THE INFLUENCE OF ELECTRON EMISSION ON THE CHARGE AND EFFECTIVE POTENTIAL OF A DUST PARTICLE IN PLASMA

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UDC 538

The dynamics of charging of a dust particle in an electron-ion plasma in the presence of the external volume-ionization sources generating the plasma is investigated by means of numerical methods with regard for the electron photoemission from the surface of a dust particle. The stationary distributions of electron and ion concentrations in the neighborhood of the dust particle, as well as its charge and effective potential, are calculated. It is shown that the sign of this charge is determined by both the emission properties and the intensity of the external sources of ionization. The results of numerical calculations are presented in the graphical form.

1. Introduction

It is known that there exist several mechanisms of charging of dust particles in plasma, in particular, those involving plasma currents when a particle is charged negatively (a glow discharge) and the secondary electron emission and photoemission (when a particle is charged positively). The latter mechanism is investigated in more details, and a thorough analysis is given to both the case where collisions in plasma can be neglected [1—6] (the theory of bounded orbits) and the case of the drift-diffusion dynamics of plasma [7—13] (see also reviews [14, 15] and the references therein). These investigations are necessary in calculating the effective potentials of the interaction between dust particles that determine the formation of structures in dust plasma. Studying the mechanisms of charging of dust particles as well as their potentials gains a special actuality in view of the experiments with dust plasma performed under microgravitation conditions [10, 16—18]. As the majority of laboratory and cosmic experiments were carried out under conditions when the drift-diffusion approximation can be applied, a special attention was recently paid to studying the dynamics of charging of dust particles on the basis of just the mentioned approximation [8—13, 19]. The numerical simulations and analytical calculations were performed on the assumption that all plasma particles were absorbed with dust ones and were not taken into account in the sequel. The emission of electrons from the surface of a dust particle is not sufficiently studied [20—22], and this problem remains open to a great extent. One can assume that, depending on the experimental conditions, this factor exerts an essential influence especially in the case where the work function of an electron is lower than the ionization potential of atoms of the gas forming a plasma. In this case (in the absence of external radio-frequency fields and provided that the energy of light quanta is lower than the ionization potential), the electron emission represents the only source of plasma under optical irradiation of the "gas—dust particles" mixture [16]. A similar situation will be observed in the plasma of combustion products of metallized mixtures.

The aim of this work lies in generalizing the calculations of the charge and effective potential of dust particles in collisional plasma, i.e. under conditions of the applicability of the drift-diffusion description of plasma, with regard for the electron emission from the surface of dust particles.

Let's consider an isolated dust particle, whose surface emits electrons that can subsequently ionize a buffer gas. The coefficients of ionization of the atomic gas by electron impact, the recombination constant, and the diffusion coefficients of plasma particles as well as their temperatures are considered to be specified. In this case, a volume-ionization source may be present. Depending on the experimental conditions, the emission and volume ionization can be associated with either optical and ultraviolet radiation (photoemission, photoionization) or a high temperature of plasma (thermionic emission, thermal ionization). In the present paper, we consider electrons to be generated due to photoemission and photoionization. The system of input equations for the described model coincides with the equations used for investigating the processes of charging of dust particles in a glow discharge [8, 9, 13] except for the equation for the charge of a dust particle and the additional electron-source term in the electron continuity equation.

The input equations were solved numerically for a wide range of parameters of the system (the size of a dust particle, the degree of plasma nonisothermality, the intensity of a volume-ionization source). The rest of the parameters corresponds to the values considered in [17].

2. Charging of Dust Particles in Plasma in the Presence of Electron Emission from the Surface (the Problem Statement and Input Equations)

Let's consider a dust particle in the gas medium subjected to ultraviolet radiation. Due to the photoionization and electron emission from the dust particle surface, there appears the plasma environment around it. If the energy of a light quantum exceeds the work function of an electron for the material of the dust particle, but is lower than the ionization energy of gas atoms (molecules), the only plasma source is represented by photoelectrons emitted by the dust particle, as well as the impact ionization caused by them. The presence of the plasma environment results in the appearance of the flows of free electrons and ions that will be captured by the dust particle. The charge of the dust particle is determined by both the electron emission and self-consistent dynamics of plasma in its neighborhood. We assume that the plasma generated under the influence of radiation is weakly ionized, which implies that its behavior can be described within the framework of the drift-diffusion approximation. The input system of equations describing the kinetics of charging can be presented as

$$\frac{\partial n_e}{\partial t} + \mathrm{div}\vec{j}_e = Q + k_{\mathrm{ion}} n_e N - \beta_{ei} n_e n_p + \left(\frac{\partial n_e}{\partial t}\right)_{\mathrm{ph}}, \quad (1)$$

$$\frac{\partial n_p}{\partial t} + \mathrm{div}\vec{j}_p = Q + k_{\mathrm{ion}} n_e N - \beta_{ei} n_e n_p, \quad (2)$$

$$\mathrm{div}\vec{E} = \frac{1}{\varepsilon_0}\sum_\sigma \rho_\sigma, \quad (3)$$

where n_e, n_p are the concentrations of electrons and ions, respectively,

$$\left(\frac{\partial n_e}{\partial t}\right)_{\mathrm{ph}} = v_{\mathrm{ph}} n_{\mathrm{ph}} \delta(r-a)$$

— the intensity of the surface source of photoelectrons which is considered to be proportional to the initial density n_{ph} and the velocity v_{ph}, N — the concentration of neutral particles; Q — the rate of gas ionization by the external ionization source; k_{ion} — the rate constant of gas ionization by proper electrons of plasma; β_{ei} — the coefficient of dissociative electron-ion recombination; $\vec{j}_e$, $\vec{j}_p$ — the electron and ion flux densities; and $\vec{E}$ — the electric field intensity.

The flux densities of electrons and ions in a plasma volume specified in the drift-diffusion approximation have a form

$$\vec{j}_e = n_e \mu_e \vec{E} - D_e \nabla n_e, \quad (4)$$

$$\vec{j}_p = n_p \mu_p \vec{E} - D_p \nabla n_p, \quad (5)$$

where μ_e, μ_p — the mobilities, while D_e, D_p — the diffusion coefficients of electrons and ions, respectively.

The problem was solved under the following boundary conditions on the surface of the dust particle of radius $r = a$:

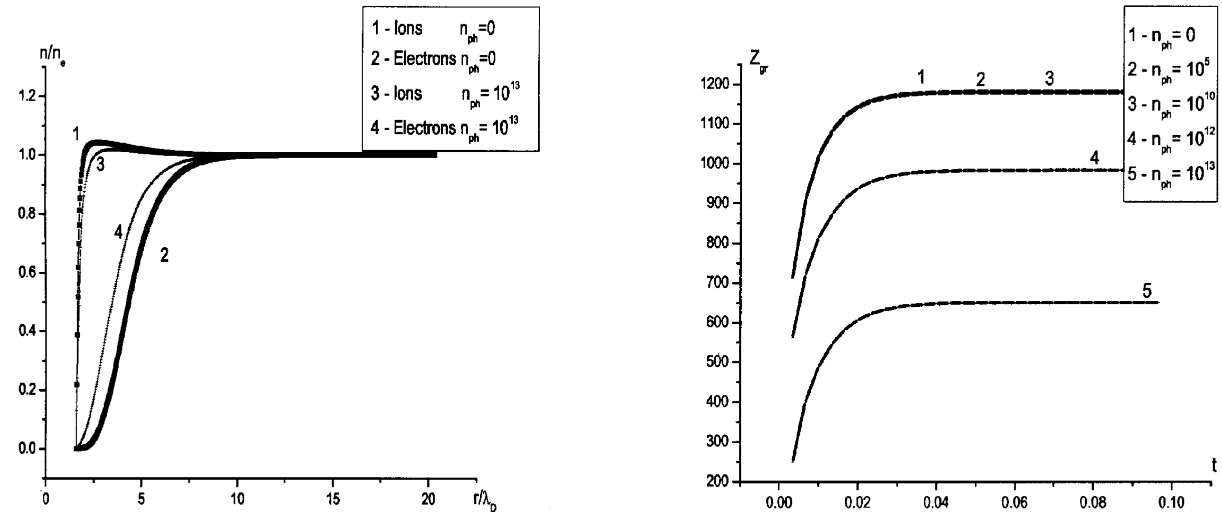
$$n_e|_{r=a} = 0, \quad (6)$$

$$n_p|_{r=a} = 0. \quad (7)$$

In this case, the equation for the dust particle charge takes the form

$$\left.\frac{dZ_{\mathrm{gr}}(t)}{dt}\right|_{r=a} = -4\pi\, a^2\, (j_e - j_p - j_{\mathrm{ph}}), \quad (8)$$

where j_{ph} is a surface value of the radial component of the photocurrent $j_{\mathrm{ph}} = v_{\mathrm{ph}} n_{\mathrm{ph}}$, where $n_{\mathrm{ph}} = \mathrm{const} \times I$ and I is the ultraviolet source intensity.



a **b**

Fig. 1. Distributions of electrons and ions in the neighborhood of a dust particle (a) and the evolution of its charge (b) in the presence of volume-ionization sources $Q = 10^{22}$ m^{-3}/s for various intensities of photoemission ($a = 4.8$ μm; $T_e/T_p = 1$, $T_p = 300$ K)

The velocity of photoelectrons coming from the surface of a dust particle $v_{\rm ph}$ is derived from the equation describing the photoeffect

$$\hbar\omega = A + \frac{m_e\, v_{\rm ph}^2}{2} - e_e\varphi, \tag{9}$$

where A stands for the work function of an electron. Hence,

$$v_{\rm ph} = \sqrt{\frac{2}{m_e}(\hbar\omega - A + e_e\varphi)}. \tag{10}$$

According to the assumption that the potential of a dust particle is close to the Coulomb one, we obtain

$$\phi = \frac{Z_{\rm gr}e_e}{4\pi\varepsilon_0 a}. \tag{11}$$

The delta function in Eq.(1) is approximated by the δ-like function

$$\delta(r-a) \simeq \frac{\alpha}{\sqrt{\pi}}\exp(-\alpha^2(r-a)^2),$$

while the parameter α is chosen to be equal to $\alpha_{\rm max} = 10^9({\rm m}^{-1})$ in such a way that exceeding this value does not change the results of numerical calculations.

In the numerical model, we solved the system consisting of the continuity equation and the Poisson equation by means of the method of finite differences with a nonuniform mesh in accordance with the explicit and implicit Crank—Nicolson technique and making use of the sweep technique (the Thomas method). The algorithm used in the computation program is described in [8] in detail.

3. Analysis of Numerical Solutions

Here, we represent the results of numerical calculations of the dynamics of charging of a dust particle and the stationary distributions of electrons and ions in its neighborhood with regard for the photoemission of electrons. The calculations were carried out for the following values of the parameters of the problem: $D_e = 0,01$ m^2/s, $D_p = 2,05 \times 10^{-6}$ m^2/s, $\mu_e = -0,386$ m^2/(B×s), $\mu_p = 7,92 \times 10^{-5}$ m^2/(B×s).

The energy of a light quantum amounted to 12 eV, while the work function was chosen to be equal to 6 eV. The concentration of neutral particles $N = 2.5 \times 10^{25}$ m^{-3}; the rate of gas ionization by the external ionization source $Q = 10^{22}$ m^{-3}/s; the rate constant of gas ionization by proper electrons of plasma was respectively equal to $k_{\rm ion} = 10^{-21}$ m^3/s; and the coefficient of dissociative electron-ion recombination $\beta_{ei} = 2.0 \times 10^{-12}$ m^3/s. Within the order of magnitude, these values correspond to the parameters of a plasma generated in a high-frequency discharge in photoemission cells. We considered several values of the radii of dust particles ($a = 2.0$; 4.8; 13.6 μm) and the nonisothermality parameters $T_e/T_p = 1$ and $T_e/T_p \simeq 33$.

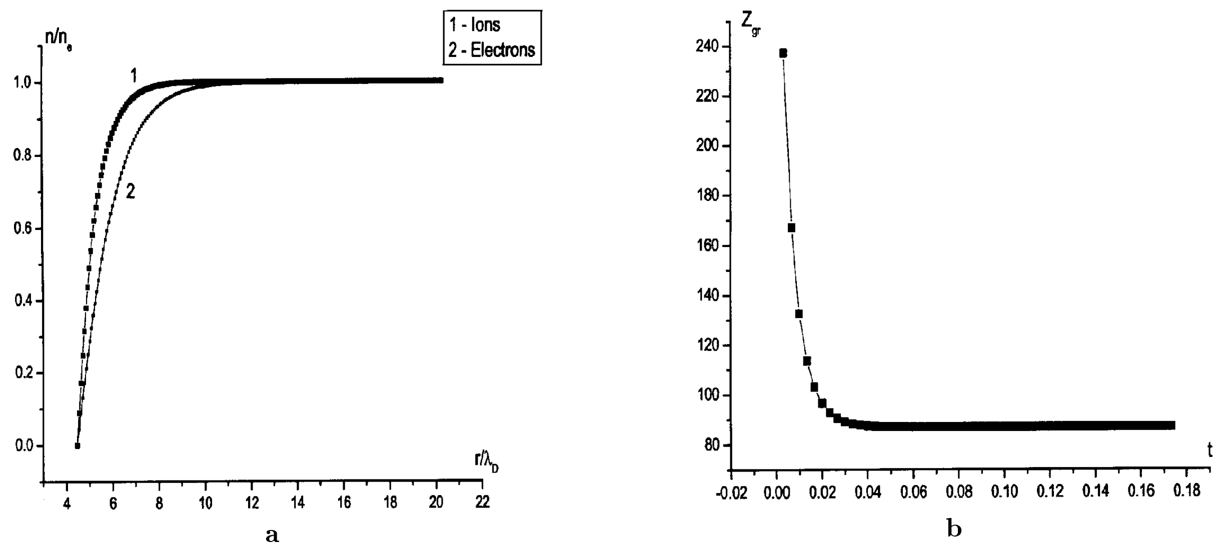


Fig. 2. The same dependences as in Fig. 1 for $n_{\rm ph} = 10^{15}$, $a = 13.6\ \mu$m

In Fig. 1, we depict the stationary distributions of electron and ion concentrations which are established around the dust particle due to the self-consistent dynamics of plasma (Fig. 1,a), as well as the temporal evolution of the charge of the dust particle (Fig. 1,b) in the presence of volume-ionization sources, $Q = 10^{22}$ m^{-3}/s.

The calculations demonstrate that, for the chosen parameters of the problem, the influence of photoemission starts to manifest itself at the values $n_{\rm ph} > 10^{10}$ m^{-3}. Otherwise ($n_{\rm ph} < 10^{10}$ m^{-3}), the results don't depend on $n_{\rm ph}$ and coincide to a high accuracy with those obtained in [8] in the presence of a volume source alone (Fig. 1). It is typical that an increase of $n_{\rm ph} > 10^{10}$ m^{-3} results in a decrease of the stationary value of the charge of the dust particle (Fig. 1,b). Moreover, though the charge of a dust particle remains negative at small $n_{\rm ph}$ (Fig. 1,b), its sign changes at sufficiently large $n_{\rm ph}$ (Fig. 2,b). This means that the plasma currents cannot compensate the photocurrent, and the particle acquires a positive charge. Correspondingly, the plasma environment is reconstructed (Fig. 2,a).

The situation changes essentially in the absence of volume-ionization sources, i.e. at $Q = 0$ (Fig. 3). This case illustrates rather vividly the competition of two mechanisms that cause the charging of a dust particle, namely, photoemission and plasma currents. As follows from the results of calculations, at small values of $n_{\rm ph}$ (at $a = 4.8\ \mu$m, $n_{\rm ph} = 10^{13}$ m^{-3}), the charge of a dust particle at the initial stage is positive (which is absolutely natural because, at this stage, photoemission is of fundamental importance, whereas plasma currents are absent). But, in the course of time, it becomes negative (Fig. 3,b). It implies that, in spite of the absence of volume sources and, consequently, a primary plasma, the flows of the secondary plasma generated due to the impact ionization not only compensate the loss of photoelectrons but also provide the accumulation of the negative charge. The calculations were carried out for various values of the rate constant of gas ionization by proper electrons of the plasma $k_{\rm ion}$.

In this case, the effective potential also has the corresponding form (Fig. 4). It can be either attractive ($a = 4.8\ \mu$m, $n_{\rm ph} = 10^{13}$ m^{-3}) or repulsive $a = 4.8$,13.6 μm, $n_{\rm ph} = 10^{14}$ m^{-3} or zero $a = 13.6\ \mu$m, $n_{\rm ph} = 10^{13}$ m^{-3} in case where photoemission is almost completely compensated by electron plasma currents.

It is obvious that both the distribution of plasma and the evolution of charge must essentially depend on the nonisothermality of plasma. This fact is confirmed by numerical calculations. In particular, an increase of the electron temperature up to 1 eV ((with the rest of parameters being the same as for Figs. 1—4) is accompanied with a rise of the stationary values of the charge by a factor of 20 (Fig. 5).

For all the figures, the charge of a dust particle $Z_{\rm gr}$ is dimensionless and measured in the units of the electron charge $e_e = -1.6 \times 10^{-19}$ Q, while the ion and electron concentrations are normalized to the electron concentration in the unperturbed region.

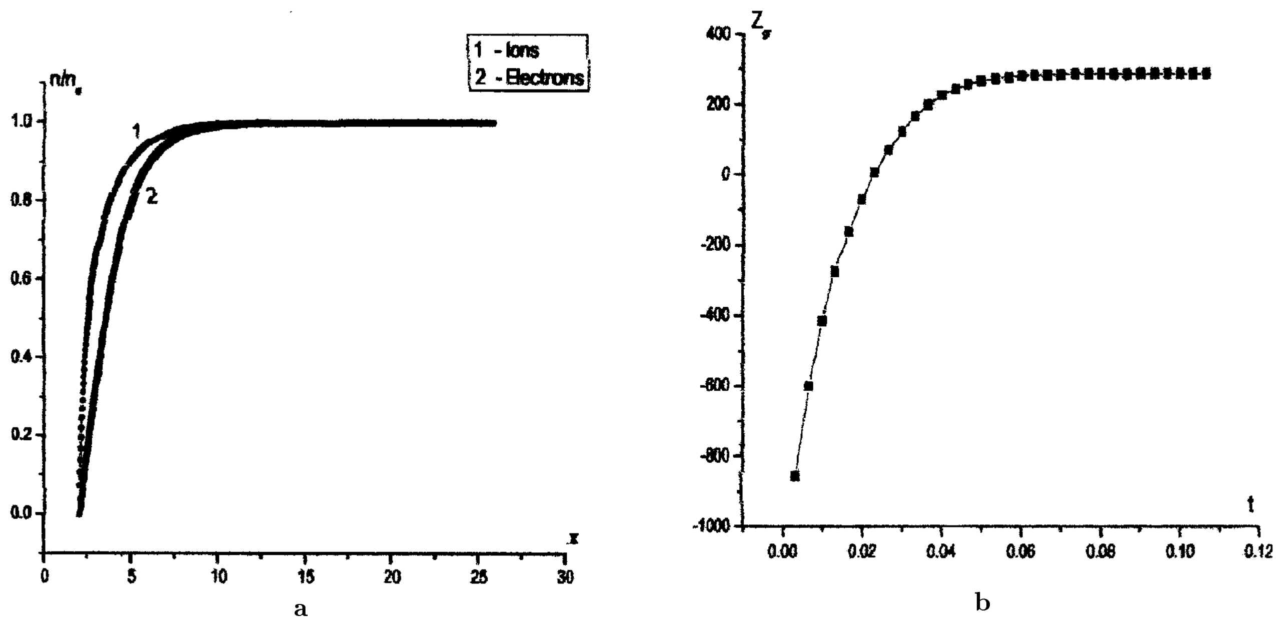


Fig. 3. Distribution of density numbers of electrons and ions in the neighborhood of a dust particle (a) and a variation of the dust particle charge with time (b) in the absence of a photoionization source $Q = 0$ m^{-3}/s for $a = 4.8$ μm, $n_{\rm ph} = 10^{14}$, $T_e/T_p = 1$, $T_p = 300$ K, $k_{\rm ion} = 10^{-20}$ m^3/s

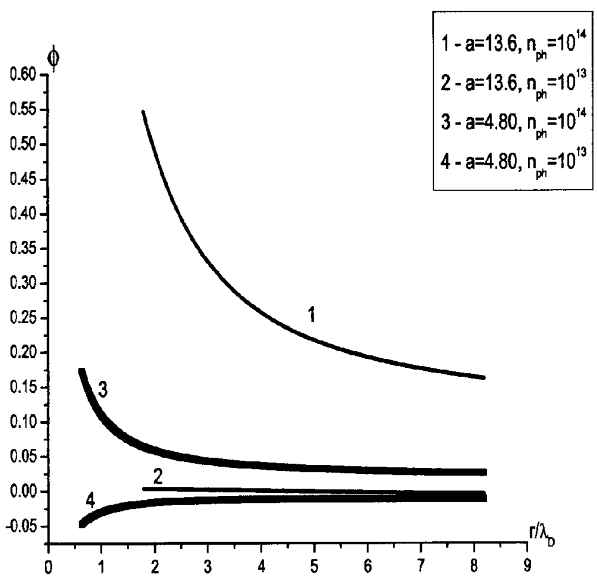


Fig. 4. Distribution of the potential for dust particles of radii $a = 4.8$, 13.6 μm; $T_e/T_p = 1$, $T_p = 300$ K, for $n_{\rm ph} = 10^{13}$, $n_{\rm ph} = 10^{14}$

4. Conclusions

On the basis of the numerical solution of the evolution problem, we have investigated the process of charging of a dust particle by plasma currents with regard for the photoemission of electrons from its surface and calculated the stationary distributions of electrons and ions around the dust particle. The influence of the volume ionization on the process of accumulation of charge and distributions of plasma particles is considered.

It is demonstrated that, in the absence of volume-ionization sources, the stationary charge of a dust particle is determined by the competition of photoemission and plasma currents coming onto its surface. The dust particle can be charged positively or negatively, depending on the intensity of photoemission. As was expected, the numerical calculations have confirmed that, with the intensity of photoemission being equal, its influence increases with the size of a dust particle. The plasma environment around a dust particle is formed in accordance to the sign and magnitude of its charge.

It is established that an increase of the electron temperature (a deviation from the isothermality) results in the amplification of the influence of plasma currents, which is expressed, in particular, through the intense accumulation of the negative charge by a dust particle and increasing the neutralization of photoemission.

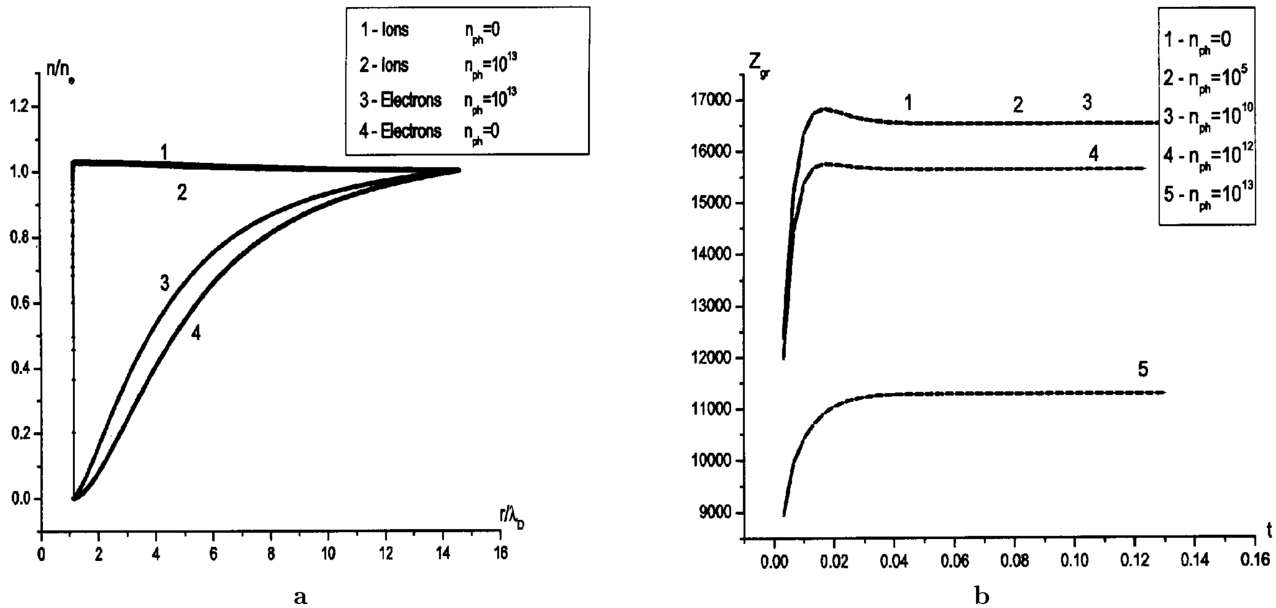


Fig. 5. Distributions of electrons and ions in the neighborhood of a dust particle (a) and the evolution of its charge (b) in the presence of a volume-ionization source $Q = 10^{22}$ m^{-3}/s and $T_e = 10000$ K, $T_p = 300$ K for various intensities of photoemission $a = 4.8$ μm

It is proved that the presence of volume-ionization sources increases the effects conditioned by plasma currents. For example, in the last case, the stationary value of the negative charge of a dust particle is several times higher by absolute magnitude than the corresponding value established in the absence of volume sources with all other conditions being equal.

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Received 10.03.04.
Translated from Ukrainian by H. Kalyuzhna

ВПЛИВ ЕМІСІЇ ЕЛЕКТРОНІВ НА ЗАРЯД ТА ЕФЕКТИВНИЙ ПОТЕНЦІАЛ ПОРОШИНКИ У ПЛАЗМІ

А. Загородній, В. Мальнев, С. Румянцев

Р е з ю м е

Числовими методами досліджено динаміку процесу заряджання порошинки в електрон-іонній плазмі за наявності зовнішніх джерел об'ємної іонізації, що утворюють плазму, та з урахуванням фотоемісії електронів з її поверхні. Розраховано стаціонарні розподіли концентрацій електронів та іонів в околі порошинки, її заряд та ефективний потенціал. Показано, що знак заряду порошинки визначається як її емісійними властивостями, так і інтенсивністю зовнішніх джерел іонізації. Результати чисельних розрахунків представлено у вигляді графіків.