J. Plasma Fusion Res. SERIES, Vol. 9 (2010)

Cryogenic effect on dust grain charging in a plasma

Wataru SEKINE and Osamu ISHIHARA

Faculty of Engineering, Yokohama National University

79-5 Tokiwadai, Hodogaya-ku, Yokohama, 240-8501, Japan

(Received: 30 October 2009 / Accepted: 2 February 2010)

Charging mechanism of dust particles in a nonuniform discharge plasma under cryogenic environment is studied theoretically. The plasma density and temperature effects on dust grain charging are investigated with characteristic time scales of density variation and temperature relaxation in consideration. The charge of a dust grain, initially placed in a discharge plasma and cooled to cryogenic temperature, is governed by the time-dependent ion temperature and ion-neutral collisions. The magnitude of a dust charge decreases with the decrease of ion temperature. The charge at a cryogenic temperature is found to be much smaller than that at the room temperature, in agreement with experimental observation reported earlier. It is suggested that charged dust grains at cryogenic temperature make the formation of a strongly coupled system of dust particles.

Keywords: Complex plasma, dust charging, cryogenic temperature, ion-neutral collision effect, characteristic time scale

1. Introduction

Complex plasma including dust grains and plasma particles has attracted great interests to plasma community because of its novel feature as a strongly coupled system. Because of large charges carried by dust grains, Coulomb crystal could be formed in a plasma [1,2]. The strength of correlation is described by a coupling parameter Γ_{d},

$$\Gamma_{\mathrm{d}} = \frac{Z_{\mathrm{d}}^2 e^2}{4\pi\varepsilon_0 d k_{\mathrm{B}} T_{\mathrm{d}}} \exp(-\kappa), \tag{1}$$

where Z_{d} is the charge number of a dust particle, e is an elementary charge, ε_0 is a permittivity of free space, d is an interparticle distance, k_{B} is a Boltzmann constant, κ is a shielding parameter, and T_{d} is a dust temperature. Γ_{d} could be much larger than 1 in a complex plasma, and strongly coupled system could be formed if the dust particles keep the charge with low kinetic energy level. The kinetic energy of dust particles could be effectively suppressed in a complex plasma in cryogenic environment [3,4].

Complex plasma has been studied extensively since the middle 1990s [5-7]. Study on the growth of dust particles during fusion plasma discharge was reported [8]. On the other hand, the study on a complex plasma in a cryogenic environment has only started. [3,9]. Earlier experimental studies suggested the production of cryogenic plasma by pulse discharge in liquid helium [10,11] and ultracold plasma by a method of laser cooling [12]. Rosenberg *et al*. suggested a unique nature of two-dimensional dust structure on the surface of liquid helium [13]. Two-dimensional structures on the surface of liquid helium have been observed as macroscopic electron dimples, each holding about 10^7 electrons, on the surface of liquid helium [14] and the phase transition on a liquid helium surface was reported [15]. Experimental results by Antipov *et al*. showed a decrease in the interparticle spacing in dust structure in cryogenic dc glow discharge and the increase in the density of dust particles with decreasing temperature of the gas in the discharge [16,17].

Dust charge and kinetic temperature of dust particles, which characterize a complex plasma, are still to be explored at cryogenic temperature. In an earlier work, we studied expansion process of dust particles placed in the center of a plasma based on kinetic theory, where a plasma is surrounded by cryogenic liquid helium vapor [18]. Recently dust charges in cryogenic environment were measured in the experiments [19,20]. In one experiment, dust charge was determined by the use of damping oscillation of dust particles near the equilibrium position balanced by the gravity and the sheath electric force [19]. In another experiment, a localized plasma was produced in the vapor of liquid helium above the surface of liquid helium. Dust charge was determined by the trajectories of dust particles [20]. Both experiments led to a conclusion that dust charge decreased as the decrease of ion temperature. Collisional effect by cryogenic neutrals greatly contributed to dust charge, because neutral density at cryogenic temperature becomes about 100 times larger than that at room temperature at the same neutral gas pressure. Dust grain charge is determined by the balance of the flux of electrons and ions flowing onto the dust surface.

Author's e-mail: d07sd202@ynu.ac.jp

Ion-neutral collision affects not only ion temperature but also electron and ion number density. At cryogenic temperature, it is important to consider the change of ambient plasma density and temperature including collisional effects affecting on the dust charge. Detailed analysis should be done to clarify the decharging process observed in the cryogenic complex plasma experiments.

In this paper, we study the dust charge in a plasma embedded in the cryogenic neutrals. The temporal change of background plasma density and ion temperature are considered and we evaluate the characteristic time scales of density variation, temperature relaxation, and dust grain charging. Dust charge is found to decrease with the decrease of ion temperature and ion-neutral collisions. As a result, the charge at cryogenic temperature is much smaller than that at the room temperature, in agreement with results reported by complex plasma experiments under cryogenic environment. Our model may shed light on the decharging process of dust particles in a localized plasma at cryogenic temperature [20]. It is suggested that charged dust grains at cryogenic temperature can make the formation of a strongly coupled system of dust particles.

This paper is organized as follows. Section 2 describes our model and formulation. Numerical solutions are described in Section 3. We discuss the results and analyze the cryogenic effect on the dust grain charging in Section 4. Section 5 concludes the paper.

2. Model

2.1 Plasma model and basic assumptions

Localized and nonuniform plasma at low temperature in background cryogenic helium neutrals in a finite system is considered. We consider dust grains embedded in the plasma. The initial plasma is characterized by $T_\mathrm{e} >> T_\mathrm{i} >> T_\mathrm{n}$, where T_e is temperature of electrons, T_i is temperature of ions, and T_n is temperature of cryogenic neutral particles. Ions are considered to approach cryogenic temperature through collisions with neutrals at time rate τ_T, where τ_T is a temperature relaxation time scale while electron temperature is assumed to be constant. We consider the transition process where the plasma will be characterized by $T_\mathrm{e} >> T_\mathrm{i} \approx T_\mathrm{n}$ in the final state. Dust grains are massive and assumed to be immobile. They are assumed to have initial charges, Q_d0 as a result of the flux balance of ions and electrons on the dust surface. Ion and electron number density n_i and n_e vary due to two processes 1) ambipolar diffusion process in the system at time scale τ_D and 2) absorption of plasma particles onto the dust grain surface at time scale τ_A. Dust number density n_d is assumed to be constant. In the model, dust number density is given, which is much smaller than ion and electron number density, namely,

$$n_\mathrm{i}/n_\mathrm{e} = 1 - n_\mathrm{d} Z_\mathrm{d}/n_\mathrm{e} \approx 1. \tag{2}$$

For typical parameters in laboratory complex plasma experiments at room temperature, n_e, n_i ~ 10^9 cm^{-3} and $|Z_\mathrm{d}|$ ~ 10^3 for dust radius a ~ 1 μm, Eq. (2) is satisfied if n_d is much less than 10^5 cm^{-3}.

2.2 Formulations

Here we describe the formulation of characteristic time scales. Basic equations for ambient plasma density variation, temperature relaxation and dust grain charging are shown.

The characteristic time scale of plasma loss by ambipolar diffusion, τ_D is given by

$$\tau_\mathrm{D} = \Lambda^2 / D_\mathrm{a}, \tag{3}$$

where Λ is a characteristic length of the system [21] and D_a is ambipolar diffusion coefficient given by

$$D_\mathrm{a} \equiv \frac{\mu_\mathrm{i} D_\mathrm{e} - \mu_\mathrm{e} D_\mathrm{i}}{\mu_\mathrm{i} - \mu_\mathrm{e}}, \tag{4}$$

$$D_\mathrm{j} \equiv \frac{k_B T_\mathrm{j}}{m_\mathrm{j} \nu_\mathrm{jn}}, \quad \mu_\mathrm{j} \equiv \frac{e_\mathrm{j}}{m_\mathrm{j} \nu_\mathrm{jn}} \quad (\mathrm{j} = \mathrm{e}, \mathrm{i}), \tag{5}$$

where D_j is diffusion coefficient and μ_j is mobility. m_j is mass, $e_\mathrm{e} = -e$, $e_\mathrm{i} = e$ and ν_jn represents collision frequency. In case of $|\mu_\mathrm{e}| >> \mu_\mathrm{i}$, ambipolar diffusion coefficient is described by

$$D_\mathrm{a} = (1 + T_\mathrm{e}/T_\mathrm{i}) D_\mathrm{i}. \tag{6}$$

Substituting (5) and (6) into (3) with thermal velocity of ions $v_\mathrm{Ti} = (k_\mathrm{B} T_\mathrm{i}/m_\mathrm{i})^{1/2}$, we find

$$\tau_\mathrm{D} = \frac{3\sqrt{\pi}\Lambda^2}{2\sqrt{2} l_\mathrm{in} v_\mathrm{Ti} (1+\tau)}, \tag{7}$$

where $l_\mathrm{in} = v_\mathrm{Ti}/\nu_\mathrm{in}$ is a mean free path of ion-neutral collisions and the dimensionless temperature ratio $\tau = T_\mathrm{e}/T_\mathrm{i}$ is introduced.

The characteristic time scale of plasma loss by absorption onto the surface of a dust particle, τ_A is given by

$$\tau_\mathrm{A} = \langle n_\mathrm{d} \sigma_\mathrm{id} v_\mathrm{i} \rangle^{-1} = \left(\frac{n_\mathrm{d}}{n_\mathrm{i}} \int d\mathbf{v} \sigma_\mathrm{id} v f_\mathrm{i} \right)^{-1}, \tag{8}$$

where f_i is the distribution function of ions, v_i is ion velocity and σ_id is dust cross section. If the distribution is assumed to be Maxwellian, Eq. (8) gives

$$\tau_\mathrm{A} = \frac{1}{2\sqrt{2\pi} a^2 n_\mathrm{d} v_\mathrm{Ti} (1 + z\tau)}, \tag{9}$$

where a is a dust radius and z is a normalized charge defined as

$$z \equiv \frac{|Z_{\rm d}|e^2}{4\pi\varepsilon_0 a k_{\rm B} T_{\rm e}}. \tag{10}$$

When dust number density is high, the loss by absorption onto dust surface becomes large resulting in decrease of $\tau_{\rm A}$. But absorption due to the dust grain is considered to be ineffective when the dust number density is sufficiently low. The absorption of electrons is considered to be negligible because electrons and dust particles repel each other.

With two characteristic timescales $\tau_{\rm D}$ in Eq. (7) and $\tau_{\rm A}$ in Eq. (9), the time scales of plasma density variation $\tau_{\rm Le}$ and $\tau_{\rm Li}$ for electrons and ions are described by

$$\tau_{\rm Le} = (1/\tau_{\rm D})^{-1}, \tag{11}$$

$$\tau_{\rm Li} = (1/\tau_{\rm D} + 1/\tau_{\rm A})^{-1}. \tag{12}$$

With Eqs. (11) and (12), basic equations for plasma density variation are given by

$$\frac{\partial n_{\rm e}}{\partial t} = -\frac{n_{\rm e}}{\tau_{\rm Le}}, \tag{13}$$

$$\frac{\partial n_{\rm i}}{\partial t} = -\frac{n_{\rm i}}{\tau_{\rm Li}}. \tag{14}$$

The ion temperature relaxation time scale $\tau_{\rm T}$ is considered to relate to ion-neutral collision frequency $\nu_{\rm in}$ because ions can be cooled down to cryogenic temperature through frequent collisions with background cryogenic neutral particles. The relaxation time scale is given by

$$\tau_{\rm T} = l_{\rm in}/v_{\rm Ti}, \tag{15}$$

where mean free path of ions with neutral collisions is described by

$$l_{\rm in} = \frac{1}{\sigma_{\rm in} n_{\rm n}}, \qquad n_{\rm n} = \frac{p}{k_{\rm B} T_{\rm n}}. \tag{16}$$

Here p is a neutral gas pressure and $\sigma_{\rm in}$ is a cross section of ion-neutral collision. The cross section $\sigma_{\rm in}$ is on the order of 10^{-19} m^2 for helium ions in helium gas and is independent of the ion temperature [22]. When the gas pressure and the temperature of neutrals are given, we obtain the mean free path of ions by Eq. (16). A basic equation for ion temperature relaxation process is given by

$$\frac{dT_{\rm i}}{dt} = -\frac{T_{\rm i} - T_{\rm n}}{\tau_{\rm T}}. \tag{17}$$

The dynamics of dust grain charging is described by

$$\frac{dQ_{\rm d}}{dt} = I_{\rm e} + I_{\rm i} = 2\sqrt{2\pi}a^2(-e) \times [n_{\rm e} v_{\rm Te} e^{-z} - n_{\rm i} v_{\rm Ti}(1 + \tau z + H(\beta)(\tau z)^2(\frac{\lambda}{l_{\rm in}}))], \tag{18}$$

where $Q_{\rm d}(= Z_{\rm d} e)$ is dust charge, $I_{\rm i}$ is ion current, $I_{\rm e}$ is electron current flowing onto the dust grain surface and $v_{\rm Te} = (k_{\rm B} T_{\rm e}/m_{\rm e})^{1/2}$ is electron thermal velocity. Khrapak *et al.* discussed the effect of ion-neutral collisions on the steady-state dust charge in a plasma [23]. Ion-neutral collision effect was incorporated in the balance of electron and ion current explicitly [24]. The collision term includes a function $H(\beta)$ defined in Ref. 23 ($\beta = z\tau(a/\lambda)$). Here λ is a screening length. In our model, $\lambda \sim \lambda_{\rm Di}$, where $\lambda_{\rm Di}$ is an ion Debye length defined by $\lambda_{\rm Di} = (\varepsilon_0 k_{\rm B} T_{\rm i}/n_{\rm i} e^2)^{1/2}$. Note that $\lambda_{\rm Di}$ depends on time. In our model, $\beta \sim 10^0$ - 10^2. For $\beta >> 1$, $H(\beta)$ is estimated to be $H(\beta) \sim \beta^{-2}\ln\beta \sim 0.01$ - 0.1. With the temporal charge fluctuation time scale τ_Q, the charge variation may be given by

$$dQ_{\rm d}/dt \cong -(Q_{\rm d} - Q_{\rm deq})/\tau_{\rm Q}. \tag{19}$$

Here $Q_{\rm deq}$ is an equilibrium charge in steady state. Setting $Q_{\rm d} = \delta Q_{\rm d} + Q_{\rm deq}$ in Eq. (18) and expanding for small deviations $\delta Q_{\rm d}$, we have [25-27],

$$\tau_Q \sim [\sqrt{2\pi} n_0 \lambda_{\rm De0}^2 (l_{\rm in}/\lambda)/(a n_{\rm i} v_{\rm Ti} \tau^2 H(\beta) z_{\rm eq}^2)], \tag{20}$$

where $z_{\rm eq}$ is a normalized charge for $Z_{\rm d} \to Z_{\rm deq}$ (or $Q_{\rm d} \to Q_{\rm deq}$) in Eq. (18) and n_0 is initial plasma density or $n_0 = n_{\rm e}, n_{\rm i}$ at $t = 0$. Initial Debye length $\lambda_{\rm De0} = (\varepsilon_0 k_{\rm B} T_{\rm e}/n_0 e^2)^{1/2}$ is introduced.

3. Numerical solutions

3.1 Evaluation of characteristic time scales

Here we consider the temporal change of characteristic time scales. It is convenient to introduce mass ratio of electron to ion $m = m_{\rm e}/m_{\rm i}$ and initial electron plasma frequency $\omega_{\rm pe0} = (n_0 e^2/\varepsilon_0 m_{\rm e})^{1/2}$. Normalized formulations of Eqs. (7), (9), (15) and (20) are given by

$$\tilde{\tau}_{\rm D} = \frac{3\sqrt{\pi}}{2\sqrt{2}} \tilde{\Lambda}^2 \tilde{l}_{in}^{-1} \frac{\tau^{1/2}}{m^{1/2}(1+\tau)}, \tag{21}$$

$$\tilde{\tau}_{\rm A} = \frac{(\tilde{n}_{\rm d} \tilde{a}^2)^{-1}}{2\sqrt{2\pi}} \frac{\tau^{1/2}}{m^{1/2}(1+\tau z)}, \tag{22}$$

$$\tilde{\tau}_{\rm T} = \tilde{l}_{\rm in} \frac{\tau^{1/2}}{m^{1/2}}, \tag{23}$$

$$\tilde{\tau}_Q = \frac{\sqrt{2\pi}}{H(\beta)z_{\rm eq}^2}\,\tilde{a}^{-1}\,\tilde{n}_i^{-1}m^{-1/2}\tau^{-3/2}\,\tilde{l}_{\rm in}\,\tilde{\lambda}^{-1}. \quad (24)$$

Here $\tilde{\tau}_{\rm D} = \tau_{\rm D}\omega_{\rm pe0}$, $\tilde{\tau}_{\rm A} = \tau_{\rm A}\omega_{\rm pe0}$, $\tilde{\tau}_{\rm T} = \tau_{\rm T}\omega_{\rm pe0}$, $\tilde{\tau}_{\rm Q} = \tau_{\rm Q}\omega_{\rm pe0}$, $\tilde{l}_{\rm in} = l_{\rm in}/\lambda_{\rm De0}$, $\tilde{\Lambda} = \Lambda/\lambda_{\rm De0}$, $\tilde{n}_{\rm d} = n_{\rm d}\lambda_{\rm De0}^3$, $\tilde{a} = a/\lambda_{\rm De0}$, $\tilde{n}_{\rm i} = n_{\rm i}/n_0$, and $\tilde{\lambda} = \lambda/\lambda_{\rm De0}$. When ion temperature decreases, ambipolar diffusion time scale and absorption time scale become shorter because of $\tilde{\tau}_{\rm D}, \tilde{\tau}_{\rm A} \propto \tau^{-1/2}$. On the other hand, temperature relaxation time becomes longer due to $\tilde{\tau}_{\rm T} \propto \tau^{1/2}$, which implies that decrease rate of ion temperature becomes saturated with time. It should be noted that charging time scale depends on $\tilde{n}_{\rm i}^{-1}$, $\tilde{\lambda}^{-1}$ and $\tau^{-3/2}$. When the ion number density decreases, charging time of dust grain becomes longer. When the ambient plasma density and ion temperature change, time dependent grain charging should be considered.

3.2 Temporal dust charge

The dynamic nature of grain charging is shown by numerical solutions. A system of Eqs. (10), (13), (14), (16), (17) and (18) for dynamics of ambient plasma density, ion temperature and dust grain charge is solved numerically with characteristic time scales given by Eqs. (7), (9), (11), (12) and (15).

Electron temperature and density, $k_{\rm B}T_{\rm e}$ ~ 3 - 4 eV and n_0 ~ 10^9 cm^{-3} are considered. Background neutral temperature $T_{\rm n}$ = 4 K is chosen based on the cryogenic helium neutrals and m is chosen to be on the order of 10^{-4}. The initial temperature ratio $\tau(=T_{\rm e}/T_{\rm i})$ is set to be 10^2. As we mentioned in 2.1, the number densities of plasma particles as well as dust particles are assumed to satisfy the condition, $n_{\rm e} \approx n_{\rm i} >> |Z_{\rm d}|n_{\rm d}$. Finite system on the order of $\Lambda/\lambda_{\rm De0}$ ~ 10 is assumed here. We consider micron sized dust grains ($\lambda_{\rm De0}/a$ ~ 10^2) in our model.

Figure 1 shows normalized dust charge z versus temperature ratio $\tau(=T_{\rm e}/T_{\rm i})$ for pressures 2 Pa and 10 Pa. In a collisionless regime, collision term (last term in Eq. (18)) is neglected indicating no contribution of ion-neutral collisions onto the dust surface directly. It is shown that the initial dust charge declines with the decrease of ion temperature. Charge in a collisionless regime is estimated to be much higher than that in a collisional regime as shown in the Fig. 1.

Time evolution of dimensionless parameter $\xi = (H(\beta)\tau z(\lambda/l_{\rm in}))^{-1}$ versus $\omega_{\rm pi0}t$ where $\omega_{\rm pi0}$ is the initial ion plasma frequency, for pressures 2 Pa and 10 Pa is shown in Fig. 2. Here ξ represents contribution by the ion-neutral collisions to ion current onto the dust grain. Neglecting unity compared to $z\tau$ in Eq. (18), ion current is rewritten as

$$I_{\rm i} = 2\sqrt{2\pi}a^2 en_{\rm i}v_{\rm Ti}\tau z[1 + H(\beta)(\tau z)(\frac{\lambda}{l_{\rm in}})]. \quad (25)$$

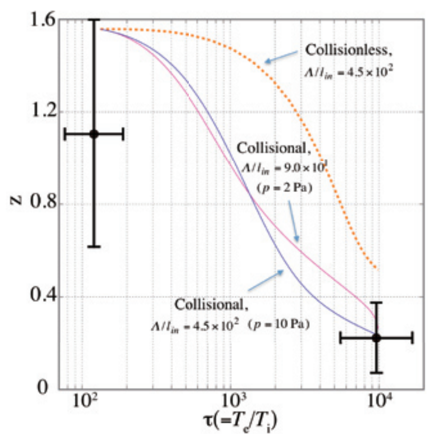

Fig. 1. Normalized charge z vs temperature ratio $\tau(=T_{\rm e}/T_{\rm i})$ for various neutral gas pressures at $k_{\rm B}T_{\rm e} = 3.4\,{\rm eV}$ and $a = 1$ μm. Experimental results were shown with the error bars [19, 20].

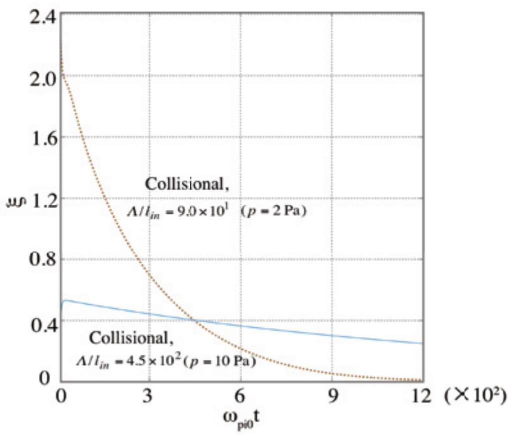

Fig. 2. Temporal evolution of dimensionless parameter ξ. The parameter ξ is defined as $\xi = [H(\beta)\tau z(\lambda/l_{\rm in})]^{-1}$ in the equation of charge dynamics. One curve is in collisional regime at 2 Pa ($\Lambda/l_{\rm in}$ = 9.0×10^1) and the other curve is the same regime at 10 Pa ($\Lambda/l_{\rm in}$ = 4.5×10^2).

Note that ion-neutral collision is dominant when $\xi < 1$ ($1 < H(\beta)(\tau z)(\lambda/l_{\rm in})$). In case of 2 Pa, collisional effect becomes dominant as time progresses. When the collisionality is high (10 Pa), collision term plays a major role from the beginning because the mean free path becomes shorter due to frequent ion-neutral collisions. We see that the dust grain charge decreases with ion temperature and decreases with increasing ion-neutral collisionality. The experimental results [19,20] were shown in Fig. 1 to compare with theoretical predictions. The charge of dust particles measured at room temperature was z ~ 1.1, while the charge measured in a liquid helium vapor was z ~ 0.2. We see that drastic decrease in dust charge z with the temperature ratio τ is well predicted by our collisional theory.

4. Discussion

4.1 Effect of ion temperature on ion flux

As shown in Fig. 1, dust grain reduces the charge due to the decrease of ion temperature. The ion current, with the assumption of Maxwellian ion distribution without collisions, is given by

$$I_{\mathrm{i}} \sim \int_0^\infty dv\, v^3 \sigma_{\mathrm{id}} f_{\mathrm{i}}(v) \underset{T_{\mathrm{i}} \to 0}{\sim} \frac{1}{\sqrt{T_{\mathrm{i}}}}, \tag{26}$$

indicating the enhancement of the ion current flowing onto the dust surface with decreasing ion temperature. Such an enhancement of ion current results in the decrease of magnitude of dust charge. As seen in Fig. 1, the value of normalized charges decreases with increasing temperature ratio. It should be noted the charge in a collisional regime is much less than the chare in a colissionless regime at $\tau >> 100$. We discuss the effect of ion-neutral collisions next section.

4.2 Collisional effect on the dust charge

We have considered ion-neutral collision effect on the dust charge. Here we discuss the dust charge in more detail and compare with numerical solutions. As shown in Fig. 1, z = 0.2 - 0.3 at τ = 9 × 10^3. Since the ion-neutral collision is dominant in 10 Pa, Eq. (25) is approximated by $I_{\mathrm{i}} = 2\sqrt{2\pi}a^2 e n_{\mathrm{i}} v_{\mathrm{Ti}} H(\beta)(\tau z)^2(\lambda/l_{\mathrm{in}})$, while electron current is given by $I_{\mathrm{e}} = 2\sqrt{2\pi}a^2(-e)n_{\mathrm{e}} v_{\mathrm{Te}}$ under assumption $z << 1$. Using the ion and electron currents with $dQ_{\mathrm{d}}/dt = 0$, the normalized dust charge is given by

$$z \sim \left(\frac{n_{\mathrm{e}}}{n_{\mathrm{i}}}\right)^{1/2} \left(\frac{v_{\mathrm{Te}}}{v_{\mathrm{Ti}}}\right)^{1/2} \left(H(\beta)\tau^2\right)^{-1/2} \left(\frac{l_{\mathrm{in}}}{\lambda}\right)^{1/2}. \tag{27}$$

In our model, $n_{\mathrm{e}}/n_{\mathrm{i}}$ = 1 (both densities decrease by ambipolar diffusion process), $H(\beta)$ = 0.01, τ = 9 × 10^3, l_{in}/λ = 1, and m^{-1} = 7 × 10^3 are considered, so we obtain a normalized charge z = 0.1, which is close to the numerical solution result as shown in Fig. 1. For $k_{\mathrm{B}}T_{\mathrm{e}}$ = 3 - 4 eV, a = 1 μm, z = 0.1 - 0.3, the charge $|Z_{\mathrm{d}}|$ is on the order of 10^2. Initial dust charge, $|Z_{\mathrm{d}}| \sim 10^3$ decreases by one order of magnitude in a plasma at cryogenic temperature in our model.

The accurate dust charge should be determined with accurate values of the mean free path of ions. Ion-neutral collisions affect not only the dust grain charge but also the decrease of ion temperature. Screening length is also important factor not only to the dust grain charge but also Coulomb crystal of dust particles. Interparticle distance is comparable to the screening length. In our model, screening length is dominated by ion Debye length. The screening length is a scale length for the formation of dust structure.

4.3 Complex plasma experiment

According to the complex plasma experiments at cryogenic temperature [20], decharging of dust particles was observed. In the experiment, dust particles go through a localized plasma in liquid helium vapor near the liquid helium surface. When dust grains pass the localized plasma, drastic change of ambient plasma in density and ion temperature will occur around dust grains. In this case, we have to consider the dynamics of grain charging taking time-dependent ambient plasma state into account. Our model explains the decharging mechanism in the complex plasma experiment at cryogenic temperature.

Background plasma parameters and neutral gas temperature are important parameters to determine dust motion or dust charge. Spatial temperature gradient of neutral gas affects on the dust particle as thermophoretic force, $F_{\mathrm{th}} \sim (a^2\eta/v_{\mathrm{Tn}})\nabla T_{\mathrm{n}}$ [28], where is a is dust radius, v_{Tn} is thermal velocity of neutral particles, η is coefficient of heat conductivity, and ∇T_{n} is a temperature gradient.

4.4 Coupling parameter of dust particles

To estimate the coupling parameter, we consider Γ defined by $\Gamma = \Gamma_{\mathrm{d}}\exp(\kappa)$. Shielding parameter κ = d/λ is typically in the range of 0.3 - 10. Here interparticle distance is governed by the screening length as $d \sim \lambda \sim \lambda_{\mathrm{Di}}$ and $T_{\mathrm{e}}/T_{\mathrm{d}} \sim \tau$ for $T_{\mathrm{i}} \sim T_{\mathrm{d}}$. The ratio of Γ/Γ_0 (subscript 0 indicates the value at initial state) is described by $\Gamma/\Gamma_0 \sim \varepsilon_z^2/(\varepsilon_{T_{\mathrm{d}}}\varepsilon_{T_{\mathrm{i}}}^{1/2})$, where ε_z = z/z_0, $\varepsilon_{T_{\mathrm{d}}}$ = $T_{\mathrm{d}}/T_{\mathrm{d0}}$, $\varepsilon_{T_{\mathrm{i}}}$ = $T_{\mathrm{i}}/T_{\mathrm{i0}}$. Considering $\varepsilon_z \sim 10^{-1}$, $\varepsilon_{T_{\mathrm{d}}} \sim 10^{-2}$ and $\varepsilon_{T_{\mathrm{i}}} \sim 10^{-2}$ in our model, $\Gamma/\Gamma_0 \sim 10$ is obtained, indicating the value of coupling parameter could increase in cryogenic condition. For example, dust charge number at room temperature is $|Z_{\mathrm{d}}| \sim 10^2$ - 10^3 with a ~ a few μm, d ~ 100 μm to 1 mm and $k_{\mathrm{B}}T_{\mathrm{e}}$ ~ a few eV, while the dust charge number at a liquid helium temperature is $|Z_{\mathrm{d}}| \sim 10^2$. Thus the coupling parameter Γ_{d} becomes much larger than 1 at T_{d} ~ a few K.

5. Conclusion

Charging mechanism of dust grains in a plasma under cryogenic environment was studied by solving a system of equations, involving the time-dependent nature of characteristic time scales as plasma density variation and ion temperature relaxation. We revealed that both ion temperature and ion-neutral collisions play important roles in the dust grain charging. With the decrease of ion temperature due to ion-neutral collisions, the magnitude of dust grain charge decreased accordingly. The grain charge in a collisionless regime is estimated to be much higher than that in a collisional regime. It is found that the dust grain charge at cryogenic temperature was determined by the change of ion temperature and the ion-neutral collisions. The magnitude of the grain charge at cryogenic temperature was smaller than that at a room temperature, in agreement with the results observed decharging of dust particles near a localized plasma in cryogenic environment.

Acknowledgements

This research is supported by the Asian Office of Aerospace Research and Development under AOARD-084116 and the Japan Society for the Promotion of Science Grant-in-Aid for the Scientific Research (B) No. 19340173.

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