Chapter 4

Role of Shadowing force in formation of 3D dust crystal

Here, molecular dynamics (MD) simulative study on the role of attractive force on Coulomb crystal formation has been done. The interaction attractive potential among the dust grains is taken as Shadowing force that is caused by asymmetrical ion flow to the grains. A comparative study has been made for the effects of purely repulsive Yukawa and the combined Yukawa-Shadowing potential on phase transition of dust crystal by calculating pair-correlation function, for different values of Coulomb coupling parameter $\Gamma$, screening constant $\kappa$, and grain radius $r_d$.

4.1 Introduction:

The physics of dusty plasmas has recently attracted considerable interest due to their applications in many phenomena e.g., in the acceleration of particles and in the formation of dust particles into regular crystalline structures. The formation of dust crystals in plasma is relatively a new area of research. Plasma crystals are example of strongly coupled system. With the development of plasma crystal, it has become possible to study self-organization of many body system with high resolution imaging.
Chaotic motion of particles can be investigated by studying the interaction among few particles and their response to external forces\textsuperscript{165}. Some of the major advantages of plasma crystals are charge neutrality, fast response, easy experimental control, detailed imaging, fine time resolution of the dynamics of individual particles\textsuperscript{166}.

In this chapter we have studied the effect of attractive Shadowing force on the dynamics of dust particles immersed in plasma using a molecular dynamics code. The interaction potential among the grains is assumed to be consisted of two parts, Yukawa potential and the attractive Shadowing potential. Due to the Yukawa potential, the grains arrange themselves in crystalline pattern. However, this arrangement will be modified in presence of the attractive Shadowing force. A comparative study has been made for the role of purely repulsive Yukawa (Debye-Huckel) and the combined Yukawa-Shadowing potential on phase transition of dust crystal from solid to fluid and then to gaseous states.

The attractive Shadowing force between the particles may arise due to asymmetrical ion flow to the surface of the dust grains. The ions when collide with grains, they transfer momentum to the grains. For an isolated dust, the ion flow would be symmetric and net transfer of momentum is zero. If there are two isolated grains, the plasma flow becomes asymmetric and that results in an attractive force. This theory was developed by Tsytovich et al.\textsuperscript{167} and the force is known as shadowing force or the LeSage gravity, after the French scientist who proposed a similar explanation of universal gravitation in the 18th century\textsuperscript{168}. The origin of Shadowing force is sketched schematically in Fig.4.1.

Although the Shadow force is caused by the redistribution of the ion momentum flux, its magnitude is proportional to the electron temperature. The reason is that the electron temperature determines the grain charge and, accordingly, the net current of the absorbed ions. Since the electric potential of the grain behaves asymptotically as $1/r^2$, at large distances, the electric repulsion changes with the shadow attraction. In
Figure 4.1: Shadow interaction between two dust grains. The ions with velocities lying within the shadow region do not reach the grains.
their study, Khodataev et al.\textsuperscript{169} presented both analytically and numerically the dependence of the Shadowing interaction force on the distance. The attraction between two isolated grains has not yet been observed experimentally; however, Samsonov et al.\textsuperscript{170} have made an experimental study of long-range attractive and repulsive forces between the negatively charged particles of a monolayer plasma crystal and a negatively biased wire. It has been reported that the particles close to the wire were repelled from it electrostatically, while the far particles were attracted due to the drag of the ion flow deflected toward the wire.

A number of other mechanisms of grain interaction that may be responsible for binding them together and organizing them in regular crystal-like fashion have been discussed in the literature.

The concept of the wake field in dusty plasmas was introduced by Nambu et al.\textsuperscript{171}. In recent years, this theory of the wake potential\textsuperscript{172,173} has attracted much attention. For dust Coulomb crystals Takahashi et. al.\textsuperscript{174} have experimentally demonstrated the role of the wake potential in a plasma with a finite ion flow. Vladimirov and Nambu\textsuperscript{173} first showed that the collective interaction of the static dust particulate with low frequency oscillations in the ion flow in a dusty plasma can provide an attractive oscillatory wake potential along the ion flow direction. Vladimirov and Ishihara\textsuperscript{175} and Ishihara and Vladimirov\textsuperscript{176} extended this theory to consider periodic structures along and perpendicular to the ion flow direction. Recently, Nasim\textsuperscript{177} studied wake-field excitations in a multi-component dusty plasma by using the fluid as well as the Vlasov-Poisson model. The form of the wake field was found to critically depend upon the size of the test charge velocity relative to the dust acoustic speed. More recently, Ali\textsuperscript{178} has studied attractive wake field formation due to an array of dipolar projectiles in a multi-component dusty plasma for modified dust acoustic waves.

The dust grains formed in laboratory and astrophysical environments may have
any shape and size. Elongated dust grains are assumed to be formed by coagulation of smaller particulates in partially or fully ionized plasmas by some attractive forces\textsuperscript{179,180}, the details of which are not fully understood. However, it is thought that inelastic, adhesive, and collective interactions between micrometer-sized dust particles give rise to kilometer-sized bodies, which are known as planetesimals. Recently, Shukla\textsuperscript{181,182} has investigated the formation of wake potentials in an unmagnetized dusty plasma consisting of electrons, ions, and elongated dust grains, by neglecting the dust particle dynamics.

In a strongly coupled dusty plasma, attractive force between the particles may also arise due to dipole-dipole interactions\textsuperscript{145,183,184,185,186}. The attractive dipole-dipole force may be responsible for attracting large, irregular shaped particles and for subsequent formation of dust structures\textsuperscript{145}, as well as planetesimals or planetary seedlings\textsuperscript{179,187}.

Here in this Chapter, the modelling of the system and simulation are written in section 4.2. Section 4.3 deals with the calculated results and discussions. Conclusions of this study are included in section 4.4.

\section*{4.2 Formulation:}

It is well known that dust particles in plasma acquire a significant negative charge, which causes strong interaction between the dust particles themselves and between dust and plasma particles. These negatively charged micro particles attract the ions surrounding them, leading to a constant flow of ions to the surface. If two grains are close to each other, the plasma flux onto one grain is shaded by the other one. This results in difference in pressure exerted by the plasma particles between the outer and inner sides, which gives rise to the attractive Shadowing force between the two
grains. This Shadowing force is given as\cite{167, 188}

\[ F_{\text{shadow}} = \frac{3}{8} \frac{r_d^2 Z_d^2 e^2}{\lambda_D^2} \]

where \( r_d, Z_d, \lambda_D, \) and \( r_{ij} \) represent the grain size, number of charges residing on the dust grain surface, the ion Debye screening length and inter-particle distance respectively. The Shadowing forces are \( \lambda_D^2/r_d^2 \) times less than the Coulomb forces and, thus, not being screened, can operate only at distances larger than the Debye screening length and may play a major role in the process of dust crystal formation. However, statistical Shadowing from many dust grains in a plasma can substantially reduce the Shadowing force. The Shadowing force is proportional to \( r_d^4 \) and increases sharply with an increase in the grain size. The size of dust particles is growing slowly but continuously in many existing experiments (e.g. on plasma etching) and the role of the Shadowing force in these conditions increases with time.

In this Chapter, we have studied the structural properties of the 3D dusty system of identical, spherical particles of mass \( m_d \) and charge \( Q_d \) immersed in a neutralizing background plasma by developing a molecular dynamics (MD) code. In such a system, the interaction potential between the dust grains is usually described by screened Coulomb or Yukawa potential given by equation (3.3.2) in Chapter 3.

The effect of the attractive Shadowing force on the structure of strongly coupled dusty plasma is studied by comparing Yukawa potential and combined Yukawa-Shadowing potential given by

\[ \phi(r_{ij}) = \frac{Q_d^2}{4\pi\varepsilon_0 r_{ij}} \exp \left( -\frac{r_{ij}}{\lambda_D} \right) - \frac{3}{8} \frac{r_d^2 Q_d^2}{\lambda_D^2} \]

In MD scaling the combined Yukawa-Shadowing potential can be expressed as

\[ \phi'(r_{ij}') = \Gamma \kappa \left( \frac{1}{r_{ij}'} \exp(-r_{ij}') \right) - \Gamma \kappa \left( \frac{3}{8} \frac{r_d^2}{\lambda_D^2} \right) \]

where \( r_{ij}' = r_{ij}/\lambda_D, r_d' = r_d/\lambda_D \) and \( \lambda_D = \lambda_D / \lambda_D \). The simulations are performed with 686 particles for BCC crystal structure and 500 particles for FCC structure, by
using the following plasma parameters \( n_e = 4.39 \times 10^{13} \text{m}^{-3} \), \( n_s = 1.0 \times 10^{14} \text{m}^{-3} \), 
\( T_i = 300K \), \( T_e = 2320K \), \( r_d = 0.7 \times 10^{-6} \text{m} - 2.7 \times 10^{-6} \text{m} \), \( n_d = 3.74 \times 10^{10} \text{m}^{-3} \), 
\( T_d = 100K \). To find out structural correlation of the grains, pair correlation function \( g(r) \) is calculated for this system in presence of both the Yukawa force and combined Yukawa-Shadowing forces. A comparative study between the two forces has been made for different values of \( \kappa \), \( \Gamma \) and grain size \( r_d \).

4.3 Results and Discussions:

In this Chapter we have compared the results found from both the Yukawa and combined Yukawa-Shadowing forces. In our results, the pair correlation factor \( g(r) \) has been plotted for Yukawa potential and then they are plotted for combined Yukawa and Shadowing potential. In Fig.4.2, \( g(r) \) has been plotted for \( \kappa=1.6 \) and \( \Gamma=130 \), 300, 444 and 1389 respectively. The black line represents the effect due to combined Yukawa and Shadowing force, whereas the red line represents that due to the Yukawa force only.

With the increase in the Coulomb coupling factor, it is expected that dusty system transits to ordered crystalline state. The plots for both Yukawa and coupled Yukawa-Shadowing forces show solidification with the increase in the value of \( \Gamma \). It is seen from the graphs that the sharpness of the peaks becomes more prominent for combined Yukawa-Shadowing force than for Yukawa force alone with the increase in \( \Gamma \). A slight shift in the position of the peaks towards smaller value of inter-particle distance is observed for coupled Yukawa-Shadowing force. In MD scaling, the combined Yukawa-Shadowing potential is expressed in terms of coupling parameter \( \Gamma \), as given in equation (4.2.3). Due to this dependence, the sharpness of the peaks due to coupled Shadowing-Yukawa force may increase. In our simulation, the coupling pa-
Figure 4.2: Plot of $g(r)$ vs. $r/\lambda_D$ for $\kappa=1.6$ and $\Gamma=130, 300, 444, 1389$ respectively.
Figure 4.3: Plot of $g(r)$ vs. $r/\lambda_D$ for $\Gamma=2025$ and $\kappa=1.5$, 2.0, 2.5, 3.0 respectively.
parameter is controlled by temperature of the dust particles $T_d$. The velocity of particles increases with the rise in temperature. The Shadowing force may become ineffective for particles moving with high velocity, and as a result the plots of $g(r)$ overlap with each other for the two potentials for smaller values of $\Gamma$.

In Fig. 4.3, we have compared the effect of the screening parameter on crystal formation taking into account the existence of attractive Shadowing force along with the Yukawa force for $\Gamma = 2025$ and $\kappa = 1.5, 2.0, 2.5$ and $3.0$ respectively. It is seen from the plot that for small values of $\kappa$ both the curves almost overlap and Shadowing force is not much effective. However, as the value of $\kappa$ increases, the two sets of RDF's are quite different in peak height and shape. The positions of peaks for combined Yukawa-Shadowing force shift towards smaller value of inter-particle distance. Thus $\kappa$ plays a major controlling role over Shadowing force. Contrary to the Coulomb force, Shadowing force is not screened and dominate for distances larger than the Coulomb field screening length. Yukawa force decreases exponentially with the increase in the value of $\kappa$, whereas the absolute value of Shadowing force increases with screening parameter. For $\kappa = 3.0$, the $g(r)$ plot shows that dust particles transit to fluid state when only Yukawa force is considered. The results of combined Yukawa-Shadowing potential shows that the particles still occupy ordered crystalline state. The Shadowing force might significantly exceed the electrostatic force at large distances, which results in the attraction of the particles.
Figure 4.4: Plot of $g(r)$ vs. $r/\lambda_D$ for grain radius $r_d=0.7$, 1.3, 2.0, 3.0 $\mu m$ respectively.
Fig. 4.4 shows the plots for \( g(r) \) for four different values of radius of the grain. For \( r_d = 0.7 \mu m \), the dust particles are in fluid state. As the grain size is increased, the system gradually transits to solid state. The charge on the dust particle depends on its size. Hence the height of the peak increases when size is increased, indicating more ordered arrangement of the particles. It is observed from the figures that the Shadowing force becomes more and more dominant with the increase in radius. The positions of the peaks gradually shift towards shorter inter-particle distance. Since the Shadowing force is proportional to fourth power of the grain radius, influence of Shadowing force is more for grains with larger size. The Shadowing force is attractive in nature and the particles with large size, may come closer to each other resulting in the shifting of positions of peaks towards smaller inter-particle distance.

4.4 Conclusion:

In this Chapter, by using MD simulation a comparative study has been made between the effects of Yukawa force and the coupled Yukawa-Shadowing force on dust crystal formation. The interaction among the dust grains consists of two parts: normal Yukawa force and then the Shadowing force that arises due to asymmetrical current flow to the grain. From our study it is observed that the attractive Shadowing force plays a dominating role for grains with large size and for large screening parameter. The Coulomb coupling parameter does not have significant effect on Shadowing force. These observations confirm the theoretical and experimental studies made on the role of Shadowing force in crystal formation.