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The effects of ion temperature on dust charging in the sheath of dusty plasmas

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Abstract. Dust charging in the sheath is investigated with the single dust model. The sheath profile and variation of dust charge are revealed under the effect of ion temperature. It is shown that the dust particles are rapidly positively charged in the pure ion sheath near the wall and that the ion motion effectively shifts the zero-point of the dust charge to the wall.

1. Introduction

There has recently been an interest in the charging of dust grains in plasma and its effect not only on dust dynamics in astrophysical and solar system environments, but also in laboratory plasma processing and semiconductor manufacturing. Also, it has been discovered experimentally that dust grains can cause serious problems in the manufacturing of semiconductor material during plasma processing. In order to develop methods by which to remove such contaminants from the system, a proper understanding of grain charging becomes essential. A number of theoretical and experimental investigations have carried out for understanding the charging of dust grains in a plasma under different conditions [1–13]. Barkan et al. [4] investigated the charging of dust grains in a plasma in which there are Maxwellian electron and ion collection currents. They theoretically calculated the dust grain surface potential by the condition of zero net current, and also conducted a laboratory experiment to verify their theoretical result. Similarly, Walch et al. [5] studied the charging of dust grains in a plasma containing Maxwellian electrons and ions as well as energetic electrons. They also verified their theoretical results in their laboratory experiments. Konstantin et al. [6] investigated dust charging in dusty plasmas subjected to strong UV radiation. Mamun and Shukla [7] investigated the role of negative ions on the charging of dust grains in a plasma. They brought two models for negative ion distributions and compared the two kinds of results. Vladimirov and Cramer investigated equilibrium and levitation of dust in a collisional plasma with ionization [8] and Samarian and Vladimirov theoretically and experimentally studied the charge of dust particles in a plasma [9]. Ostrikov et al. [10] and Robertson et al. [11] investigated dust charging and trapping in the sheath of a fluorocarbon plasma with negative ions.

In this paper, using a single dust particle model we study the dust charging in the sheath in a plasma composed of Boltzmannian electrons and warm ions

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as well as single dust particles. This single dust charging model is one in which the dust particles are considered to be isolated from one another; that is, the influence on the charging of one particle by the other neighboring particles can be ignored. This model is satisfactory for a dust cloud in which the Debye spheres (spherical volume around the dust particles outside which the dust particle charge is effectively screened out by the plasma) of the dust particles do not overlap [12]. In Sec. 2, the analytical model of the sheath structure of the dusty plasma and the dust charging model are formulated. In Sec. 3, the numerical results of ion temperature effects on the sheath structure and the dust charging in the sheath are presented. Finally, a short summary is given in Sec. 4.

2. Analytical model for the dust grains in the sheath

We consider the steady, collisionless and unmagnetized plasma sheath in contact with a planar wall. The boundary between the plasma ($x < 0$) and the sheath ($x > 0$) is at $x = 0$. The boundary is also called the sheath edge where spatial potential is assumed to be zero.

The electron is assumed to be in thermal equilibrium due to its mobility, and therefore the electron density obeys the Boltzmannian distribution,

$$n_{\mathrm{e}} = n_{0\mathrm{e}} \exp\left(\frac{e\phi}{kT_{\mathrm{e}}}\right) \tag{1}$$

where ϕ is the spatial electric potential in the sheath, e is the electron charge, T_{e} is the electron temperature and $n_{0\mathrm{e}}$ is the electron density at the sheath edge where $x = 0$ and $\phi = 0$.

The ion obeys equations of continuity

$$n_{\mathrm{i}} v_{\mathrm{i}} = n_0 v_0 \tag{2}$$

where n_{i} and v_{i} are the positive ion density and velocity in the sheath, respectively, v_0 is the ion entering-sheath velocity towards the wall and n_0 is the ion density at the sheath edge, and the momentum

$$m_{\mathrm{i}} v_{\mathrm{i}} \frac{dv_{\mathrm{i}}}{dx} + \frac{T_{\mathrm{i}}}{n_{\mathrm{i}}} \frac{dn_{\mathrm{i}}}{dx} = -e\frac{d\phi}{dx}, \tag{3}$$

where m_{i} and T_{i} are ion mass and temperature, respectively.

The dust charge q_{d} is determined by equation

$$\frac{dq_{\mathrm{d}}}{dt} = I_{\mathrm{e}} + I_{\mathrm{i}} \tag{4}$$

which describes charge conservation. In fact, the variable dust charge is determined by the electron and ion currents entering the particle, as governed by the potential difference between the particle surface and the local plasma. Other effects, such as secondary-electron and photoelectron currents associated with possible high-energy electrons and intense UV radiation, are not considered. Thus, the particle current from the Boltzmannian electrons is [1]

$$I_{\mathrm{e}} = -\pi r^2 e \left(\frac{8T_{\mathrm{e}}}{\pi m_{\mathrm{e}}}\right)^{1/2} n_{\mathrm{e}} K_{\mathrm{e}}(q_{\mathrm{d}}) \tag{5}$$

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and that from the ions is [1]

$$I_{\rm i}=\pi r^2 e n_{\rm i} v_{\rm i}\left[\frac{\exp\left(-m_{\rm i}v_{\rm i}^2/2T_{\rm i}\right)}{\sqrt{\pi}\sqrt{m_{\rm i}v_{\rm i}^2/2T_{\rm i}}}+\left(1+\frac{T_{\rm i}}{m_{\rm i}v_{\rm i}^2}-\frac{2eq_{\rm d}}{rm_{\rm i}v_{\rm i}^2}\right)\operatorname{erf}\left(\sqrt{m_{\rm i}v_{\rm i}^2/2T_{\rm i}}\right)\right] \tag{6}$$

where r is the dust particle radius, $K_{\rm e}(q_{\rm d})=\exp(eq_{\rm d}/rT_{\rm e})$ when $q_{\rm d}<0$, and $K_{\rm e}(q_{\rm d})=1+eq_{\rm d}/rT_{\rm e}$ when $q_{\rm d}>0$. We note that the characteristic time for dust motion is of the order of tens of milliseconds for micrometer-sized grains, while the dust charging time, or that for the grain to be charged from zero to the (relative to the ambient plasma) floating potential, is typically of the order of 10^{-8} s [13]. Thus, we approximately have $I_{\rm i}+I_{\rm e}=0$.

The system is completed by the Poisson equation

$$\frac{d^2\phi}{dx^2}=-4\pi e(n_{\rm i}-n_{\rm e}). \tag{7}$$

For simplicity, we introduce dimensionless quantities $\Phi=-e\phi/T_{\rm e}$ and $\Phi_{\rm d}=eq_{\rm d}/rT_{\rm e}$, which is the normalized dust surface potential, and normalize the x coordinate $X=x/\lambda_{\rm e}$ with respect to the electron Debye length $\lambda_{\rm e}=(T_{\rm e}/4\pi n_{\rm e0}e^2)^{1/2}$. We also define the ion Mach number $M_{\rm i}=v_{\rm i0}/c_{\rm is}$, where $c_{\rm is}=(T_{\rm e}/m_{\rm i})^{1/2}$, and thus $V_{\rm i}=v_{\rm i}/c_{\rm is}$ is the normalized ion velocity. Accordingly, the above equations can be written as:

$$N_{\rm e}=n_{\rm e}/n_{\rm e0}=\exp(-\Phi), \tag{8}$$

$$N_{\rm i}=n_{\rm i}/n_{\rm i0}=M_{\rm i}/V_{\rm i}, \tag{9}$$

$$\left(V_{\rm i}-\frac{T_{\rm ie}}{V_{\rm i}}\right)\frac{dV_{\rm i}}{dX}=\frac{d\Phi}{dX}, \tag{10}$$

where $T_{\rm ie}=T_{\rm i}/T_{\rm e}$ and

$$K_{\rm e}(\Phi_{\rm d})-\alpha M_{\rm i}\exp(\Phi)K_{\rm i}(\Phi_{\rm d},V_{\rm i})=0 \tag{11}$$

where $K_{\rm e}(\Phi_{\rm d})=\exp(\Phi_{\rm d})$ when $\Phi_{\rm d}<0$, and $K_{\rm e}(\Phi_{\rm d})=(1+\Phi_{\rm d})$ when $\Phi_{\rm d}>0$, as well as $\alpha=(\pi m_{\rm e}/8m_{\rm i})^{1/2}$ is a coefficient which is approximately 0.0023 for an argon plasma, and

$$K_{\rm i}(\Phi_{\rm d},V_{\rm i})=\frac{\exp\left(-V_{\rm i}^2/2T_{\rm ie}\right)}{\sqrt{\pi}(V_{\rm i}\sqrt{2T_{\rm ie}})}+\left(1+\frac{T_{\rm ie}}{V_{\rm i}^2}-\frac{2\Phi_{\rm d}}{V_{\rm i}^2}\right)\operatorname{erf}(V_{\rm i}/\sqrt{2T_{\rm ie}}). \tag{12}$$

The Poisson equation becomes

$$\frac{d^2\Phi}{dX^2}=-N_{\rm e}+N_{\rm i}. \tag{13}$$

3. Numerical results of ion temperature effects

We have numerically calculated (8)–(13) with the parameters $r=1\ \mu$m, $T_{\rm e}=2$ eV for an argon plasma. We assumed $M_{\rm i}=1.2$, according to the Bohm sheath criterion [14]. Figure 1 shows that the electron and ion densities in the sheath vary in the cases of different temperature ratios γ. Both the electron density and ion density fall slowly due to the ion thermal velocity. Moreover, the slower the two densities fall, the higher the ion temperature $T_{\rm i}$ becomes. For a certain temperature ratio γ, there exists a position ($x=10-20\lambda_{\rm e}$) where electrons begin to vanish and the

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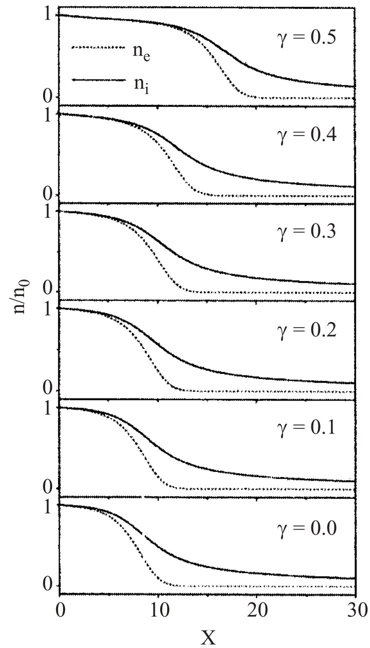

Figure 1. Normalized density profiles of ions and electrons n_i, n_e versus spatial position X with different γ values.

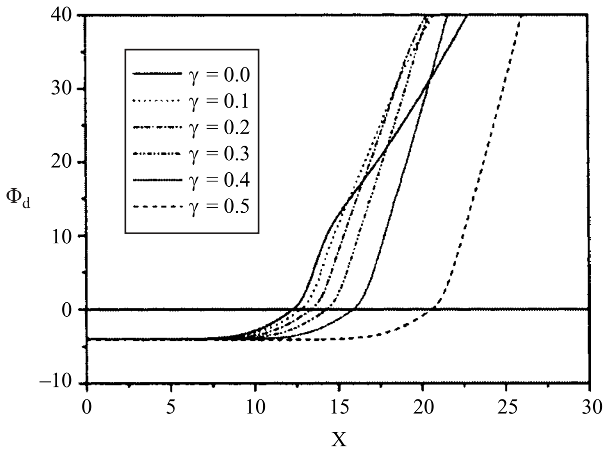

Figure 2. Normalized surface potential Φ_d versus spatial position X with different γ values.

sheath becomes a pure ion one. Figure 2 shows dust charging in the sheath in cases of different γ. Near the sheath edge within the sheath the dust particles are charged negatively and along with the distance to the wall the negative charge is monotonically decreasing to zero in magnitude. The position where the charge of dust is zero becomes farther out of the sheath edge for larger γ. Then the dust particles are charged positively. Furthermore, the positive charge of dust increases rapidly away from the sheath towards the wall. The electrostatic force on dust is towards the wall when the dust is charged positively and, therefore, the dust

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particles are quickly transmitted to the wall. This is the reason why positively-charged particles are not found in the experiment.

4. Summary

In summary, our analysis of dust charging in the sheath is based on the single model in which the dust density must roughly satisfy $n_d < 7 \times 10^4$ cm^{-3} for a plasma with $n_e \approx n_i = 10^9$ cm^{-3}, $T_e = 1$ eV and $T_i = 0.1$ eV. Otherwise, if the dusts are too dense, we have to use the continuous medium model. In this paper, we investigated the dust charging in the sheath by considering the effect of ion temperature. It was shown that ion thermal movement will act to make both ion and electron densities fall slowly in the sheath. At the same time, the ion thermal movement serves to make the zero-point of dust charge move toward the wall. In the pure-ion sheath near the wall, the dusts are rapidly charged positively.

Acknowledgements

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