*33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, O-2.020 (2006)*

Screening and attraction of dust particles in plasmas

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The collective effects on dust-dust interactions in plasmas [1] can modify the usual Debye screening and result in long range attraction of negative dust particles: in a plasma with $\tau = T_i/T_e \ll 1$ (where T_e, T_i are the electron and ion temperatures), if the plasma source is proportional to the electron density, the screening length can be of the order of the electron Debye length λ_{De} ($\gg \lambda_{Di} \approx \lambda_D$) and dust-dust attraction exists [2]. Numerical simulations also predict the formation of attractive potentials between positively charged grain in the presence of thermionic emission [3]. Lampe et al. [4],[5] have shown that it is important to include the effects of trapped ions to investigate the charging and shielding of dust grains in collisional plasmas. A recent paper [6] has been dedicated to the orbital theory of the shielding potential around a dust grain, including the effects of emission, but neglecting the collisions and the collective dust-dust interactions. Dust ordered structures were observed in thermal dusty plasma under atmospheric pressure and temperatures of 1700-2200 K [7],[8]. In such conditions, the dust charging occurs not only collecting electrons and ions, but also emitting electrons. In many astrophysical problems and in experiments where the plasma source is radioactivity or photo-ionization of the dust particles, the plasma source is proportional to the dust-not to the electron-density and the thermal plasma condition $\tau \approx 1$ is often valid. It is shown here that, for negatively charged dust grains in thermal plasmas, the screening length can substantially exceed the plasma Debye length and, if the dust grains are sources of plasma, dust-dust attraction is possible, due to collisional and collective interactions, thus extending the investigation reported in [2].Because of the absorption of plasma particles on dust, dusty plasmas are open, dissipative systems and a plasma source is always needed to achieve equilibrium. In the present model, the background dust grains are essentially represented as a continuous, immovable, uniform "dust medium", which is a source and sink for ions and electrons, contributes to the charge density and produces friction forces on the plasma particles. On this medium is then superposed a single additional discrete dust grain, which can be a local source or sink of plasma particles, and we follow the system’s linear response, taking into account also the perturbations of the dust charges, arising from the perturbed plasma fluxes. It is worth noting that the effect of trapped ions has been neglected. This assumption is well justified if the mean kinetic energy of the ions is greater than the binding potential, as occur in thermal plasmas. The nonlinear regime has been considered in [9].

Taking consistently into account the ion/electron collisions with dust particles and the fluctuations of the dust charge, the kinetic theory of dusty plasmas has been developed in Refs. [10]-[14] for the case of non fluctuating plasma sources. The kinetic equation for electrons and ions ($\alpha = e, i$), can be written in the form:

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} - \frac{e_\alpha}{m_\alpha}\nabla\Phi\cdot\frac{\partial}{\partial \mathbf{v}}\right) f^\alpha = S_\alpha - \nu_{d,\alpha} f^\alpha + s_{\alpha T}\delta(r-a) + I^\alpha(f^\alpha) \qquad (1)$$

where e_α, m_α are the charge and mass of electrons or ions, $f^\alpha(\mathbf{v},\mathbf{r},t)$ their distribution functions, S_α represent sources of plasma particles, $s_{\alpha T}\delta(r-a)$ is a source or a sink localized at the surface of the test dust particle and $\nu_{d,\alpha} f^\alpha$ the sink of plasma particles due to absorption on dust. The collision frequency for capture on dust is given by (the dust velocity is always neglected with respect to the electron or ion velocity): $\nu_{d,\alpha} = \int v\sigma_\alpha(q,v) f^d dq d\mathbf{v}' \simeq v\sigma_\alpha(q_o,v) n_d$, where $\sigma_\alpha(q,v)$ is the cross-section for the charging collisions, $f^d(q,\mathbf{v}',\mathbf{r},t)$ the dust distribution function of dust velocity ($\mathbf{v}'$) and dust charge (q) and the last approximate equality follows from the approximation of small charge fluctuations around the value q_o (which amounts to the assumption $f^d(q,\mathbf{v}',\mathbf{r},t) \simeq \delta(q-q_o) F^d(\mathbf{v}',\mathbf{r},t)$ in integrals over charge) and the normalization conditions: $\int f^d dq d\mathbf{v}' = \int F^d d\mathbf{v}' = n_d$ with n_d number density of dust grains. The collision integral is given by: $I^\alpha(f^\alpha) = \frac{\partial}{\partial v_i} D^{d,\alpha}_{i,j} \frac{\partial f^\alpha}{\partial v_j}$ where $D^{d,\alpha}_{i,j}$ is the diffusion coefficient due to plasma particles-dust collisions. In the present case we have considered only elastic collisions.

It will be assumed that the source S_α is uniform in space, constant in time and isotropic in velocity. Moreover, neglecting the perturbing test charge, the equilibrium dust distribution is uniform in space and given by $f^d_{eq} \simeq \delta\left(q - q_{eq}\right) F^d(\mathbf{v}')$ The equilibrium dust charge q_{eq} is defined as the value for which there is zero net flux of plasma particles to a dust particle.

Linear perturbations around the equilibrium state are considered, in the form: $f^\alpha(\mathbf{r},\mathbf{v},t) = F^\alpha(v) + \delta f^\alpha(\mathbf{r},\mathbf{v},t)$. It will be assumed that the distribution function of dust particles in velocity space is not affected by the perturbing test charge, that is: $f^d \simeq \delta\left(q - (q_{eq} + \delta q)\right) F^d(\mathbf{v}')$ where $\delta q(\mathbf{r},t)$ is the charge perturbation due to the perturbed plasma fluxes.

In the equilibrium system, taking into account the neutrality condition, the Poisson equation can be written as:

$$\nabla^2\Phi = -\frac{q_T}{a^2}\delta(r-a) - 4\pi\sum_\alpha e_\alpha \int \delta f^\alpha d\mathbf{v} - 4\pi n_d \delta q \qquad (2)$$

The collision frequency, expanding the cross-section in charge, can be written as $\nu_{d,\alpha} = \nu^o_{d,\alpha}(v) + \delta\nu_{d,\alpha}(\mathbf{r},\mathbf{v},t)$, where $\nu^o_{d,\alpha}(v) = n_d v\sigma_\alpha(q_{eq},v)$ and $\delta\nu_{d,\alpha}(\mathbf{r},\mathbf{v},t) = n_d v\sigma'_\alpha(q_{eq},v)\delta q(\mathbf{r},t)$ where σ'_α is the derivative of σ_α with respect to grain charge.

The linearized kinetic equation for the perturbations is given by:

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\frac{\partial}{\partial \mathbf{r}} + \nu^o_{d,\alpha}\right)\delta f^\alpha = \frac{e_\alpha}{m_\alpha}\nabla\Phi\cdot\frac{\partial F^\alpha}{\partial \mathbf{v}} + s_{\alpha T}\delta(r-a) - n_d v F^\alpha \sigma'_\alpha \delta q + I^\alpha(\delta f^\alpha) \qquad (3)$$

The system is closed by the equation for the dust charge perturbations:

$$\left(\frac{\partial}{\partial t} - \sum_\alpha e_\alpha \int v\sigma'_\alpha F^\alpha d\mathbf{v}\right)\delta q(r,t) = \sum_\alpha e_\alpha \int v\sigma_\alpha(q_{eq},v)\delta f^\alpha d\mathbf{v} \qquad (4)$$

To find the response $\varepsilon_{\mathbf{k},\omega}$ of the system to the test charge, we consider the Fourier transforms of equations (2, 3, 4) and expand the perturbed distributions in Legendre polynomials of the angle between the velocity and the wavenumber. The expansion is taken to first order, assuming small anisotropy.

Once the system's response (permittivity) $\varepsilon_{\mathbf{k},\omega}$ is found, the potential around a spherical "test" dust particle of radius a and charge q_T, can be calculated from the following expression, for isotropic plasma dielectric permittivity:

$$\Phi(r) = -\frac{i}{2\pi r}\left[\int_{-\infty,L(0^+)}^{+\infty}\left(q_T + 2\pi^2\Gamma_{k,0}\right)\frac{e^{ikr}}{k\varepsilon_{k,0}}dk + \int_{-\infty,L(0^-)}^{+\infty}\left(q_T + 2\pi^2\Gamma_{k,0}\right)\frac{e^{ikr}}{k\varepsilon_{k,0}}dk\right] \qquad (5)$$

and the result is determined by the poles in the complex k-plane, that is by the zeroes of the static permittivity. The symbols $L(0^+)$, and $L(0^-)$ specify the Landau contours for $\omega = 0^+$ and $\omega = 0^-$. This bypassing rule of the poles is determined by the even frequency spectra corresponding to the static case and, when applied to the problem considered in [2], gives the same result discussed there. It is worth to note that the effect of plasma emission/absorption at the surface of the "test" dust particle is represented in Eq. (5) by the term $\Gamma_{k,0}$.

To evaluate the potential, the Orbit Motion Limited cross-section has been used and it has been assumed that the sources and losses result in Maxwellian distributions. Two poles dominate, both imaginary: the potential around the dust particle is then found in good agreement with the result of hydrodynamic model [9]:

$$\Phi(r) = \frac{q_T}{r}\left[g_1 e^{-\frac{r}{\lambda_1}} + g_2 e^{-\frac{r}{\lambda_2}}\right] \qquad (6)$$

The screening function is a combination of exponentials with screening lengths which can substantially differ from the linear Debye length λ_{Dlin} : for $a \ll \lambda_{Dlin}$ it is found $\lambda_1 < \lambda_{Dlin}$,

$O(\lambda_1/\lambda_{Dlin}) = 1$, $\lambda_2 \ll \lambda_{Dlin}$. Moreover, potential wells can occur. The key effect that can lead to attraction of negatively charged grains is the emission of ion flux from the grain in the presence of friction forces. As a result, the ions are much more concentrated around the source than in the adiabatic case. This effect can produce under-screening, if the the grain is a sink ($g_2 > 0$), or over-screening and attraction if the the grain is a source ($g_2 < 0$). If the local source at any grain surface is $s_{\alpha T} = v^o_{d,\alpha} F^\alpha \left(2\pi n_d a^2\right)^{-1}$, then the macroscopic source S_α is found as the volume average of the local dust sources, and the values of the coefficients $g_1, g_2, \lambda_1, \lambda_2$ are close to the values reported in [15] (when collision with the neutrals can be neglected). In this case, potential wells occur at a distance from the grain surface of the order $\lambda_1 |\ln(a^2)|$, which is of the same order of the correlation distances between charged grains observed in thermal plasma experiments [7], [8].

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