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ORIGINAL ARTICLE

Contributions to Plasma Physics

Impacts of neutral shadowing force on dust particle dynamics in cryogenic plasma

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Recently, it was shown that the neutral shadowing force can have a strong impact on the structural properties of the charged dust particles in cryogenic dusty plasmas. Therefore, in this work, we have investigated the impact of the neutral shadowing force on the dynamical properties by means of molecular dynamics simulations. By computing the velocity auto-correlation function of particles and their spectrum, we found that the neutral shadowing force has a strong impact on the dust particle dynamics if the mean free path of neutrals exceeds the mean inter-dust particle distance.

KEYWORDS
cryogenic dusty plasmas, neutral shadowing force, velocity auto-correlation function

1 | INTRODUCTION

A dusty plasma, being experimentally relatively easy realizable and observable, attracts interest as a system for investigation of many-particle physics; e.g., waves and wakefield.[1–6] Dusty plasma experiments were carried out under various conditions, including both terrestrial[2,3] and space (microgravity)[7–9] as well as cryogenic.[10–12] It was found that in complex plasmas, interaction between particles deviates from the screened Coulomb potential due to a non-equilibrium state of a plasma.[13–15] For the case of cryogenic complex plasmas, a unique nature of the two-dimensional dust structure on the surface of liquid helium was anticipated.[16] Additionally, a possible impact of the quantum effects on a dust particle-dust particle interaction was speculated.[17] Some possible applications of cryogenic plasmas were also discussed.[18] Therefore, the experimental realization and investigation of cryogenic complex plasmas became of interest.

The first experiments on cryogenic complex plasmas at pressure $P \sim 100\,\mathrm{P}$ and neutral particle temperature $T_\mathrm{n} \sim 10$ K have revealed highly dense system of dust particles.[10,11] This observation was explained by much shorter screening length and lower charge value of a dust particle in comparison with those at room temperature. In this case, at $P \sim 100\,\mathrm{P}$, the mean inter-dust particle distance a is comparable with the dust particle size, a_d. In contrast, in the latter cryogenic experiments at much lower values of pressure $P = 0.6 - 10\,\mathrm{P}$ (at $T_\mathrm{n} \lesssim 10\,\mathrm{K}$), the system of dust particles with a mean inter-dust particle distance much larger than the dust particle size was observed. This difference was shown to be the result of the impact of a neutral shadowing force.[19] It was found that in the cryogenic dusty plasmas at $T < 10$ K and $P < 10$ P, the surface temperature of the dust particle is much higher—up to 10 times—than that of the temperature of neutrals (at a large distance from the dust particle surface).[19] Because of this effect, a strong neutral shadowing force appears, which reads[15]

$$F = -\frac{3\pi}{8}\frac{a_\mathrm{d}^4 P}{a}\frac{(T_\mathrm{s} - T_\mathrm{n})}{T_\mathrm{n} R^2}, \tag{1}$$

where R is the distance between dust particles in the units of a (mean inter-dust particle distance) and T_s is the temperature of the dust particle surface. Under cryogenic conditions and at $P < 10$ P, this neutral shadowing force was shown to be comparable with the screened Coulomb potential.

At room temperature, the neutral shadowing force is always negligible in comparison with the screened Coulomb potential.[20] The appearance of the strong neutral shadowing force is unique for cryogenic plasmas. Therefore, it is interesting to investigate a possible impact of the neutral shadowing force on the dynamics of the dust particles in a cryogenic environment. In this work, this impact is studied by computing the velocity auto-correlation function of dust particles via molecular dynamics simulations.

2 | SIMULATION METHOD AND RESULTS

In ref. [[19]], it was found by properly computing $(T_s - T_n)$ that under cryogenic conditions the neutral shadowing interaction (1) is independent of the gas pressure. However, the mean free path of neutrals l depends on pressure. The mean free path determines the range of action of the neutral shadowing force. At $P \lesssim 10$ P, the mean free path can be both larger than a (at 0.6 Pa) and smaller than a (at 10 Pa). To proceed further, we consider both of these cases. First, we introduce the following pair potential of interaction between dust particles:

$$\frac{\Phi(R)}{k_b T_d} = \frac{\Gamma}{R}\exp(-k_S R) + \frac{\alpha}{R}, \tag{2}$$

where $k_b T_d$ characterizes thermal energy of dust particles, $\Gamma = Q_d^2/(k_b T_d a)$ is the coupling parameter for dust particle-dust particle interaction, k_S is the screening parameter that is taken $k_S = 1$. In Equation (2), we have introduced a new dimensionless parameter describing the repulsion due to the neutral shadowing force:

$$\alpha = \begin{cases} \frac{3\pi}{8}\frac{a_d^4 P}{a k_b}\frac{(T_s - T_n)}{T_n T_d}, & \text{if } R < l/a = r_{cut} \\ 0, & \text{otherwise} \end{cases}, \tag{3}$$

where the cut-off radius r_{cut} was defined by the mean free path of neutrals as it was discussed above.

In previous work,[19] it was determined that α can change in the range from $0.1\times\Gamma$ to Γ. We set $\alpha = 0.1\times\Gamma$ and $\alpha = 0.2\times\Gamma$ and consider $r_{cut} = 1$ and $r_{cut} = 2$. Apparently, the $\alpha = 0$ case is equivalent to the Yukawa system that is well understood.[21,22] Additional neutral shadowing interaction in Equation (2) leads to a stronger repulsion between dust particles at $R < r_{cut}$.

We consider the 2D geometry, where the mean inter-dust particle distance (the Wigner-Seitz radius) is given by $a = 1/\sqrt{\pi n}$ and the characteristic 2D plasma frequency is defined as $\omega_p = \sqrt{2\pi n Q_d^2/ma}$. The velocity auto-correlation function of dust particles was computed using molecular dynamics simulations. In the simulation, the number of particles is taken equal to 4,081. More details about molecular dynamics as well as the verification of the simulation correctness were reported in our previous works.[23–25]

In Figure 1, the values of the velocity auto-correlation function are shown for different Γ and α. The left panel corresponds to the case $r_{cut} = 1$ and the right panel to the case $r_{cut} = 2$. Time is given in units of inverse plasma frequency ω_p. Form Figure 1, we clearly see that the neutral shadowing force does not affect the velocity auto-correlation function in the case $r_{cut} = 1$. In contrast, in the case $r_{cut} = 2$, a strong impact of the neutral shadowing force can be seen. In this case, the influence of the neutral shadowing force becomes stronger with an increase in α. Note that the dependence of the features of the velocity auto-correlation function on Γ and k_S was investigated in detail by Donkó et al.[28]

In Figure 2, we present the spectrum of the velocity auto-correlation function,

$$Z(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} Z(t)\exp(i\omega t)dt. \tag{4}$$

As it was shown by Schmidt et al.,[29] the position of the peak of $Z(\omega)$ close to ω_p corresponds to the characteristic frequency of the longitudinal oscillations and behaviour of $Z(\omega)$ close to the peak at lower values of the frequency is related to the transverse fluctuations. Some oscillations at $\omega < 0.1\omega_p$ are related to simulation errors and periodic boundary conditions. From Figure 2, we see that at $r_{cut} = 1$ the neutral shadowing force almost does not impact the spectrum of the velocity auto-correlation function (see left panel). In contrast, in the case $r_{cut} = 2$ a strong influence of the neutral shadowing force on $Z(\omega)$ is observed (see right panel). In the latter case, the neutral shadowing force leads to a stronger manifestation of the transverse oscillations. In addition, at $r_{cut} = 2$, the neutral shadowing force leads to a significant increase of the characteristic frequency of the longitudinal oscillations. This is also illustrated in Figure 3, where the characteristic frequency of the longitudinal oscillations, $(\omega/\omega_p)_{max}$, is shown for both cases $r_{cut} = 1$ and $r_{cut} = 2$. In the case $r_{cut} = 1$, the characteristic frequency of the longitudinal oscillations is not influenced by the neutral shadowing interaction.

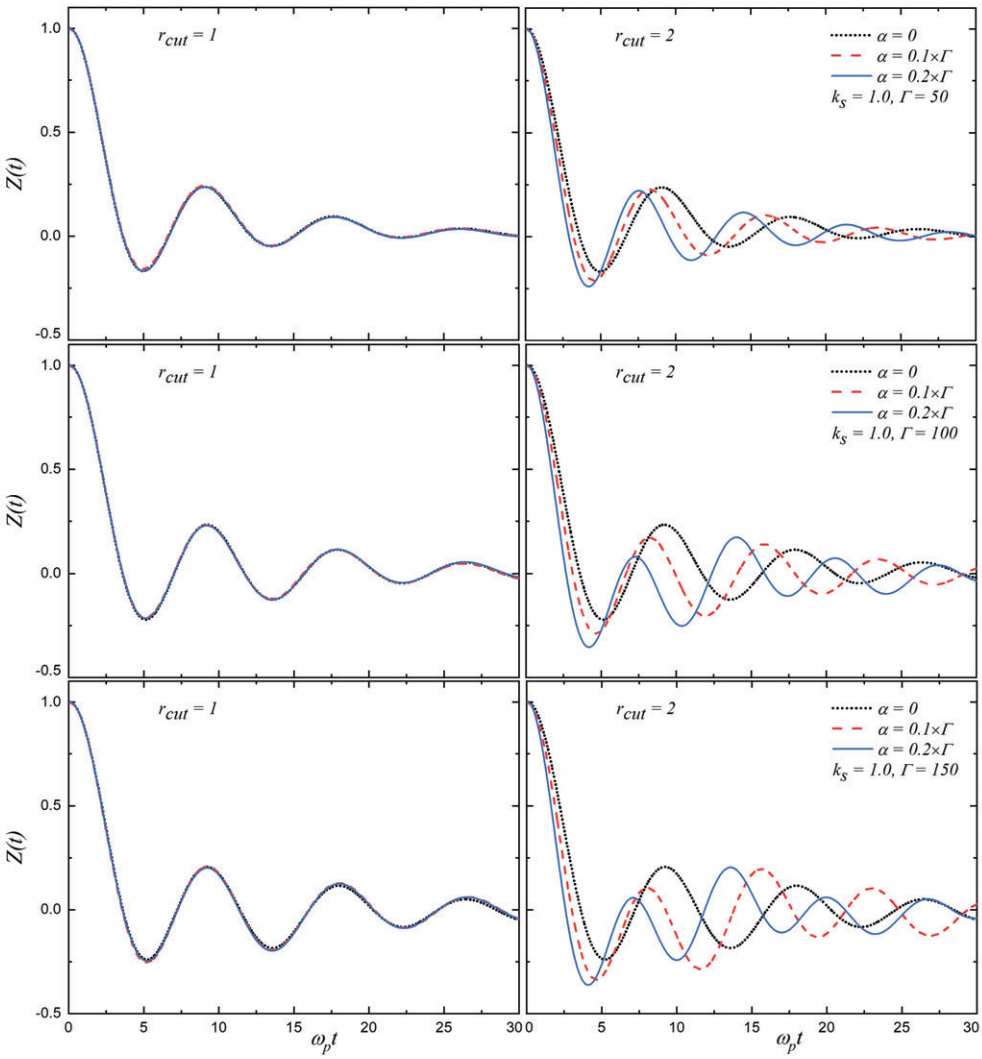

FIGURE 1 Velocity auto-correlation function at $r_{\mathrm{cut}} = 1$ (left panel) and $r_{\mathrm{cut}} = 2$ (right panel)

TABLE 1 The values of a sound speed, $c/(a\omega_p)$, at $k_S = 1$

		$\alpha = 0.1$		$\alpha = 0.2$	
Γ	**$\alpha = 0$, (Yukawa)**	**$r_{\mathrm{cut}} = 1$**	**$r_{\mathrm{cut}} = 2$**	**$r_{\mathrm{cut}} = 1$**	**$r_{\mathrm{cut}} = 2$**
50	0.84 ± 0.06	0.82 ± 0.06	0.87 ± 0.06	0.8 ± 0.05	0.9 ± 0.06
100	0.79 ± 0.05	0.78 ± 0.05	0.86 ± 0.06	0.77 ± 0.05	0.95 ± 0.06
150	0.8 ± 0.05	0.79 ± 0.05	0.88 ± 0.05	0.8 ± 0.05	0.97 ± 0.05

Finally, we discuss the impact of the neutral shadowing force on the sound speed in the system. For the 2D Yukawa systems, the sound mode and the corresponding sound speed are well studied.[26,27] Here, we use the velocity auto-correlation function to extract information about sound speed.

The velocity auto-correlation function has decaying oscillations that end with noise oscillations and a sound peak. The latter is due to the periodic boundary conditions.[28] The sound peak appears periodically with a time interval, which is determined by the ratio of the size of the simulation box to the sound speed. The described features can be seen from Figure 4, where curves are shifted and the sound peaks for different values of α are connected by a thin line for the clarity. The signature of the sound speed allows us to evaluate the impact of the neutral shadowing force on the sound speed. The results are summarized in Table 1. In this table, one can see that at $r_{\mathrm{cut}} = 1$ the value of the sound speed is not affected by the neutral shadowing force. In the case $r_{\mathrm{cut}} = 2$, the neutral shadowing interaction results in larger values of the sound speed. For example, at $\Gamma = 150$ and $\alpha = 0.2 \times \Gamma$, the sound speed is increased by approximately twenty percent.

Recently, the dynamical properties of the 2D Coulomb systems were considered by Khrapak et al.[30] In the case of the 2D Coulomb systems, the sound mode is not present. Therefore, it is natural to ask whether the sound mode of the Yukawa system is transformed into another mode (e.g., similar to that of a 2D Coulomb system) due to the additional Coulomb interaction with

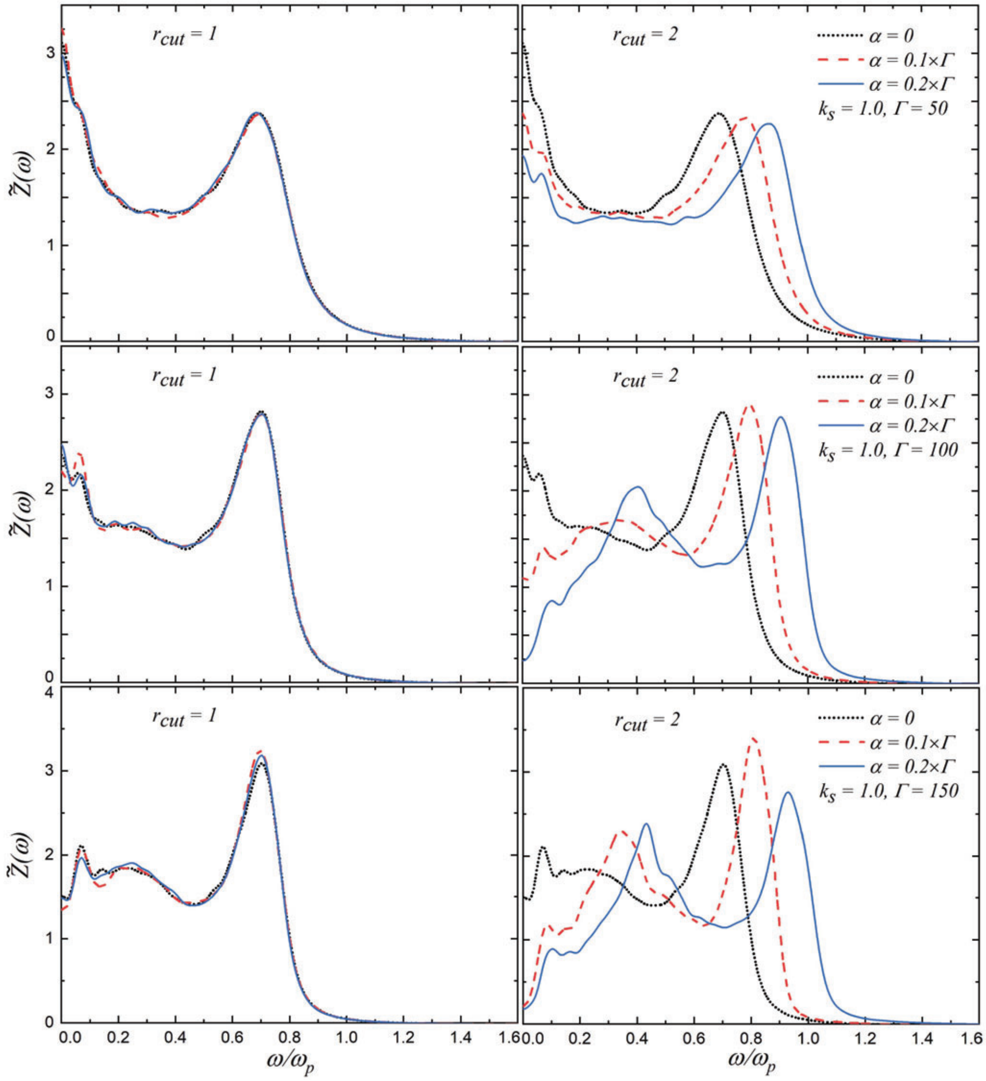

FIGURE 2 Spectrum of the velocity auto-correlation function at $r_{\mathrm{cut}} = 1$ (left panel) and $r_{\mathrm{cut}} = 2$ (right panel)

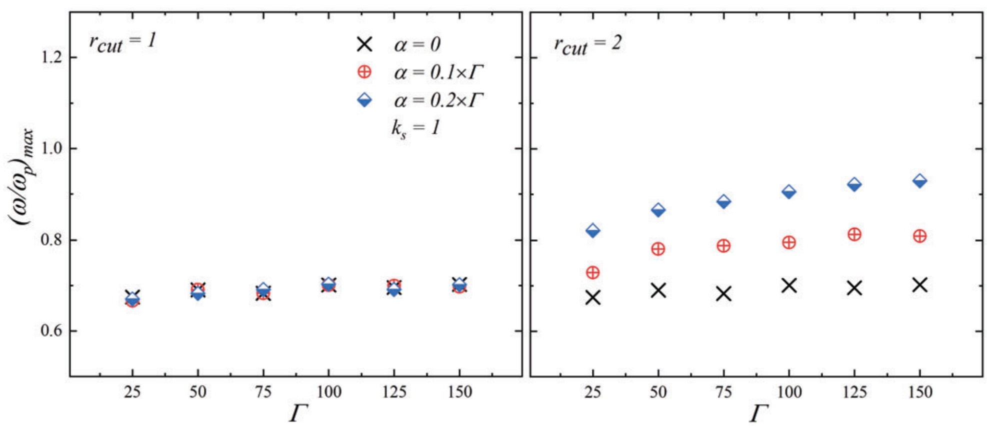

FIGURE 3 Characteristic frequency of longitudinal oscillations, $(\omega/\omega_{\mathrm{p}})_{\max}$, for $r_{\mathrm{cut}} = 1$ and $r_{\mathrm{cut}} = 2$ at $k_{\mathrm{S}} = 1$ as a function of Γ

a cut-off radius. If it is the case, then the sound speed computed in this work should depend on the number of particles (the size of the simulation box). To check this, we have performed simulations with different number of particles ($N = 2{,}040$, $N = 3{,}060$, and $N = 4{,}081$) for the case $r_{\mathrm{cut}} = 2$, $k_{\mathrm{S}} = 1.0$, and $\Gamma = 50$. As a result, we found that the measured sound speed is independent of the considered number of particles (within the margin of error). Therefore, the presented results show that the additional Coulomb interaction with a cut-off radius is not dominant over the Yukawa potential. Indeed, the cut-off radius mimics the screening, suppressing the manifestation of the effects related to a long-range character of the bare Coulomb potential.

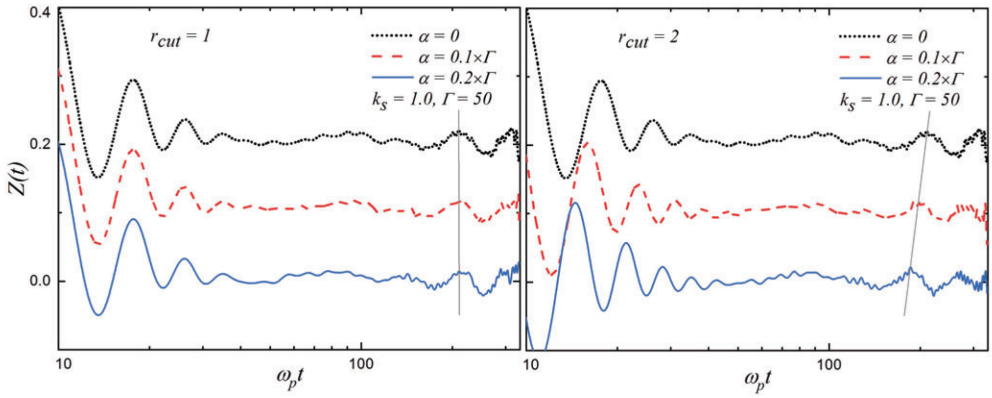

FIGURE 4 Sound peaks in the velocity auto-correlation function at $r_{\mathrm{cut}} = 1$ (left panel) and $r_{\mathrm{cut}} = 2$ (right panel) are illustrated. The sound peaks for different α are indicated by a thin line and curves are shifted vertically for the clarity

3 | CONCLUSION

Motivated by the dusty plasma experiments under cryogenic conditions, we investigated a possible influence of the neutral shadowing interaction between dust particles on their dynamics. A strong neutral shadowing interaction is expected to manifest itself at $T < 10$ K and $P < 10$ Pa[19] due to much higher value of the dust particle's surface temperature in comparison with the temperature of the background neutral particles. The action range of the neutral shadowing interaction is limited by the mean free path of the neutrals. Investigating the velocity auto-correlation function, we found that the neutral shadowing force has a strong impact on the dust particle dynamics only if its effective range of influence exceeds the mean inter-dust particle distance. Particularly, we found that the neutral shadowing force can result in a higher value of the characteristic longitudinal oscillation frequency, more pronounced transverse mode, and an increase of the sound speed.

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