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Charging of dust grains in weakly ionized plasma

J.Vanchinkhuu[1], L.N.Hau[2]

[1] Department of Physics, NUM, 210646, Ulaanbaatar, Mongolia
[2] Institute of Space Science, NCU, Jhongli, Taiwan

The charging of dust grains in weakly ionized high pressure plasma is considered in drift-diffusion approximation which is valid for dusty plasma under high pressure as atmospheric plasma. The dependence of dust potential on the number density of grains and the temporal evolution grain charge are taken. It is shown that the charging time of grain in high pressure plasma is smaller than that of grain in low pressure plasma. By using the Poisons equation, the potential distribution around the dust particle is taken.

Introduction

For last years, the studies of dusty plasma and its contemporary applications have become one of the most attracting subjects in plasma physics [12]. The primary point in dusty plasma research is charging process of dust grains and this has been studied by various authors [3, 4]. Dust grains in plasma can be charged due to various mechanisms namely, emission, impact ionization and the attachment of charged particles to the grain surface. The grains in low temperature plasma are charged mainly by collecting plasma particles to itself. When charged plasma particles (electrons and ions) hit the surface of grains, they are attached to it and finally recombine on it. In real case, every plasma particle hitting the grain's surface is not attached to grains and so, one should introduce an attaching coefficient characterizing the attachment however, in present case, this coefficient is not so important and can be chosen equal to 1. To describe the charging process of dust grains in low temperature plasma, one uses OLM approximation in which charging process depends on charging cross sections determined by the impact parameter of plasma particles to a grain. In this approach, plasma particles approaching grains to distances smaller than the particle size are assumed to be attached. This approach is valid when the size of dust grains, r_d are greatly smaller than l, the mean free path of plasma particle, $r_d << l_e, l_i$ [051]. But, for a weakly ionized, high pressure plasma in which the inequality $l << r_d$, λ_D holds [5], we can not use the OLM approximation in describing the charging process. In this case, the diffusion character of plasma particles' motion determines their attachment to the grains and the charging of grains are described in drift-diffusion approximation [6].

This paper addressed to the charging process of dust particles in weakly ionized, high pressure plasma by drift diffusion approximation.

Basic theory of charging in drift-diffusion approximation

We consider charging process of dust grains in weakly ionized high pressure plasma. The charging equation of dust grains is given by

$$\frac{dQ_d}{dt} = \sum_j I_i , \qquad (1)$$

where Q_d -the charge of grain, I_j -charging current corresponding to the current carried by j species of plasma particles, t- time.

Assuming that the motion of charged particles is determined by diffusion and drift by the action of electric field of charged grains, one can get the following equation for the charging current at r distance [6]

$$I_j = 4\pi r^2 (\mu_j n_j E - D_j \frac{dn_j}{dr}), \qquad (2)$$

where n_j -number density of charged particles, D_j , μ_j -the diffusion coefficient and the mobility for j species of plasma particles, $E = -\frac{d\varphi_d}{dr} = -\frac{Q_d}{r^2}$ -the electric field around the dust grain, φ_d -grain's potential, Q_d –the charge of dust grain. The charging current can be independent of r, if there are not recombinations in space. So, this equation is assumed as the equation for the number density of charging particles. The number density of charging particles equals to zero at the grain surface and tends to the equilibrium value at large distance from the grains. So, the following boundary conditions are imposed on the equations for the number density

$$n_j(r = r_d) = 0,\ n_j(r = \infty) = n_{j0}. \qquad (3)$$

Solving the equation with the given boundary conditions, one can find the ion and electron currents to the grain surface as respectively,

$$I_i = \frac{4\pi e^2 Q_d D_i n_{i0}}{T_i} \Big/ \left\{ \exp\left(\frac{Q_d e}{T_i r_d}\right) - 1 \right\}, \qquad (4)$$

$$I_e = -\frac{4\pi e^2 Q_d D_e n_{e0}}{T_e} \Big/ \left\{ 1 - \exp\left(-\frac{Q_d e}{T_e r_d}\right) \right\} \qquad (5)$$

where $\varphi_d \equiv \frac{Q_d}{r_d}$ - grain surface potential. Here, we have used the Einstein relation,

$$D_j / \mu_j = T_j / e_j. \qquad (6)$$

The equilibrium charge neutrality condition in dusty plasma reads

$$en_{i0} - en_{e0} + Q_{d0} n_d = 0. \qquad (7)$$

Because of high mobility of electrons, the corresponding electron current to the grain surface exceeds ion current and the neutral grain are charged negatively in initial stages of charging process. Since the negative potential of the grain repulses electrons and attracts ions, the grain charge varies until two currents equal to each other. Therefore, one can find the grain charge by using this equilibrium current,

$$I_e + I_i = 0. \qquad (8)$$

This equation with charge neutrality condition gives the following equation for the grain potential:

$$4\pi r_d n_d \lambda_{De} \frac{\varphi_d e}{T} = 1 - \frac{\mu_e}{\mu_i} \exp\left(-\frac{\varphi_d e}{T}\right). \qquad (9)$$

This is written for the number of electron's charge, z_d on the grain as

$$-B_e \frac{z_d e^2}{r_d T} = 1 - \frac{\mu_e}{\mu_i} \exp\left(-\frac{z_d e^2}{r_d T}\right), \qquad (10)$$

where $B_e = 4\pi r_d \lambda_{De} n_d$. This equation enables us to evaluate the charge and potential of charged grains. By using this relation, we can also find the dependence of grain's charge on dust number density (Fig. 1).

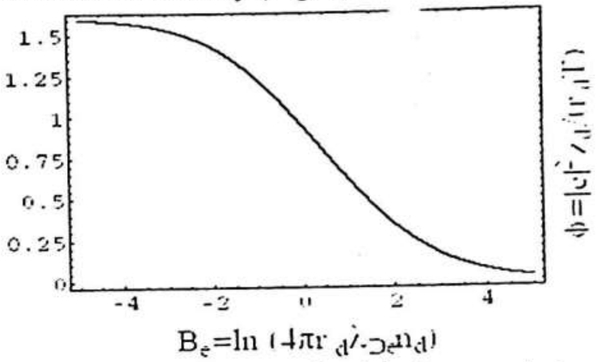

Fig. 1. The dependence of grain's charge on dust number density

Charge evolution

The charge evolution on a dust grain is given by the charging equation. Inserting (4), (5) into (1) with the assumptions $n_{e0} = n_{i0} = n_0$, $T_i = T_e$ yields

$$\frac{dQ_d}{dt} = \frac{4\pi e^2 Q_d N_0}{T} \frac{D_i - D_e \exp\left(\frac{Q_d e}{Tr_d}\right)}{\exp\left(\frac{Q_d e}{Tr_d}\right) - 1} \qquad (11)$$

The exact numerical solution for the equation (11) is shown on Fig. 2. This shows that the grains are charged very quickly and its value saturates to $\sim 10^4 e$. The temporal change for the number of electron on grain, $z_d = Q_d / e$ depicted on Fig. 2 shows that the grain charge depends substantially on grain sizes.

When the equality, $\frac{eQ_d}{Tr_d} << 1$ holds true, this equation is changed to

$$\frac{dQ_d}{dt} = 4\pi e Q_d n_0 \left(D_i - D_e - \frac{D_i + D_e}{2} \frac{q_d e}{Tr_d} \right). \qquad (12)$$

The analytical solution of this equation is given as

$$Q_d = Q_{d0}(1 - e^{-t/\tau}) \qquad (13)$$

where $Q_{d0} = \frac{2Tr_d}{e}\frac{D_i - D_e}{D_i + D_e}$ gives the maximum or equilibrium value of the grain charge, $\tau = \frac{2\pi e^2 n_0}{T}(D_e + D_i)$ -the charging time which does not obviously depend on grain size. In a plasma of $T = 1.5$ eV, N_0 =2.3x10^{10} cm^{-3}, a spherical grain of radius r_d =.0001 cm acquires $Q_{d0} = -0.000299$ Vxcm charge in $\tau \sim 8.8\cdot 10^{-8}$ s. This shows that grains in weakly ionized, high pressure plasma are charged more rapidly compared to grains in low pressure plasma [6, 8]. These estimations are quite agreed to experimental results [7].

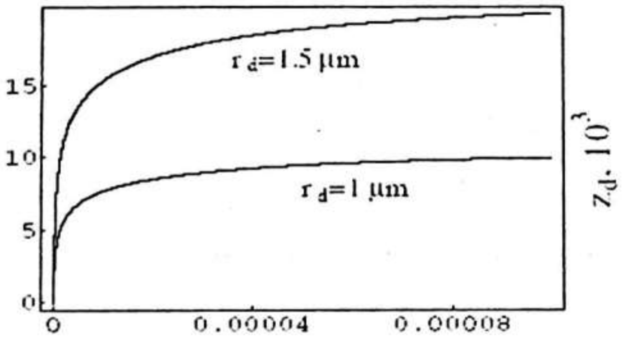

Fig.2 Temporal change of electron numbers embedded on dust grain.

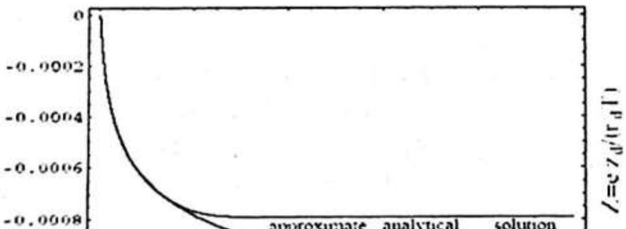

Fig. 3. Temporal evolution of dust grain's charge

The exact and approximate numerical solutions for the equation (11) are shown on Fig. 3.

Potential distribution around dust

In this approach, we can find the potential distribution around a charged grain by using the charge neutrality condition and the Poisson equation in the spherical coordinate:

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\varphi}{dr}\right) = 4\pi e(n_e - n_i - \frac{Q_d}{e}n_d)$$

$$n_{e0} - n_{i0} - \frac{Q_d}{e}n_d = 0$$

The number density of electron and ion are found from equation (2) as:

$$n_j(r) = \frac{I_j T_j}{4\pi e^2 Q_d D_j}\left(e^{\frac{eQ_d}{T_j}\left(\frac{1}{r}-\frac{1}{r_d}\right)} - 1\right).$$

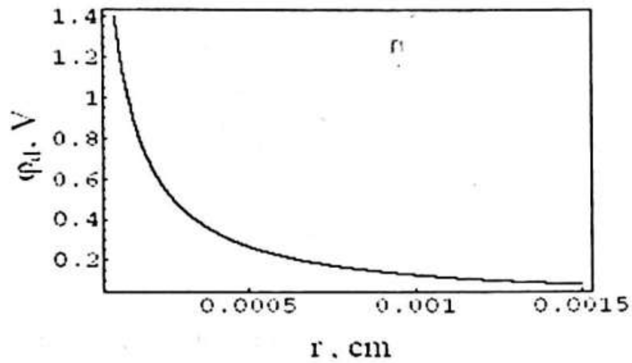

Fig.4 Potential distribution around the dust particle in weakly ionized plasma.

We assume that dusts don't participate in formation Debay's screening. In this case, the third term in the right hand side of the equation is ignored. But, a for high pressure plasma, dust grains have effects and in this case, the potential distribution is depicted on Fig. 4.

Conclusion and discussion

We have considered the charging process of a monodispersed dust particles in weakly ionized plasma. All the numerical result are taken by using Mathematica. Although it is not shown in the Fig. 4, the potential around dust increases on sufficiently far from the particle. In our opinion, this shows that dust potential has the unscreened part. This may be resulted from the non Debay potential of the dust particle in weakly ionized plasma. The results are applicable to dusts in weakly ionized dusty plasma like near Earth plasma.

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