34th EPS Conference on Plasma Phys. Warsaw, 2 - 6 July 2007 ECA Vol.**31F**, P-4.132 (2007)

Characterization of the electrostatic potential behind an absorbing dust particle in highly collisional drifting plasma

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Introduction

Complex (dusty) plasma is a multicomponent system which contains electrons, ions, highly charged dust grains and neutral gas. In absence of emission the dust grains become negatively charged due to the higher mobility of electrons. Very often these grains levitate in a self-consistent large scale electric fields which induce plasma flows relative to the grains. The focus of this paper is to characterize the electric field behind a charged absorbing grain in highly collisional plasma with flowing ions. It is shown that plasma absorption has a dominant effect on the field.

Model

We consider a stationary, negatively charged spherical dust grain with charge Q which is placed in a quasineutral, highly collisional plasma. The presence of external electric field causes the ions to flow with subthermal velocity whereas the electrons form almost stationary background (ambipolar diffusion regime). Due to the effect of plasma absorption on the grain surface, the dust grain represents a plasma sink. It is also assumed that in the vicinity of the grain no ionization/recombination processes occur.

The hydrodynamic description for ions contains continuity and momentum equations:

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

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

The electron density satisfies Boltzmann relation

$$n_e \simeq n_0 \exp\left(e\phi/T_e\right). \quad (3)$$

Here $n_{i(e)}$ is the ion (electron) density, $\mathbf{v}_i$ and m_i are the ion velocity and mass, J_i is the ion flux to the grain surface, $v_{T_i} = \sqrt{T_i/m_i}$ is the ion thermal velocity, ν is the (constant) momentum transfer frequency in ion-neutral collisions, n_0 is the unperturbed plasma density (far from the grain), $T_{i(e)}$ is the ion (electron) temperature, and $\mathbf{E}$ is the total electric field. The above set of equations is closed with the Poisson equation

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

Results

Using linear dielectric response formalism and assuming plasma perturbation $\propto \exp(i\mathbf{kr})$ we get for the electric potential [1]

$$\phi_1(\mathbf{r}) = \frac{4\pi Q}{(2\pi)^3}\int \frac{\exp(i\mathbf{kr})d\mathbf{k}}{\chi_1(\mathbf{ku},k)} + \frac{4\pi e}{(2\pi)^3}\int \frac{\exp(i\mathbf{kr})d\mathbf{k}}{\chi_2(\mathbf{ku},k)}, \quad (5)$$

where

$$\chi_1(\mathbf{ku},k) = k^2 + k_{\mathrm{D}e}{}^2 + k_{\mathrm{D}i}{}^2\left[1 - \frac{\mathbf{ku}\,(\mathbf{ku} - i\nu)}{k^2 v_{T_i}{}^2}\right]^{-1}, \quad (6)$$

$$\chi_2(\mathbf{ku},k) = i\frac{k^2 v_{T_i}^2\left(k^2 + k_{\mathrm{D}}{}^2\right) - \mathbf{ku}\,(\mathbf{ku} - i\nu)\left(k^2 + k_{\mathrm{D}e}^2\right)}{J_i\,(\mathbf{ku} - i\nu)}. \quad (7)$$

Here $k_{\mathrm{D}i(e)}$ is the inverse ion (electron) Debye radius and $k_{\mathrm{D}} = \sqrt{k_{\mathrm{D}e}^2 + k_{\mathrm{D}i}^2}$ is the inverse linearized Debye radius. The first term in Eq. (5) corresponds to the potential behind the pointlike non-absorbing grain in the limit of high collisionality. [2] The second term arises due to the ion absorption on the grain. Considering the applicability condition for the hydrodynamic approximation $k \ll 1/\ell_i$ and the limit of very slow drift $k \gg u/\ell_i v_{T_i}$ we get the expression for the perturbed electric field downstream from the grain as:

$$\begin{aligned} E_1 = \left(Qk_{\mathrm{D}}^2\right)\frac{(1+x)\exp(-x)}{x^2} - \left(\frac{Q\nu u k_{\mathrm{D}i}^2}{2k_{\mathrm{D}} v_{T_i}^2}\right)\frac{4 - \left(x^3 + 2x^2 + 4x + 4\right)\exp(-x)}{x^3} \\ - \left(\frac{eJ_i\nu}{v_{T_i}{}^2}\right)\frac{1 - (1+x)\exp(-x)}{x^2} \\ - \left(\frac{eJ_i u\nu^2}{2v_{T_i}^4 k_{\mathrm{D}}}\right)\left(1 - \frac{2k_{\mathrm{D}e}{}^2}{k_{\mathrm{D}}{}^2}\right)\frac{4 - \left[\left(1 - k_{\mathrm{D}e}^2/k_{\mathrm{D}i}^2\right)^{-1}x^3 + 2x^2 + 4x + 4\right]\exp(-x)}{x^3}, \end{aligned} \quad (8)$$

where $x = rk_{\mathrm{D}}$ is the normalized distance from the grain. The integration over k has been formally performed from zero to infinity. The approximate expressions for χ_1 and χ_2 are valid only between $k_{\min} = u/v_{T_i}\ell_i$ and $k_{\max} = 1/\ell_i$. However, if $k_{\min} \ll k_{\mathrm{D}}$ and $k_{\max} \gg k_{\mathrm{D}}$ this does not affect the result considerably since it can be shown that the contribution to the integral from small and large ranges of k are of minor importance. The first and second terms represent respectively the isotropic Debye-Hückel potential and anisotropic electric field behind nonabsorbing dust grains. The third and fourth terms represent respectively the isotropic and anisotropic electric fields associated with the plasma absorption on the grain surface.

From Eq. (8) we get for the long-range asymptote of the electric field in the absence of absorption $E_1 \approx -(2Qu\nu/\omega_{pi}^2 r^3)(k_{\mathrm{D}i}/k_{\mathrm{D}})^4$.

In the presence of absorption the long-range asymptote of the anisotropic part of the electric field becomes: $E_1 \approx -(2Qu\nu/\omega_{pi}^2 r^3)(k_{\mathrm{D}i}/k_{\mathrm{D}})^4[1 + (e/Q)(J_i\nu/\omega_{pi}^2)(1-2k_{\mathrm{D}e}^2/k_{\mathrm{D}}^2)]$. Thus, for negatively charged particle the effect of absorption decreases the amplitude of the anisotropic part of electric field and can even change its sign. The important point is that the long range asymptote of the electric field is determined completely by the isotropic part associated with absorption: $E_1 \approx -(eJ_i\nu/\omega_{pi}^2 r^2)(k_{\mathrm{D}i}/k_{\mathrm{D}})^2$. Introducing dimensionless grain charge $Z = |Q|e/aT_e$, the thermal Mach number for drifting ions $M_T = u/v_{T_i}$, the electron-to-ion temperature ratio, $\tau = T_e/T_i$, normalized ion mean-free path, $\xi = \ell_i/\lambda_{\mathrm{D}}$, scattering parameter $\beta = Z\tau(a/\lambda_{\mathrm{D}})$ and using the well known asymptotic expression for the ion flux on a infinitesimally small grain ($a \ll \lambda_{\mathrm{D}}$) in the continuum limit ($\ell_i \ll a$), $J_i \simeq 4\pi a Z\tau n_0 \ell_i v_{T_i}$, the normalized electric field can be written as:

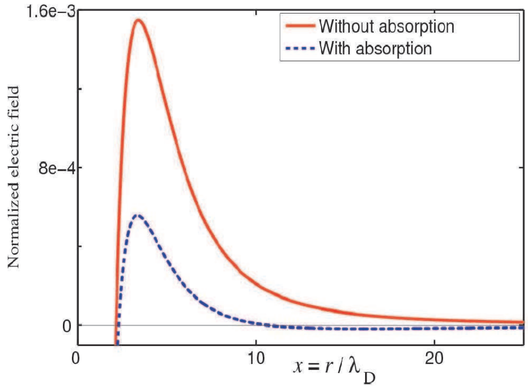

Figure 1: The variation of the electric field with and without absorption is shown. At intermediate distance the electric field changes its sign for absorbing grain though the magnitude of the field is considerably reduced compared to that for non absorbing grain

$$\tilde{E}_1 = -\frac{\beta\tau}{\tau+1}\frac{1}{x^2}\left[1+\tau^{-1}(1+x)\exp(-x)\right] + \frac{\beta M_T}{2\xi}\frac{\tau}{(\tau+1)^2}\frac{1}{x^3}\left[8-\left(x^3+4x^2+8x+8\right)\exp(-x)\right]$$

The first term represents isotropic part of the electric field while the second term represents its anisotropic part. It is clear from the above expression that the normalized electric field depends on three dimensionless parameters: τ, M_T and ξ and also proportional to the scattering parameter, β. These dependencies have been studied numerically and are shown in the figures. It is clear from the figures that the attraction between two like charged absorbing dust grains is possible in the highly collisional plasma with large drift velocities and low electron-to-ion temperature ratio.

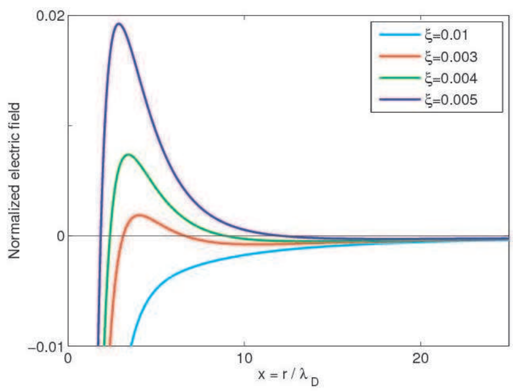

Figure 2: Spatial variation of the normalized electric field with different ion collisionality

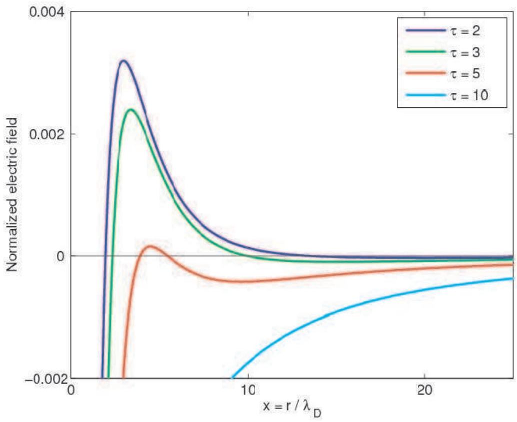

Figure 3: Spatial variation of the normalized electric field with different electron-to-ion temperature ratio

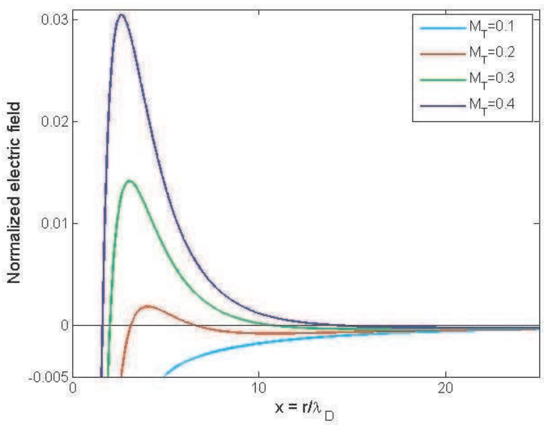

Figure 4: Spatial variation of the normalized electric field with different ion thermal mach number

Conclusion

The importance of plasma absorption in the limiting case of highly collisional flowing plasma has been discussed as it affects both isotropic and anisotropic components of the electric field behind a small spherical object. At large distances absorption completely determines the behavior of the electric field. It is shown that both short- and long-range asymptotes are repulsive for a pair of negatively charged grains, but at moderate distances attraction can take place in certain parameter regimes. This result can be important in understanding intergrain interactions in high pressure weakly anisotropic complex plasmas.

References

[1] S. A. Khrapak, S. K. Zhdanov, A. V. Ivlev, and G. E. Morfill, J. Appl. Phys. **101**, 033307 (2007)

[2] A. V. Ivlev, S. A. Khrapak, S. K. Zhdanov, G. E. Morfill, and G. Joyce, Phys. Rev. Lett. **92**, 205007 (2004).