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Polarization Effects on the Elastic Dust Grain Collisions in Complex Dusty Plasmas

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The polarization effects on the elastic dust grain collisions are investigated in unmagnetized complex dusty plasmas. The result shows that the polarization effect enhances the scattering cross section in dusty plasmas. In addition, it is found that the polarization effect on the scattering cross section increases with an increase of the collision velocity. The polarization effect increases with increasing Coulomb radius of interaction between thermal ions and the dust grain in high collision velocities.

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In recent years, there has been a considerable interest in the dynamics of complex plasmas containing charged dust grains containing collective effects, nonlinear effects, and strong electrostatic interactions.[1–4] These complex dusty plasma systems have been found not only in space plasmas but also in the various laboratory plasmas. In order to understand the physical properties of relevant plasma parameters, various physical processes have been investigated in complex dusty plasmas.[3,5] In ordinary weakly coupled electron–ion plasmas, the collision and radiation processes have been investigated using the standard Debye–Hückel potential model since the average energy of interaction between charged particles is found to be smaller than the average kinetic energy of a particle.[5,6] However, in complex plasmas containing dust grains the additional force arising due to the plasma polarization around the dust grain should be taken into account to describe the total force acting on a charged grain. In these circumstances, the interaction potential in weakly coupled complex plasmas would not be represented by the ordinary Debye–Hückel potential obtained by the classical Boltzmann distribution of charged particles because of the polarization force caused by the charged dust grain. Very recently, an excellent work[7] on the influence of the polarization force is given for the plasma waves in complex plasmas. This work shows that the polarization interaction leads to a decrease of the dust acoustic phase velocity.[7] In plasmas, the scattering of charged particles has been of great interest since the scattering cross section is closely related to the radiative process such as the Coulomb bremsstrahlung. Since the scattering cross sections of ion collision processes would be quite large, the heavy-particle collisions should be considered in plasma diagnostics and plasma modeling.[4,8,9] Hence, it is expected that the dust grain collisions would be affected by the additional polarization interaction in weakly coupled complex plasmas. In addition, it is expected that the polarization effect would play an important role for electron emissions in dust grain collisions. Hence, understanding the influence of the polarization force on the dust grain collisions has fundamental and practical importance in complex dusty plasmas. Thus, in this paper we investigate the polarization effects on the elastic dust grain collisions in weakly coupled unmagnetized complex plasmas. It has been shown that the method of stationary phase[10] provides a great advantage in the elastic collision process since the total scattering cross section would be represented in a closed integral form with the scattering phase including the information on the collision dynamics and various plasma parameters. Hence, the stationary phase method and the effective interaction potential containing the polarization part are employed in order to investigate the influence of the polarization force on the dust grain collisions as a function of the impact parameter, collision velocity, Debye radius, and Coulomb interaction radius.

Using the stationary phase method,[10] the partial-wave representation of the scattering cross section for the collisional angular momentum l would be expressed by the following form of the total elastic scattering cross section σ_{el}:

$$\sigma_{\mathrm{el}} = 8\pi \int_0^{\infty} d\rho\, \rho \sin^2 \eta(\rho), \tag{1}$$

where ρ is the impact parameter and $\eta(\rho)$ denotes the scattering phase for the interaction potential $V(r)$:

$$\begin{aligned} \eta(\rho) &= -\frac{1}{2\hbar} \int_{-\infty}^{\infty} dt\, V(r) \\ &\cong -\frac{1}{\hbar v} \int_0^{\infty} dz \exp\left(\ln V + \frac{z^2}{2}\frac{\partial_\rho V}{\rho V}\right), \end{aligned} \tag{2}$$

where $r = (\rho^2 + z^2)^{1/2}$, $t \equiv z/v$, v is the relative collision velocity between the projectile particle and the target system, and $\partial_\rho V \equiv \partial V/\partial\rho$. For the case of $\partial_\rho V/V < 0$, the total elastic scattering cross section is then represented in the following form:[10]

$$\sigma_{\mathrm{el}} = 8\pi \int_0^{\infty} d\rho\, \rho \sin^2\left[\frac{V}{\hbar v}\left(-\frac{\pi}{2}\frac{\rho V}{\partial_\rho V}\right)^{1/2}\right]. \tag{3}$$

Very recently, the accurate and useful form of the polarization force acting on the dust grains in complex dusty plasmas was suggested as follows:[7]

$$F_{\mathrm{p}}(Q, \lambda_{\mathrm{eff}}) = -\frac{Q^2}{2}\frac{\nabla\lambda_{\mathrm{eff}}}{\lambda_{\mathrm{eff}}^2}, \tag{4}$$

where Q is the dust charge, λ_{eff} $[\equiv \lambda_{\mathrm{D}i}(1 + 0.015\beta_T^{1/2} + 0.013\beta_T)]$ is the effective screening length,[11] $\lambda_{\mathrm{D}i}$ is the ion Debye length, and β_T is the ratio of the Coulomb radius of interaction between thermal ions and the dust grain and the linear Debye radius. Then, the effective interaction potential $V_{\mathrm{eff}}(r)$ between two colliding dust grains including the standard Debye–Hückel term and the additional polarization part would be represented in the following form:

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$$V_{\text{eff}}(r) = \frac{Q^2}{r}\left[\exp\left(-\frac{r}{\lambda_{\text{eff}}}\right) - \frac{r}{2\lambda_{\text{eff}}}\right]. \quad (5)$$

A detailed discussion on the scattering of charged particles without photon emission would be found in a recent excellent work by Gould.[12)] After some mathematical manipulations using the effective interaction potential with the stationary phase analysis, the total scaled elastic scattering cross section $\bar{\sigma}_{\text{el}}$ ($\equiv \sigma_{\text{el}}/\pi a^2$) in units of πa^2 for the collision of the charged dust grains with the charge Q ($= Ze$) including the polarization interaction is found to be

$$\begin{aligned}\bar{\sigma}_{\text{el}} = 8\int_0^\infty d\bar{\rho}\,\bar{\rho}\sin^2\Bigg\{&\left(\frac{\pi}{2}\right)^{1/2}\frac{Z^2}{\bar{v}_{\text{D}}}\\ &\times[\exp(-\bar{\rho}(1+0.015\beta_T^{1/2}+0.013\beta_T)^{-1}\bar{\lambda}_{\text{D}i}^{-1})\\ &-\bar{\rho}(1+0.015\beta_T^{1/2}+0.013\beta_T)^{-1}(2\bar{\lambda}_{\text{D}i})^{-1}]\\ &/[\exp(-\bar{\rho}(1+0.015\beta_T^{1/2}+0.013\beta_T)^{-1}(2\bar{\lambda}_{\text{D}i})^{-1})\\ &\times(1+\bar{\rho}(1+0.015\beta_T^{1/2}+0.013\beta_T)^{-1}(2\bar{\lambda}_{\text{D}i})^{-1})^{1/2}]\Bigg\},\end{aligned} \quad (6)$$

where $\bar{\rho}$ ($\equiv \rho/a$) is the scaled impact parameter, $\bar{v}_{\text{D}}$ [$\equiv (m/\mu)^{1/2}\bar{E}^{1/2}$] is the scaled relative collision velocity between dust grains, m is the electron mass, μ is the reduced mass of the colliding charged dust grains, $\bar{E} \equiv \mu v^2/2Ry$, Ry ($= me^4/2\hbar^2 \approx 13.6\,\text{eV}$) is the Rydberg constant, and $\bar{\lambda}_{\text{eff}}$ ($\equiv \lambda_{\text{eff}}/a$) is the scaled effective screening length. Hence, it is found that the scattering cross section has a strong dependence on the Coulomb radius in the complex plasmas. However, the total scaled elastic scattering cross section $\bar{\sigma}'_{\text{el}}$ in units of πa^2 for the collisions of the dust grains without the polarization effect is given by

$$\begin{aligned}\bar{\sigma}'_{\text{el}} = 8\int_0^\infty d\bar{\rho}\,\bar{\rho}\sin^2\Bigg[&\left(\frac{\pi}{2}\right)^{1/2}\frac{Z^2}{\bar{v}_{\text{D}}}\\ &\times\exp(-\bar{\rho}(1+0.015\beta_T^{1/2}+0.013\beta_T)^{-1}\bar{\lambda}_{\text{D}i}^{-1})\\ &\times(1+\bar{\rho}(1+0.015\beta_T^{1/2}+0.013\beta_T)^{-1}(2\bar{\lambda}_{\text{D}i})^{-1})^{-1/2}\Bigg].\end{aligned} \quad (7)$$

Recently, the accurate form of the ion-atom polarization interaction[13)] was obtained in partially ionized plasmas taking into account the quantum mechanical effects of diffraction and symmetry of particles and plasma screening effects. However, the ion-atom polarization effect is neglected in this work since the dust plasma is assumed to be completely ionized. Hence, the current form of the scattering cross section, eq. (6), is reliable for the investigation of the polarization effects on the dust grain collisions in complex plasmas.

In order to explicitly investigate the influence of the polarization force on the elastic scattering cross section, we set $\lambda_{\text{D}i} = 20a$, $Z = 80$, and the density of the dust grain is $\rho_{\text{D}} \cong 2\,\text{g}\,\text{m}^{-3}$. Figure 1 shows the scaled elastic scattering cross section including the polarization effect as a function of the parameter β_T. The scattering cross section without the polarization is also illustrated. As it is seen in this figure, the polarization effect enhances the elastic scattering cross section. It is also shown that the cross section increases with increasing Coulomb radius in complex plasmas. Figure 2 represents the surface plot of the influence of the polarization interaction G_{p} ($\equiv \sigma_{\text{el}}/\sigma'_{\text{el}}$) as a function of the parameter β_T and the scaled collision velocity $\bar{v}_{\text{D}}$. As shown in this figure, the polarization effect on the elastic scattering process increases with an increase of the collision velocity. In addition, the polarization effect is found to be increased with the parameter β_T, especially, for high collision velocities. Hence we have found that the polarization interaction plays an important role in collision dynamics in complex dusty plasmas. It can be also expected that the influence of the polarization force would also be important in the radiative processes such as the Coulomb bremsstrahlung since the scattering cross section is quite closely related to the corresponding radiative process. These results would provide useful information on the influence of the polarization force on the dust grain collisions in weakly coupled complex dusty plasmas.

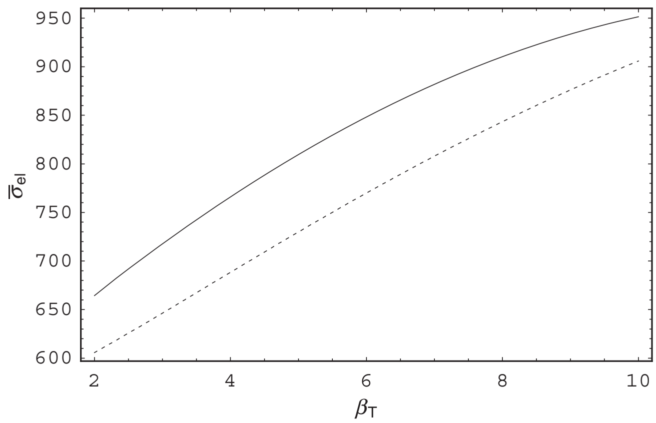

Fig. 1. The scaled elastic scattering cross section for the dust grain collsions in units of πa^2 as a function of the parameter β_T when $\bar{v}_{\text{D}}$ = 500. The solid line represents the scattering cross section with the polarization effect. The dotted line represents the scattering cross section without the polarization effect.

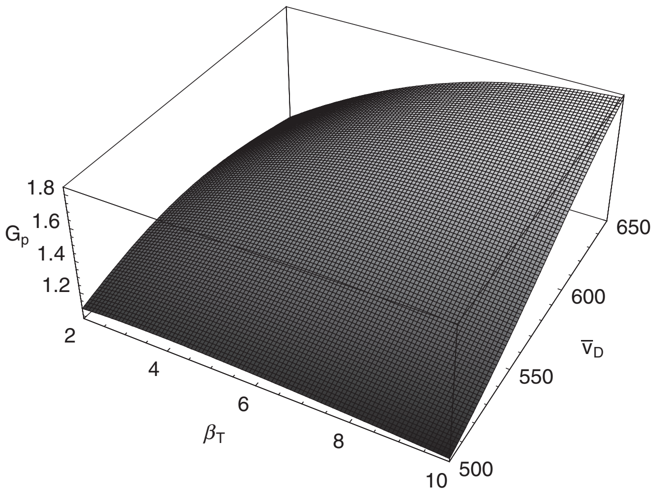

Fig. 2. The surface plot of the function of the polarization effect $G_{\text{p}}(\beta_T, \bar{v}_{\text{D}})$ as a function of the parameter β_T and collision velocity $\bar{v}_{\text{D}}$.

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