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INFLUENCE OF POLARIZATION PHENOMENA ON THE DUST GRAIN CHARGE IN PLASMAS

Abstract. It is believed in the classical treatment of dust particle charging that the material of the dust is a perfect absorber, i.e. all the plasma particles that reach the grain surface are inevitably absorbed. This typically leads to that the grain charge is determined by the buffer plasma parameters and is not material dependent. On the other hand it is known that a charged double-layer exists near the surface of solids, and whenever an attempt is undertaken to pull out an electron from a solid, the polarization phenomena come to play an essential role to cause an attraction. This results in that to extract an electron from the bulk of the solid it is necessary to perform some work, which is called the work function. The main idea of this paper is to account for the polarization effects, which should ultimately lead to a microscopic theory for the charge of the dust particle in a plasma. To do so the interaction potentials of electrons and ions of the buffer plasma with the dust particles are chosen to treat the polarization effects. For the sake of simplicity it is assumed that the material of the dust particle is a conductor, and the polarization phenomenon is simply the electrostatic induction. The latter effect is empowered within the electrostatic image method, so that the polarization is responsible for an additional effective mechanism of attraction. The aforesaid interaction potential energy between the plasma particles and the dust consists of two parts. The first part is determined by the particle charge and the distribution of the plasma around it, i.e. the sheath formation. It is that way the charging of dust particles was interpreted in the literature until recently. The second part of the potential energy is governed by the interaction with surface charges of the dust matter stemming from the polarization effects. Consideration of the charging process is carried out within the orbital motion limited approximation, in which the trajectories of plasma particles, i.e. electrons and ions, are considered ballistic such that the interparticle collisions are completely ignored. To justify such an approach the mean free paths of plasma particles should be much greater than both the size of the dust and the so-called Debye screening radius. When the polarization effects are neglected, application of the conservation laws of energy and angular momentum is sufficient to determine the absorption cross sections of electrons and ions by the dust particle. If the dust grain is assumed polarizable, further consideration turns much more complicated because of the nature of the interaction, which leads to the attraction of both electrons and ions at rather small distances from the dust surface. Although, the angular momentum with respect to the field center is still conserved, subsequent calculations turn much more difficult because the dependence of the effective potential energy on the distance proves to be non-monotonic. This necessitates a numerical solution of an equation for the position of the maximum of the effective potential energy. Nevertheless, it is possible to find an approximate solution since the respective extremum is located very close to the particle surface. This allows one to calculate the electron and ion absorption cross sections, evaluate the corresponding fluxes and then to determine the dust charge as a function of the so-called coupling parameter.
Keywords:coupling parameter, orbit motion limited (OML) theory, absorption cross sections, polarization phenomena, image charge approximation.

Introduction

It has long been known that dust particles, immersed in a plasma, can form different structures with short- and long-range orders, which can be interpreted as liquid and crystalline phases, respectively [1-4]. In such systems, even phase transitions are observed and studied by different methods [5-7]. This straightforwardly testifies that a strong interaction does exists between the dust particles in the plasma, whose average energy can significantly exceed the thermal energy of their chaotic motion. Such nonideality in the system is a consequence of that, being placed in a plasma, the dust grains starts to intensively absorb electrons and acquire a high negative electrical charge, which can reach tens of thousands of the elementary [8,9]. Thus, it is clear that an ability to predict the electric charge of dust particles is crucial for correct explanation of all the physical properties of dusty plasmas.

It is well known that the problem of theoretical calculation of the dust particle charge in a plasma is closely related to the theory of a so-called Langmuir probe, which is widely used for plasma diagnostics. The standard approach here is to use the orbital motion limited approximation [10], which assumes that the buffer plasma remains quasi-neutral and Maxwellian far away from the dust grain, and the mean free paths of plasma particles are much greater than the characteristic size of the sheath. This allows one to consider only ballistic trajectories of electrons and ions, and further use of the conservation laws of energy and angular momentum makes it possible to derive the corresponding absorption cross sections, and, hence, to determine the charge of the dust particle, or the current-voltage characteristics of the Langmuir probe.

It is implied in the classical version of the orbital motion limited approximation that the interaction energy between the plasma particles and the dust grain are monotonic functions of the distance between them, which is not always accurate. Taking into account the shielding results in the appearance of the so-called absorption radius effect, which is caused by the onset of local maxima in the curve of the effective interaction energy with a centrifugal component included [11,12]. At the same time there is a need to treat the anisotropy of the ion flow near the dust grain, which is due to the action of accelerating field of the sheath [13].

It is clear that a variety of physical conditions, under which a dusty plasma is encountered, may lead to a deviation of the velocity distribution functions of electrons and ions from the Maxwellian, which immediately affects the charge of dust particles themselves. Such deviations of the velocity distribution function are particularly frequent in space dusty plasmas and various astrophysical objects. Thus, the charge of the dust particle was studied for the spherical Lorentzian velocity distribution function [14], for the so-called bi-Maxwellian electron distribution function [15] as well as for the power distribution function [16,17], obtained in the framework of non-extensive statistics, taking into account the long-range nature of the Coulomb interaction and the processes of the secondary electron emission [18].

A more consistent approach in the framework of the orbital motion limited theory was proposed in [19], where the Vlasov kinetic equation for a collisionless plasma was solved together with the Poisson equation. This allowed the authors to determine the so-called floating potential of the dust grain by imposing the equality of electron and ion fluxes on the dust surface, and thereby to calculate its electrical charge. Such a theoretical approach has the drawback that for sufficiently large dust particles ion concentration may give imaginary values [20]. It took a further complication of the orbital motion limited theory, including an account for the acceleration of ions in an electric field of the sheath [21,22]

With the growth of the plasma density the role of collisions, especially with the neutrals, increases dramatically so that the trajectories of electrons and ions in a plasma can no longer be regarded as ballistic. To treat them consistently it is necessary to solve the kinetic equation [23], which can be done both phenomenologically [24], and using computer simulations in the framework of the particles-in-cell method [25].

It is easy to imagine that the orbital motion limited approximation presumes that the electron and ion fluxes on the dust limited are determined by their spatial distribution and the charge of the dust particle itself. In this sense, the equilibrium charge of the dust grain, usually derived from the equality of electron and ions fluxes, is completely determined by the parameters of the surrounding plasma and independent of both the material the dust particle is made of and elementary processes taking place on its surface. That is why it turns out that the orbital motion limited approximation works rather well only for the dust particles whose dimensions are small compared to the Debye radius [26]. It is obvious that the above presented interpretation, in spite of its attractiveness, is unsatisfactory from the physical point of view, since it essentially exploits the idea that the surface of the dust particle is a perfect absorber of incoming electrons and ions [27]. To avoid such an unjustified assumption an attempt was made in [28,29] to develop a true microscopic theory that takes into account the near-surface states of electrons and ions appearing as a result of the polarization of the dust particle. Moreover, the electron emission from the surface of dust particles [30], which is determined by the work function of electrons, and the secondary electron emission [31] should be thoroughly included.

It should be noted that the electric charge and its dependence on the grain size can be measured in sophisticated experiments [32], which continue to develop at present [33,34]. It is remarkable that the dust particles can themselves be used to diagnose the buffer plasma by their motion around the cylindrical Langmuir probe [35].

Dimensionless plasma parameters

For the sake of simplicity this paper deals with the hydrogen buffer plasma with the electron number densityn_e and the proton number density $n_p = n_e = n$, in which a spherical macroscopic particle of radius R and the electric charge $-Z_d e$ is placed Since the dust particle is solitary, the quasineutrality condition $n_p = n_e = n$ is imposed

The state of the electron component of the plasma is described by the density parameter:

$$r_s = \frac{a}{a_B}, \quad (1)$$

where $a = (3/4\pi n)^{1/3}$ denotes the average distance between the electrons, $a_B = \hbar^2/m_e e^2$ stands for the first Bohr radius with $\hbar$ being the Planck constant and e being the elementary electric charge.

Another dimensionless parameter relevant for description of the state of the buffer plasma is the so-called called coupling parameter given by:

$$\Gamma = \frac{e^2}{ak_BT}, \quad (2)$$

where k_B is the Boltzmann constant, T designates the ambient temperature. It should be noted that coupling parameter (2) is common to represent the ratio of the average Coulomb interaction energy of the electrons to their average kinetic energy of thermal motion.

To take into account the finite dimensions of the dust particle, the size parameter is introduced as

$$D = \frac{a}{R}, \quad (3)$$

to show how many times the average distance between the buffer plasma particles is less than the radius of the dust grain.

Note that to determine the electric charge of the dust particle in the classical case it is sufficient to only point out one dimensionless parameter

$$\Gamma_R = \frac{e^2}{Rk_BT} = D\Gamma. \quad (4)$$

Absorption cross sections of electrons and protons

Consider the interaction of a proton with a spherical dust particle, which is made of a conductive material. To account for the polarization effects of the dust grain, the potential energy of the interaction is written with the aid of the charge image method as [36]:

$$U_{dp}(r) = -\frac{Z_d e^2}{r} - \frac{e^2R^3}{2r^2(r^2-R^2)}, \quad (5)$$

Let the dust particle absorb a proton with the fixed energy E and the impact parameter ρ. It is known [37] that this process is governed by the effective potential energy defined as

$$U^{eff}_{dp}(r, \rho, E) = -\frac{Z_d e^2}{r} - \frac{e^2R^3}{2r^2(r^2-R^2)} + E\frac{\rho^2}{r^2}. \quad (6)$$

It is known that for a non-monotonic potential like in (6), ρ_{dp} is obtained from the following relation:

$$\max U^{eff}_{dp}(r, \rho_{dp}, E)_{r\geq R} = E. \quad (7)$$

The numerical solution of equation (7) is found as follows. For a fixed value of the energy E it is necessary to find such $\rho = \rho_{dp}$ that the maximum of effective potential energy (6) should exactly be equal to the total energy E. Using the fact that the position of the maximum is closely located to the dust grain surface, equation (7) can be analytically solved to yield

$$\rho_{dp} = R\sqrt{1 + \frac{e^2}{8RE}\left[8Z_d - 3 + \sqrt{1 + 16Z_d + 32\frac{RE}{e^2}}\right]}. \quad (8)$$

If the polarization effects are neglected, the following classical result is recovered

$$\rho^{cl}_{dp} = R\sqrt{1 + \frac{Z_d e^2}{RE}}. \quad (9)$$

Figures 1 and 2 show a comparison of the absorption cross section of protons $\sigma_{dp} = \pi\rho^2_{dp}$ by the dust particle, calculated from expression (7) with formulas (8) and (9) for different values of the charge number Z_d. Since polarization effects lead to an additional attraction of the proton by the dust particle, they are responsible for an increase in the corresponding absorption cross section. Comparison of Figures 1 and 2 drives us to a conclusion that increasing the dust particle charge results in the growth of the absorption cross section of protons and analytical formulas (8) and (9) better describe its behavior since the polarization effects play less significant role. It is quite natural that formula (8) treats more accurately the behavior of the absorption cross section than formula (9), which is only valid for pure Coulomb interaction.

Consider the interaction of an electron with the same spherical dust particle. In this case the potential energy of the interaction is written with the aid of the charge image method as [36]:

$$U_{de}(r) = \frac{Z_d e^2}{r} - \frac{e^2R^3}{2r^2(r^2-R^2)}. \quad (10)$$

There is a significant difference for the interaction of the electron with the dust particle in comparison with its interaction with the proton.

Due to the mutual repulsion the electron absorption is only possible when its energy reaches the critical value E_c determined as:

$$E_c = maxU_{de}(r). \qquad (11)$$

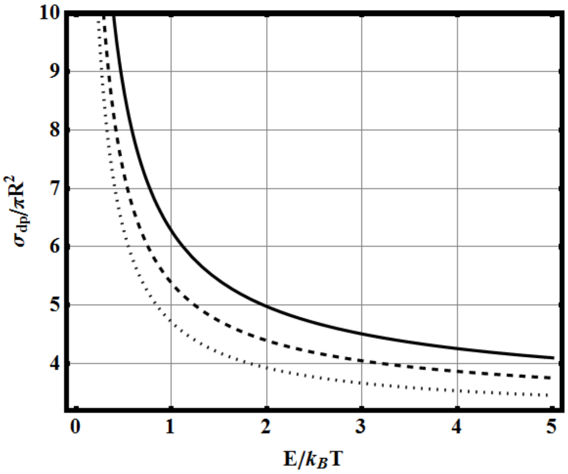

Figure 1. Absorption cross section of protons as a function of the energy of the incident proton at $Z_d = 5$, $\Gamma_R = 0.1$. Dotted line: exact value from expression (7); dashed line; formula (8); solid line: the formula (9)

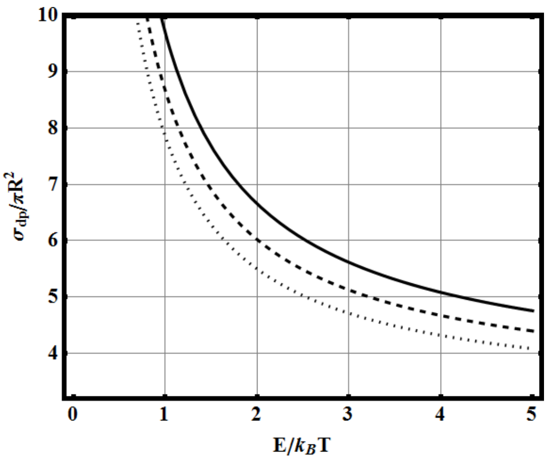

Figure 2. Absorption cross section of protons as a function of the energy of the incident proton at $Z_d = 15$, $\Gamma_R = 0.1$.. Dotted line: exact value from expression (7); dashed line; formula (8); solid line: the formula (9)

Equation (11) can be solved numerically since the rebound of electrons occurs close to the dust particle surface. Thus, an expansion in series gives rise to the following analytical result

$$E_c^a = \frac{e^2}{R}\left(Z_d + \frac{5}{8} - \frac{1}{8}\sqrt{17 + 16Z_d}\right). \qquad (12)$$

Note that in case of pure Coulomb interaction between the electron and the dust grain the critical energy is exactly found from the energy conservation law as follows

$$E_{critical} = \frac{Z_d e^2}{R}. \qquad (13)$$

Figures 3 and 4 provide comparison of exact expression (11) with approximate formulas (12) and (13). It can be seen that equation (12) better describes the exact data obtained from formula (11) than expression (13) which completely ignores the polarization of the dust particle. At the same time, it is rather obvious that the polarization phenomena cause an additional attraction of electrons, and thus the value of the critical energy is reduced as compared with the expression for pure Coulomb interaction (13).

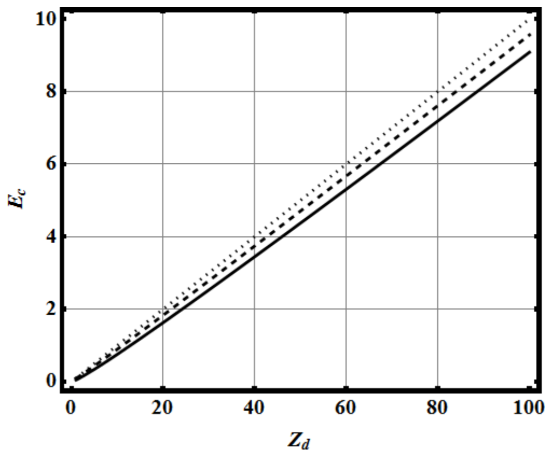

Figure 3. Ccritical energy of electrons as a function of the dust particle charge at $\Gamma_R = 0.1$. Dotted line: formula (11): dashed line: formula (12); solid line: formula (13)

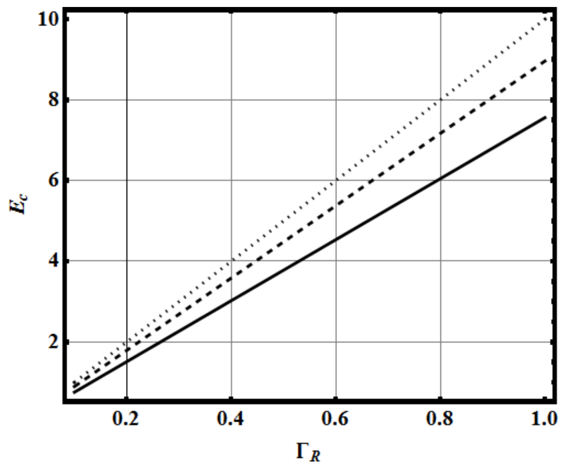

Figure 4. The dependence of the critical energy of electrons on the coupling parameter at $Z_d = 10$. Dotted line: formula (1): dashed line: formula (12); solid line: formula (13)

Let the dust particle absorb an electron with the fixed energy E and the impact parameter ρ . It is known [37] that this process is governed by the effective potential energy defined as

$$U^{eff}_{de}(r,\rho,E) = \frac{Z_d e^2}{r} - \frac{e^2 R^3}{2r^2(r^2-R^2)} + E\frac{\rho^2}{r^2}. \quad (14)$$

It is known that for a non-monotonic potential like in (14), ρ_{de} is obtained from the following relation:

$$\max U^{eff}_{dp}(r,\rho_{de},E)_{r\geq R} = E. \quad (15)$$

The numerical solution of equation (15) is found as follows. For a fixed value of the energy E it is necessary to find such $\rho=\rho_{de}$ that the maximum of effective potential energy (14) should exactly be equal to the total energy E. Using the fact that the position of the maximum is closely located to the dust grain surface, equation (15) can be analytically solved to yield

$$\rho_{dp} = R\sqrt{1-\frac{e^2}{RE}\left[Z_d+\frac{3}{8}+\frac{1}{8}\sqrt{1-16Z_d+32\frac{RE}{e^2}}\right]}. \quad (16)$$

If the polarization effects are neglected, the following classical result is recovered

$$\rho^{cl}_{dp} = R\sqrt{1-\frac{Z_d e^2}{RE}}. \quad (17)$$

In Figures 5 and 6 a comparison is made of the absorption cross section of electrons by the dust particle, calculated from the expression (15) with formulas (16) and (17) for different values of the charge number Z_d.

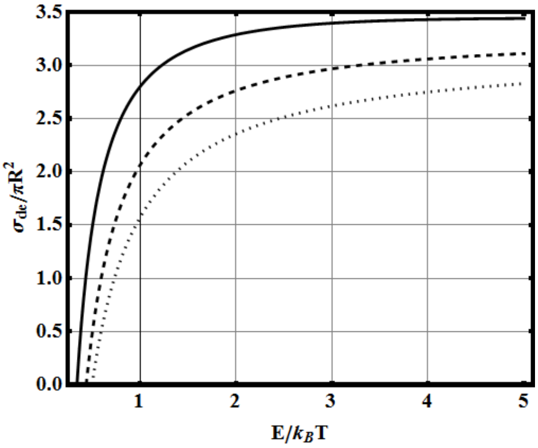

Figure 5. Absorption cross section of electrons by the dust particle as a function of the energy of the incident electron at $Z_d = 5$, $\Gamma_R = 0.1$. Dotted line: the exact value from expression (15); dashed line; formula (16); solid line: formula (17)

Since polarization effects lead to an additional attraction of electrons by the dust particle, they are responsible for an increase in the corresponding absorption cross section. A comparison of Figures 5 and 6 shows that an increase in the dust particle charge gives rise to the decrease of the absorption cross section, and analytical formulas (16) and (17) better describe its behavior since the polarization phenomena play less significant role. It is quite natural that formula (16) treats more accurately the behavior of the absorption cross section than formula (17), which is valid the case of the pure Coulomb interaction.

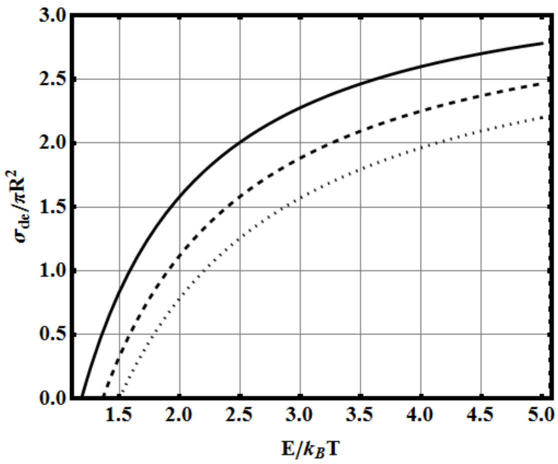

Figure 6. Absorption cross section of electrons by the dust particle as a function of the energy of the incident electron at $Z_d = 15$, $\Gamma_R = 0.1$. Dotted line: the exact value from expression (15); dashed line; formula (16); solid line: formula (17)

Dust grain charge

It is known that the proton flux on the surface of the dust particle is obtained from the relevant absorption cross section by integration over the velocity distribution function as:

$$J_p = n_p\int v\sigma_{dp} f_p(v)d\mathbf{v}, \quad (18)$$

where the Maxwellian distribution is

$$f_p(v) = (2\pi v_{Tp}^2)^{-3/2}\exp\left(-\frac{v^2}{2v_{Tp}^2}\right), \quad (19)$$

and $v_{Tp} = \sqrt{k_B T/m_p}$ stands for the thermal velocity of protons with the mass m_p.

Substituting the expression for the absorption cross section of protons obtained from (8) into (18), the following analytical approximation for the proton flux on the dust particle is found

$$J_p = \sqrt{\frac{8\pi k_B T}{m_p}}nR^2\left(1+\frac{e^2}{Rk_BT}\left[Z_d+\frac{\sqrt{1+16Z_d}}{8}-\frac{3}{8}\right]+\sqrt{\frac{\pi e^2}{8Rk_BT}}\,exp\left(\frac{e^2(1+16Z_d)}{32Rk_BT}\right)erfc\left(\sqrt{\frac{e^2(1+16Z_d)}{32Rk_BT}}\right)\right) \quad (20)$$

where

$$erfc(z) = 1-\mathrm{erf}(z) = 1-\frac{2}{\sqrt{\pi}}\int_0^z \exp(-t^2)\,dt \quad (21)$$

stands for the auxiliary error function.

Note that in the absence of the polarization effects expression (20) turns into the classical expression for the proton flux on the dust particle [9]

$$J_p^C = \sqrt{\frac{8\pi k_B T}{m_p}}\, nR^2 \left(1 + \frac{Z_d e^2}{R k_B T}\right). \qquad (22)$$

Figures 7 and 8 demonstrate a comparison of the proton flux on dust particles, calculated from expression (18), with formulas (20) and (22) for the fixed values of the charge Z_d.

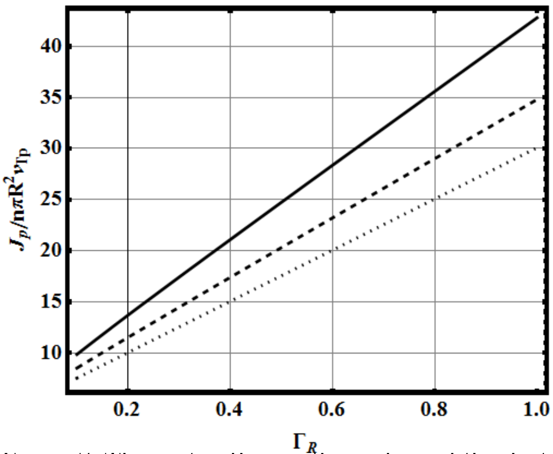

Figure 7. The proton flux on the surface of the dust particle as a function of the coupling parameter Γ_R at $Z_d = 5$. Dotted line: formula (22); dashed line: formula (20); solid line: formula (18)

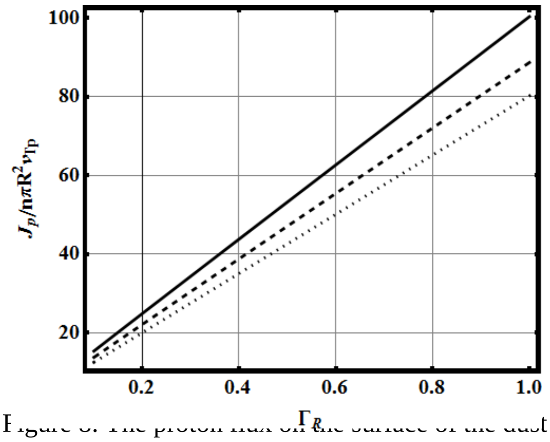

Figure 8. The proton flux on the surface of the dust particle as a function of the coupling parameter Γ_R at $Z_d = 15$. Dotted line: formula (22); dashed line: formula (20); solid line: formula (18)

Since polarization effects lead to an additional attraction of the proton by the dust particle, they result in an increase in the corresponding flux. A comparison of Figures 7 and 8 shows that the proton flux increases when the grain charge grows and analytical formulas (20) and (22) better describe its behavior since the polarization play less significant role. It is rather natural that formula (20) treats more accurately the behavior of the proton flux than formula (22), which is only valid for the case of the pure Coulomb interaction.

Similar to (19), the electron flux on the surface of the dust particle is determined by the absorption cross section as an integral over of the velocity distribution function

$$J_e = n_e \int v \sigma_{de} f_e(v) d\mathbf{v}, \qquad (23)$$

where

$$f_p(v) = (2\pi v_{Te}^2)^{-3/2} \exp\left(-\frac{v^2}{2v_{Te}^2}\right) \qquad (24)$$

and $v_{Te} = \sqrt{k_B T/m_e}$ stands for the thermal velocity of electrons with the mass m_e.

Substituting expression for the absorption cross section of electrons obtained from (16) into (23), the following analytical approximation for the electron flux on the dust particle is found

$$J_e = \sqrt{\frac{8\pi k_B T}{m_e}}\, nR^2 \Big[\Big(1 - \frac{e^2}{8Rk_BT}(\sqrt{17+16Z_d} - 2)\Big) \times \exp\Big(-\frac{e^2}{Rk_BT}\Big(Z_d + \frac{5}{8} - \frac{\sqrt{17+16Z_d}}{8}\Big)\Big)\Big) + \sqrt{\frac{\pi e^2}{8Rk_BT}} \times$$
$$\times\Big(1 + \exp\Big(-\frac{e^2(21+16Z_d - 4\sqrt{17+16Z_d})}{32Rk_BT}\Big)\Big)\sqrt{\frac{e^2}{8\pi Rk_BT}} \times$$
$$\times\sqrt{(21+16Z_d - 4\sqrt{17+16Z_d})} + erf\Big(-\sqrt{\frac{e^2}{32Rk_BT}}\Big) \times$$
$$\times\sqrt{(21+16Z_d - 4\sqrt{17+16Z_d})}\Big)\exp\Big(\frac{e^2(16Z_d-1)}{32Rk_BT}\Big) \qquad (25)$$

Note that in the absence of the polarization effects expression (25) turns into the classical expression for the electron flux on the dust particle [9]

$$J_e^C = \sqrt{\frac{8\pi k_B T}{m_e}}\, nR^2 \exp\left(-\frac{Z_d e^2}{R k_B T}\right). \qquad (26)$$

Figures 9 and 10 show a comparison of the electron flow on the dust particle, calculated from expression (23), with formulas (25) and (26) for fixed values of the charge Z_d. Since the polarization effects lead to an additional attraction of electrons by the dust particle, they result in an increase in the corresponding flux. A comparison of Figures 9 and 10 reveals that an increase in the dust particle charge results in the decrease of the electron flux, and analytical formulas (25) and (26) better describe its behavior since the polarization plays less significant role. It is rather natural that formula (25) treats more accurately the behavior of the electron flux than formula (26), which is valid for the case of the pure Coulomb interaction.

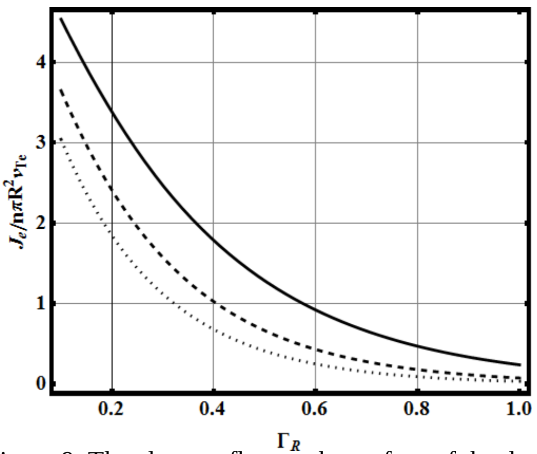

Figure 9. The electron flux on the surface of the dust particle as a function of the coupling parameter Γ_R at $Z_d = 5$. Dotted line: formula (26); dashed line: formula (25); solid line: formula (23).

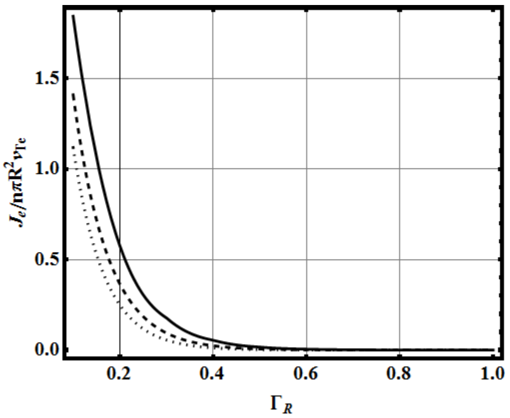

Figure 10. The electron flux on the surface of the dust particle as a function of the coupling parameter Γ_R at $Z_d = 15$. Dotted line: formula (26); dashed line: formula (25); solid line: formula (23)

It is known that the charge of the dust particle is determined by the equality of the electron and protons fluxes on its surface as

$$J_e = J_p. \tag{27}$$

In general, equation (27) must be solved numerically. However, using formulas (20) and (25) yields the following equation for the dust particle charge

$$\sqrt{\frac{m_e}{m_p}}(1+\frac{e^2}{Rk_BT}[Z_d+\frac{\sqrt{1+16Z_d}}{8}-\frac{3}{8}]+ \sqrt{\frac{\pi e^2}{8Rk_BT}}\,exp\,(-\frac{e^2(1+16Z_d)}{32Rk_BT})\,erfc\,(\sqrt{\frac{e^2(1+16Z_d)}{32Rk_BT}}))$$

$$=\left[\left(1-\frac{e^2}{8Rk_BT}\left(\sqrt{17+16Z_d}-2\right)\exp\left(-\frac{e^2}{Rk_BT}\left(\square\underline{5}\,Z_d+8-\frac{\sqrt{17+16Z_d}}{8}\right)\right)\right)+\sqrt{\frac{\pi e^2}{8Rk_BT}}\left(1+\exp\left(-\square x\frac{e^2}{32Rk_BT}\right.\right.\right.$$
$$\left.\times\,(21+16Z_d-4\sqrt{17+16Z_d})\right)\sqrt{\frac{e^2(21+16Z_d-4\sqrt{17+16Z_d})}{8\pi Rk_BT}}+$$
$$\left.\left.+\,\mathrm{erf}\left(-\sqrt{\frac{e^2(21+16Z_d-4\sqrt{17+16Z_d})}{32Rk_BT}}\right)\right)\exp\left(-\frac{e^2(16Z_d-1)}{32Rk_BT}\right)\right] \tag{28}$$

Note that in the absence of the polarization effects this equation turns into the classical equation for the dust particle charge [9]

$$\sqrt{\frac{m_e}{m_p}}\left(1+\frac{Z_de^2}{Rk_BT}\right)=\exp\left(\frac{Z_de^2}{Rk_BT}\right). \tag{29}$$

Figure 11 shows a comparison of the dust particle charge, calculated from expression (27), with formulas (28) and (28) as a function of the coupling parameter. Since the polarization effects lead to a stronger increase in the electron flux than the proton flux on the dust particle surface, this results in the growth of the grain charge. Equations (28) and (29) better describe the behavior of the grain charge at low values of the coupling parameter since the polarization plays less significant role in this case. It is rather natural that formula (28) treats more accurately the behavior of the dust particle charge than formula (29), which is valid for the case of the pure Coulomb interaction.

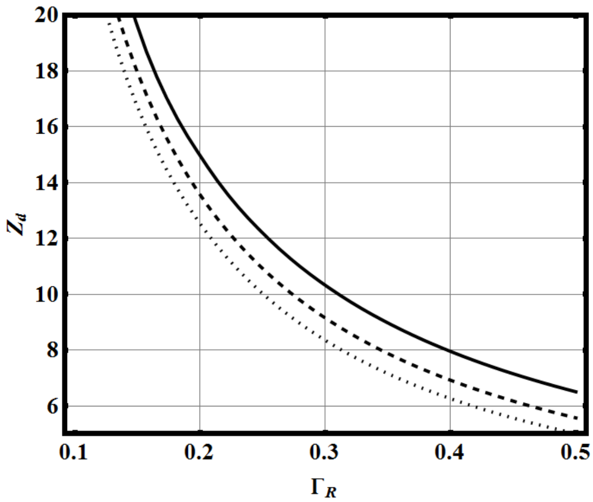

Figure 11. The charge of the dust particle as a function of the coupling parameter. Dotted line: formula (29); dashed line: formula (28); solid line: formula (27)

Conclusions

In this paper we have studied the proton and electron fluxes on the polarized dust particle immersed in the plasma. Consideration is entirely based on the orbital motion limited approximation, which implies the collisionless ballistic trajectories of plasma particles in an electric field of the charged dust grain. It has been demonstrated that the polarization effects lead to a substantial modification of the calculation technique.

It is assumed that the dust particle is negatively charged resulting in the electron repulsion and proton attraction. As a consequence, the absorption of electrons by the dust particle can only occur when the electron energy reaches a certain value, which turns linearly dependent on the charge of dust particle and the coupling parameter. It has been found that the proton and electron fluxes on the grain surface strongly depend on its charge and the coupling parameter of the buffer plasma. In particular, the proton flux grows linearly with increasing the grain charge and the coupling parameter, which is explained by their mutual attraction. The opposite pattern is observed for the the electron flux since the electrons are repelled by the negatively charged dust particle. Finally, the influence of polarization effects on the grain charge has been studied to show that it decreases when the coupling parameter grows. The polarization phenomena have been found to be responsible for an increase of the dust grain charge due to electron and proton fluxes behavior described above.

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INFLUENCE OF POLARIZATION PHENOMENA ON THE DUST GRAIN CHARGE IN PLASMAS

Abstract. It is believed in the classical treatment of dust particle charging that the material of the dust is a perfect absorber, i.e. all the plasma particles that reach the grain surface are inevitably absorbed. This typically leads to that the grain charge is determined by the buffer plasma parameters and is not material dependent. On the other hand it is known that a charged double-layer exists near the surface of solids, and whenever an attempt is undertaken to pull out an electron from a solid, the polarization phenomena come to play an essential role to cause an attraction. This results in that to extract an electron from the bulk of the solid it is necessary to perform some work, which is called the work function. The main idea of this paper is to account for the polarization effects, which should ultimately lead to a microscopic theory for the charge of the dust particle in a plasma. To do so the interaction potentials of electrons and ions of the buffer plasma with the dust particles are chosen to treat the polarization effects. For the sake of simplicity it is assumed that the material of the dust particle is a conductor, and the polarization phenomenon is simply the electrostatic induction. The latter effect is empowered within the electrostatic image method, so that the polarization is responsible for an additional effective mechanism of attraction. The aforesaid interaction potential energy between the plasma particles and the dust consists of two parts. The first part is determined by the particle charge and the distribution of the plasma around it, i.e. the sheath formation. It is that way the charging of dust particles was interpreted in the literature until recently. The second part of the potential energy is governed by the interaction with surface charges of the dust matter stemming from the polarization effects. Consideration of the charging process is carried out within the orbital motion limited approximation, in which the trajectories of plasma particles, i.e. electrons and ions, are considered ballistic such that the interparticle collisions are completely ignored. To justify such an approach the mean free paths of plasma particles should be much greater than both the size of the dust and the so-called Debye screening radius. When the polarization effects are neglected, application of the conservation laws of energy and angular momentum is sufficient to determine the absorption cross sections of electrons and ions by the dust particle. If the dust grain is assumed polarizable, further consideration turns much more complicated because of the nature of the interaction, which leads to the attraction of both electrons and ions at rather small distances from the dust surface. Although, the angular momentum with respect to the field center is still conserved, subsequent calculations turn much more difficult because the dependence of the effective potential energy on the distance proves to be non-monotonic. This necessitates a numerical solution of an equation for the position of the maximum of the effective potential energy. Nevertheless, it is possible to find an approximate solution since the respective extremum is located very close to the particle surface. This allows one to calculate the electron and ion absorption cross sections, evaluate the corresponding fluxes and then to determine the dust charge as a function of the so-called coupling parameter.

Keywords: coupling parameter, orbit motion limited (OML) theory, absorption cross sections, polarization phenomena, image charge approximation.

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ПОЛЯРИЗАЦИЯ ҚҰБЫЛЫСЫНЫҢ ПЛАЗМАДАҒЫ ТОЗАҢДАР ЗАРЯДТАЛУЫНА ӘСЕРІ

Аннотация: Тозаң бөлшектерді зарядтаудың классикалық көзқарасы бойынша тозаң материалы тамаша сіңіргіш деп саналады, сондықтан, түйіршік бетіне жанасқан барлық плазма бөлшектері түгелдей сіңіріліп әкетіледі. Осыған байланысты, жайшылықта түйіршік заряды буферлік плазма параметрлерінен анықталады және оның материалынан тәуелсіз. Тағы бір жағынан қатты денелердің беттік қабаты маңында зарядталған қос қабат болатыны белгілі. Және де, қатты денеден электрон ұшып шығатын болса, поляризация құбылысының әсерінен электрон қайта тартылады. Осының нәтижесінде электронды қатты денеден шығару үшін жұмыс мәлім жұмыс жасауға тура келеді. Бұл жұмыс шығу жұмысы деп аталады. Бұл зерттеудің негізгі идеясы поляризация эффектісін ескере отырып, соңында плазмадағы тозаң

бөлшектердің заряды үшін микроскопиялық теорияны алу. Тозаңды буферлі плазмада электрон және иондардың өзара әсерлесу потенциалын ескеру үшін поляризация эффектісі ескерілді. Берілген есепті жеңілдету мақсатында, тозаңды бөлшектің материалы өткізгіш болсын, поляризация құбылысын электростатикалық құбылысы ретінде қарасытырайық. Поляризация құбылысы қосымша эффективті жұмылдыру құбылысына жауап бергендіктен, оны электростатикалық көріністер әдісі ретінде қарастыруға болады. Жоғарыда айтылған плазма бөлшектері мен тозаңдардың өзара потенциалдық әсерлесу энергиясы 2 бөлімнен тұрады. 1 бөлімі, зарядты бөлшектер және оларды плазманың қоршай таралуы, яғни қабықшаның пайда болуы. Соңғы кезге дейін, бөлшектердің осылай зарядталуы еңбектерде талқыланбаған. Екінші бөлімі, тозаңды материяның беткейлі зарядтарымен әсерлесуінен пайда болатын потенциалдық энергия, яғни поляризация эффектісі. Зарядталу процессі шектік орбитальдық қозғалыс жуықтауында қарастырылады. Плазма бөлшектерінің (электрон, ион) траекториясы баллистикалық түрде болады, бөлшектердің өзара соқтығысуын ескермеуге болады. Мұндай жуықтауды қолдану үшін, плазманың еркін жүру жолы бөлшектердің өлшемінен және экрандалу Дебая радиусынан үлкен болу керек. Егер поляризация құбылысын ескермесек, тозаңды бөлшектің иондары мен электрондарының жұтылу қимасын анықтау үшін импульс моменті мен энергияның сақталу заңы жеткілікті. Егер тозаң түйіршіктері поляризацияланатын болса, онда беттік тозаңдар мен электрон мен иондар арасындағы салыстырмалы алыс емес ара қашықтықта өзара тартылуына алып келеді, мұндай жүйені қарастыру әлдеқайда қиын. Өріс центріне қатысты импульс моменті сақталғанымен, эффективті потенциал энергиясының ара қашықтықтан тәуелділігі монотонды болмағандықтан, есептелу қиындай түседі. Сондықтан эффективті потенциалдық энергияның максимумын табу үшін теңдеуді сандық түрде шешуге тура келеді. Бірақ, сәйкес экстремумдар бөлшектің бетіне жақын орналасқандықтан, жуық шешімдерді табуға болады. Мұндай жуықтау арқылы электрондардың қимасын және иондардың жұтылуын, олардың сәйкес ағынын, тозаңды зарядтардың байланыс параметрінен тәуелділігін табуға болады.

Түйінді сөздер: байланыс параметрі, шектелген орбитальдық қозғалыс жуықтауы, жұтылу қимасы, поляризация, кескіндеу әдісі.

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ВЛИЯНИЕ ПОЛЯРИЗАЦИИ НА ЗАРЯД ПЫЛИНКИ В ПЛАЗМЕ

Аннотация: В классической подходе к определению заряда частиц пыли считается, что материал пылинки является идеальным поглотителем, т.е. все частицы плазмы, которые достигают ее поверхности неизбежно поглощаются. Это, как правило, приводит к тому, что заряд пылинки определяется параметрами буферной плазмы и не зависит от ее материала. С другой стороны, известно, что вблизи поверхности твердых тел существует двойной заряженный слой, и всякий раз, когда предпринимается попытка вытянуть электрон из твердого тела, начинает играть существенную роль явление поляризации, приводящее к появлению притяжения. Это ведет к тому, что для извлечения электрона из объема твердого тела необходимо совершить работу, которая называется работой выхода. Основная идея этого исследования заключается в учете поляризационных эффектов, которая в конечном итоге должно привести к микроскопической теории для определения заряда частицы пыли в плазме. Для этого во взаимодействие электронов и ионов буферной плазмы с частицами пыли вводится метод электростатических изображений. Для простоты предполагается, что материал частицы пыли является проводником, а явление поляризации сводится к электростатической индукции. Это явление легко описывается в рамках метода электростатического изображения, так что поляризация отвечает за дополнительный эффективный механизм притяжения. При этом потенциальная энергия взаимодействия между частицами плазмы и пыли состоит из двух частей. Первая

часть определяется зарядом частиц и распределением плазмы вокруг нее, то есть формированием поверхностного плазменного слоя. Только этот способ рассмотрения зарядки частиц пыли рассматривался в литературе до недавнего времени. Вторая часть потенциальной энергии определяется взаимодействием с поверхностными зарядами материала пылинок и определяется поляризационными эффектами. Рассмотрение процесса зарядки осуществляется в рамках приближения ограниченного орбитального движения, в котором траектории частиц плазмы, т.е. электронов и ионов, считаются баллистическими, так что столкновениями полностью пренебрегают. Для того, чтобы оправдать такой подход длины свободного пробега частиц плазмы должна быть значительно больше, чем размер пылинок и дебаевской радиусом экранирования. Когда поляризационными эффектами можно пренебречь, применение законов сохранения энергии и момента импульса достаточно для определения сечений поглощения электронов и ионов пылевой частицей. Если пылевая частица предполагается поляризуемой, то дальнейшее рассмотрение оказывается гораздо более сложным из-за изменившегося характера взаимодействия, который приводит к притяжению электронов и ионов при сравнительно небольших расстояниях от поверхности пыли. Несмотря на то, что угловой момент относительно силового центра по-прежнему сохраняется, последующие расчеты оказываются гораздо сложнее, потому что зависимость эффективной потенциальной энергии от расстоянии оказывается немонотонной. Это приводит к необходимости численного решения уравнения для положения максимума эффективной потенциальной энергии. Тем не менее, можно найти приближенное решение, поскольку соответствующий экстремум расположен очень близко к поверхности пылевой частицы. Это позволяет вычислить сечения поглощения электронов и ионов, вычислить соответствующие потоки, а затем определить заряд пылинки в зависимости от так называемого параметра связи.

Ключевые слова: параметр связи, приближение ограниченного орбитального движения, сечения поглощения, поляризация, метод изображения.