

$$\nabla(n_i\mathbf{v}_i) = Q_I - Q_L - J_i\delta(\mathbf{r}), \tag{1}$$

$$(\mathbf{v}_i\nabla)\mathbf{v}_i = (e/m_i)\,\mathbf{E} - (\nabla n_i/n_i)\,v_{T_i}^2 - \nu_i\mathbf{v}_i, \tag{2}$$

$$\nabla(n_e\mathbf{v}_e) = Q_I - Q_L - (J_e - J_{em})\delta(\mathbf{r}), \tag{3}$$

$$(\mathbf{v}_e\nabla)\mathbf{v}_e = -(e/m_e)\,\mathbf{E} - (\nabla n_e/n_e)\,v_{T_e}^2 - \nu_e\mathbf{v}_e. \tag{4}$$

Here, $m_{i(e)}$, $n_{i(e)}$ and $\mathbf{v}_{i(e)}$ are the mass, density and velocity of the ions (electrons) respectively; $J_{i(e)}$ is the ion (electron) flux that the grain collects from the plasma whereas J_{em} is the flux of the emitted electrons; $\nu_{i(e)}$ is the ion (electron) - neutral collision frequency. In the continuity equation Q_I and Q_L represent plasma production and loss terms, respectively. In our model we consider electron impact ionization as the only mechanism responsible for plasma production, *i.e.* $Q_I = \nu_I n_e$ whereas plasma loss is due to electron-ion volume recombination, $Q_L = \nu_R n_e n_i$. Here, ν_I is the ionization frequency and ν_R is the recombination coefficient. In the unperturbed plasma, the above coefficients are related as $\nu_I = \nu_R n_0$ where $n_i \simeq n_e \simeq n_0$ is the unperturbed plasma density. This mechanism of plasma loss is relevant to high pressure plasmas. Finally, we consider the potential distribution around an individual particle and the resulting interaction between a pair of particles, thus neglecting any collective effects including plasma losses on the particle component. The above set of equations is closed with the Poisson equation:

$$\Delta\phi = -4\pi e(n_i - n_e) - 4\pi Q\delta(\mathbf{r}). \tag{5}$$

We apply the linear dielectric response formalism to calculate self consistent electrostatic potential around the absorbing point grain from equations (1) – (5). Assuming the plasma perturbation to be proportional to $\propto \exp(i\mathbf{kr})$ we get [7],

$$\phi(r) = (Q_+/r)\exp(-rk_+) + (Q_-/r)\exp(-rk_-), \tag{6}$$

where

$$Q_\pm = \mp \frac{Q\left[k_\mp^2 - k_\mathrm{D}^2 - (eJ_0/QD_i)(1 - D_i/D_e)\right]}{k_+^2 - k_-^2} \tag{7}$$

and

$$2k_\pm^2 = k_\mathrm{D}^2 + \nu_I/D_i \pm \sqrt{\left(k_\mathrm{D}^2 + \nu_I/D_i\right)^2 - 4\nu_I\left(k_{\mathrm{D}e}^2/D_i + k_{\mathrm{D}i}^2/D_e\right)}. \tag{8}$$

Here $D_{i(e)} = v_{Ti(e)}\ell_{i(e)}$, $v_{Ti(e)} = \sqrt{T_{i(e)}/m_{i(e)}}$, $T_{i(e)}$, and $k_{\mathrm{D}i(e)} = \lambda_{\mathrm{D}i(e)}^{-1}$ are the diffusion coefficient, thermal velocity, temperature, and inverse Debye radius for ions (electrons) respectively. The inverse linearized Debye radius is $k_\mathrm{D} = \sqrt{k_{\mathrm{D}e}^2 + k_{\mathrm{D}i}^2}$. In the stationary state the electron and ion fluxes collected by the particle are equal to each other, $J_i = J_e - J_{em} = J_0$. We assume here that electron emission is quite significant, so that the particle charge is positive, $Q > 0$.

Eq. (6) demonstrates that in the considered case the potential is screened exponentially, but unlike in the Debye-Hückel theory the potential contains the superposition of the two exponentials with different inverse screening lengths k_+ and k_-. Both of these screening parameters depend on the strength of plasma production through the ionization frequency ν_I. The effective charges Q_+ and Q_- both depend on the strength of plasma production and plasma fluxes collected by the particle. The short range part of the potential is determined by the first term in Eq. (6) with the effective charge Q_+ and the larger screening parameter k_+.

It can be easily shown that $Q_+ > 0$ and therefore this part is always repulsive. On the other hand, the long range asymptote of the potential is determined by the smaller screening parameter k_- with the effective charge Q_-.The long-range attraction operates when $Q_- < 0$. From Eq. (7) we derive an approximate condition for the existence of attraction: $J_0 \geq \nu_I(Q/e)$. It is obvious from the obtained inequality that attraction between two positively charged particles exists when the ionization strength is low enough. Otherwise, the potential of electrical interaction is purely repulsive as shown in Fig.1. The effect of ionization is small when $k_{\rm D}^2 \geq \nu_I/D_i$. In this case the smaller screening parameter which determines the global screening is $k_-^2 \simeq k_{\rm De}^2(\nu_I/k_{\rm D}^2 D_i)[1+(k_{\rm Di}^2 D_i/k_{\rm De}^2 D_e)]$. Usually $(k_{\rm Di}^2 D_i/k_{\rm De}^2 D_e) \ll 1$ and, therefore, $k_- \simeq k_{\rm De}\sqrt{\nu_I/k_{\rm D}^2 D_i}$. This yields a lengths scale $R \sim \lambda_{\rm De}\sqrt{k_{\rm D}^2 D_i/\nu_I} \geq \lambda_{\rm De}$ above which ionization and recombination in plasma should be taken into account. For $r \leq R$ the model neglecting ionization and recombination processes is applicable.

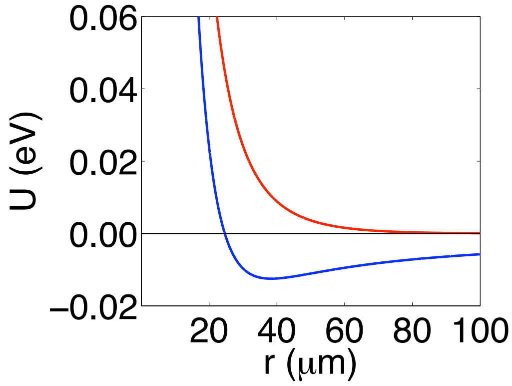

Figure 1: Interaction potential between a pair of positively charged grains ($Q \approx 100e$) in a highly collisional plasma as a function of the intergrain distance in absence of plasma ionization-loss processes ("blue" curve) and in presence of plasma ionization-loss processes ("red" curve) with $\nu_I = 6.7 \times 10^5 s^{-1}$.

For our analysis we have considered the parameter regime of "dusty combustion experiment" by Fortov *et al.* [6]. In this experiment the dust particles (CeO_2 grains of radius $a \simeq 0.4\ \mu$m) were injected into a laminar air spray at atmospheric pressure and temperature $T \sim 1700-2200$ K created by a two-flame Meeker burner. The complex (dusty) plasma constituents were air, electrons, Na^+ ions and CeO_2 particles, all in thermal equilibrium. The grains were charged positively by emitting thermal electrons up to $Q \sim 10^2 e$. At $T \sim 1700$ K the particle component formed a short range ordered structure, with the pronounced first maximum in the pair correlation function. This phenomena can be attributed to the presence of the weak attractive

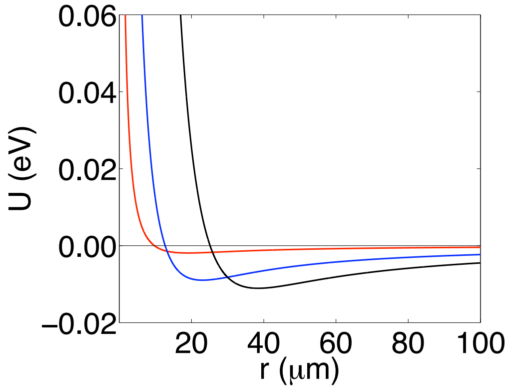

Figure 2: Pair interaction potential between positively charged grains with charge $Q \approx 100e$ (black), $\approx 30e$ (blue) and $\approx 10e$ (red) in the highly collisional plasma in presence of plasma ionization-loss processes with $\nu_R \approx 10^{-8}{\rm cm^3 s^{-1}}$.

part of the interparticle interaction potential, with the minimum of the potential corresponding approximately to the position of the first maximum in the pair correlation function [5].

However, the effects of ionization and recombination were not taken into account in Ref. [5]. Recently we have made an estimate related to the importance of ionization/recombination processes for the conditions of this experiment and it is found that in this case they play only a negligible role [7].

To summarize, ionization and recombination processes constitute an important factor which affects the distribution of electrical potential around an individual particle in plasmas and therefore is important for electrical interaction between the particles. We have shown here that ionization/recombination processes can suppress the attractive branch of the interaction potential between a pair of positively charged particles, and derived the condition when this attraction vanishes.

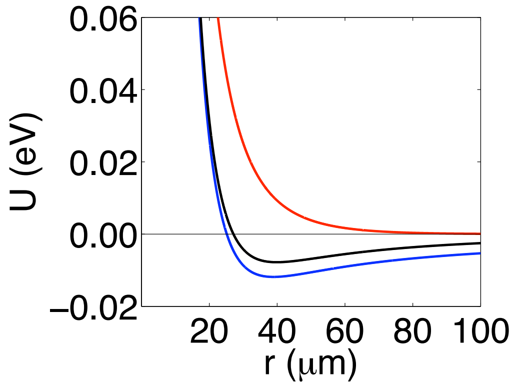

Figure 3: Interaction potential between a pair of positively charged grains ($Q \approx 100e$) in a highly collisional plasma with different ionization strengths: $\nu_I = 67 s^{-1}$(blue), $\nu_I = 6.7 \times 10^3 s^{-1}$(black) and $\nu_I = 6.7 \times 10^5 s^{-1}$(red).

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