Effects of Electric Field on Diffusion Coefficients and shear viscosity in Dusty (Complex) Plasmas

Muhammad Asif Shakoori[1], Maogang He[1*], Aamir Shahzad[2]

[1]Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education (MOE), Xi'an Jiaotong University, Xi'an 710049, People's Republic of China

[2]Modeling And Simulation Laboratory Government College University Faisalabad (GCUF), Allama Iqbal Road, Faisalabad 38040, Pakistan

Contents

- Dusty (Complex) Plasma, DPs
- Characteristics of Dust Particles
- Applications of DPs
- Dusty Plasma Parameters
- Yukawa System
- Share viscosity
- Diffusion Processes
- Order-disorder structures
- Role of External Electric Field, (EEF)
- Computer Simulation
- Simulations results and discussion
- Conclusions

1.1 Plasma and Dusty (Complex) Plasmas

西安交通大學 XI'AN JIAOTONG UNIVERSITY

Plasma

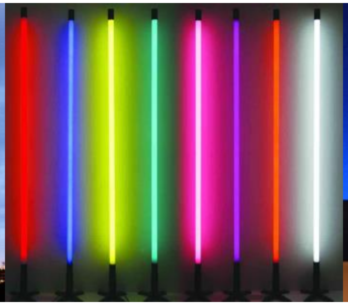
- Plasma is quasi neutral gas of charged (electrons, ions) and neutral particle which exhibit collective behavior
- It is different from ordinary gas with regards to difference of temperature and charge particle density
- Plasmas are ionized gases forming 99% of the visible matter in the Universe

Dusty Plasma

In the addition of dust Particles with electrons, ions, neutral atoms known as Dusty (complex) Plasma. complex plasmas have received much attention in recent years.

lightening

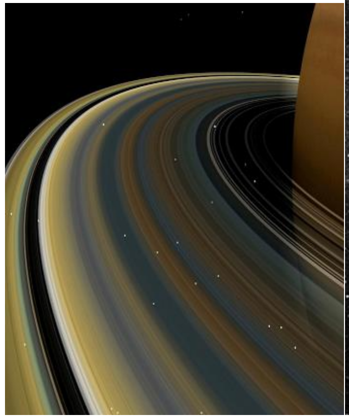
Plasma lights



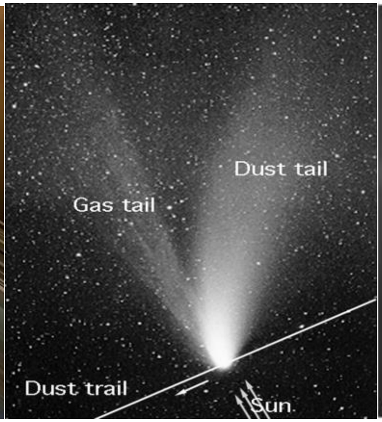
Gas discharge tube

Aurora lights

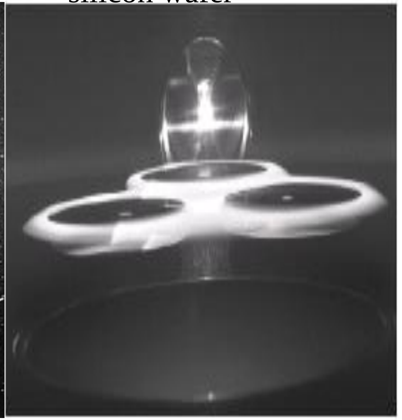
Saturn Rings



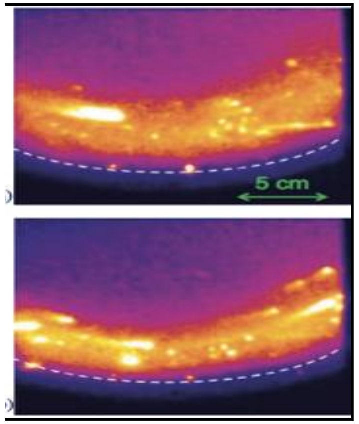
Comet Tail



Ring of DPs encircling silicon wafer



Fire ball in fusion plasma



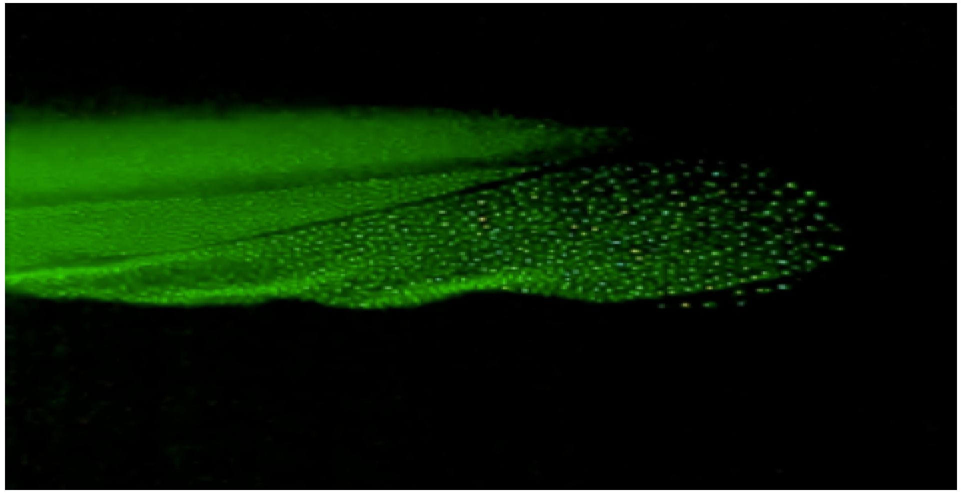
DPs in astrophysics

1.2 Dusty (Complex, fine particle, colloidal) plasmas

- Complex plasmas - four component plasma system
  - Ions
  - Electrons
  - Neutral atoms
  - Charged microparticles

- Plasma and charged microparticles - coupled via collection of ions and electrons from the background plasma.

- Presence of microparticles:
  - Modifies density and charge distribution
  - Modifies plasma instabilities
  - Introduces new dust-driven waves
  - Ubiquitous in natural and man-made plasmas



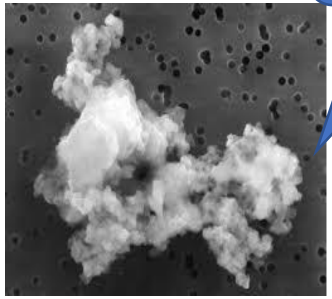
- Measurements of dust particles:
  - Forces
  - Electrostatic potential
  - Velocity distributions

1.3 Characteristics of Dust Particles

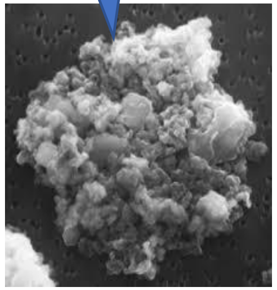
XI'AN JIAOTONG UNIVERSITY

- Dust is a elemental composition of single or different elements.
- **Size**: **µm – nm**(ranging from tens of nanometers to hundreds of microns)**: not constant**
- **Mass**: billions times heavier than ions: not constant (3.0exp-11kg)
- **Charge:** usually about 1-100 of thousand electrons depending on charging processes: not constant
- **Electric potential:** typically 1–10 V (positive or negative).
- N_d = 1-50 particles/mm^3
- Frequency in several hertz

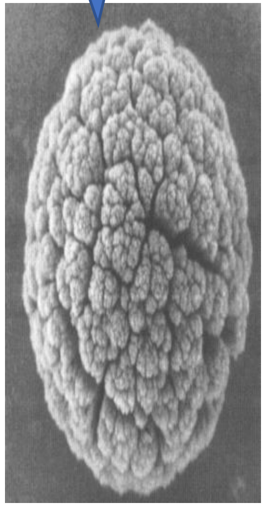
Mo dust particle ($500\mu m$) produced in Z-Pinch device



Cu dust particle ($400\ \mu m$) produced in Tokamak device



SiO_2 dust particle (650 *nm*) Obtain During Processing of Semiconductor device from radio frequency device



Dust plasma component	Temperature
Dust temperature	10 K
Molecular temperature	100 K
Ion temperature	1,000 K
Electron temperature	10,000 K

Dusty Plasma By P.M Shukla

1.4 Application of DPs and low temperature plasmas

- Paper Industry
- Manufacturing and Processing of Semiconductors
- Petroleum Industry
- Chromatography
- Packed Bed Reactors
- Large Scale Nuclear Fusion Experiments ITER France and National ignition facility in the US
- Filtration Processes
- Insulation Systems
- Enhanced oil Recovery
- Ceramic Processing
- Used to Enhance Efficiency and Stability of LED and Solar Cell
- Improved Light Source
- Display Technology
- Laser
- Medical Application in Living Tissues
- Early Cancer Detection
- Lithography tools

Plasma Coulomb Coupling Parameter (Γ)

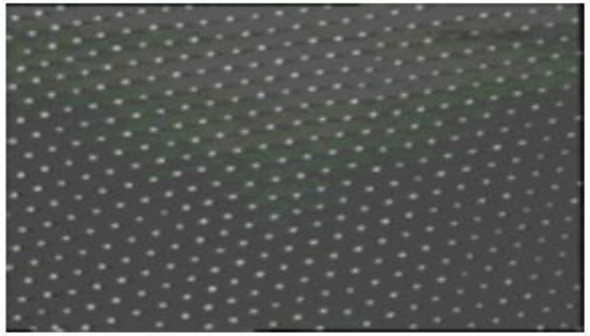
XI'AN JIAOTONG UNIVERSITY

- Γ (coupling parameter) is indicative of the self-organizing, emergent properties of dusty plasmas.
- A dusty plasma can be used as a model system to investigate problems in soft-matter physics.
- Assume dust particles interact via a screened Coulomb interaction (Yukawa, Debye-Hückel):

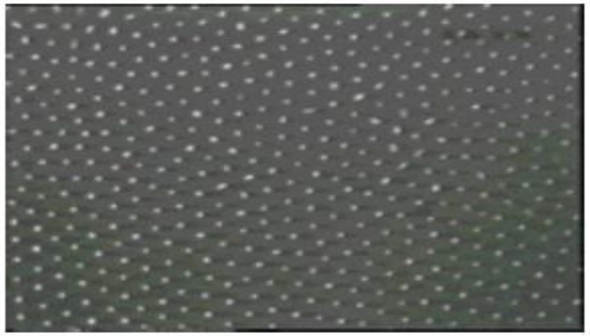
$$\varphi \sim \frac{\exp\left(-r/\lambda_D\right)}{r}$$

$$\Gamma = \frac{\text{electrostatic potential energy}}{\text{thermal energy}} = \frac{Q_d^2}{4\pi\varepsilon_0 k T_d \Delta}$$

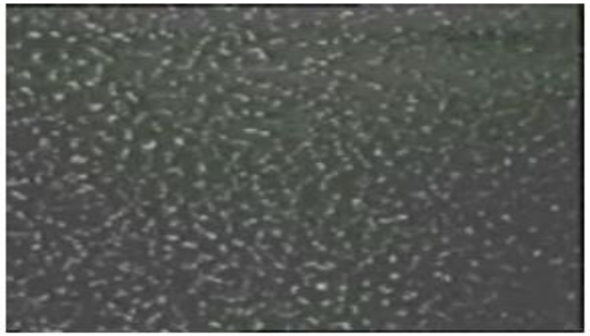
$$\Delta = \text{Wigner-Seitz radius} = \left(\frac{4\pi n_d}{3}\right)^{-1/3}$$



$\Gamma >> 1$
"solid"



$\Gamma \sim 1$
"liquid"

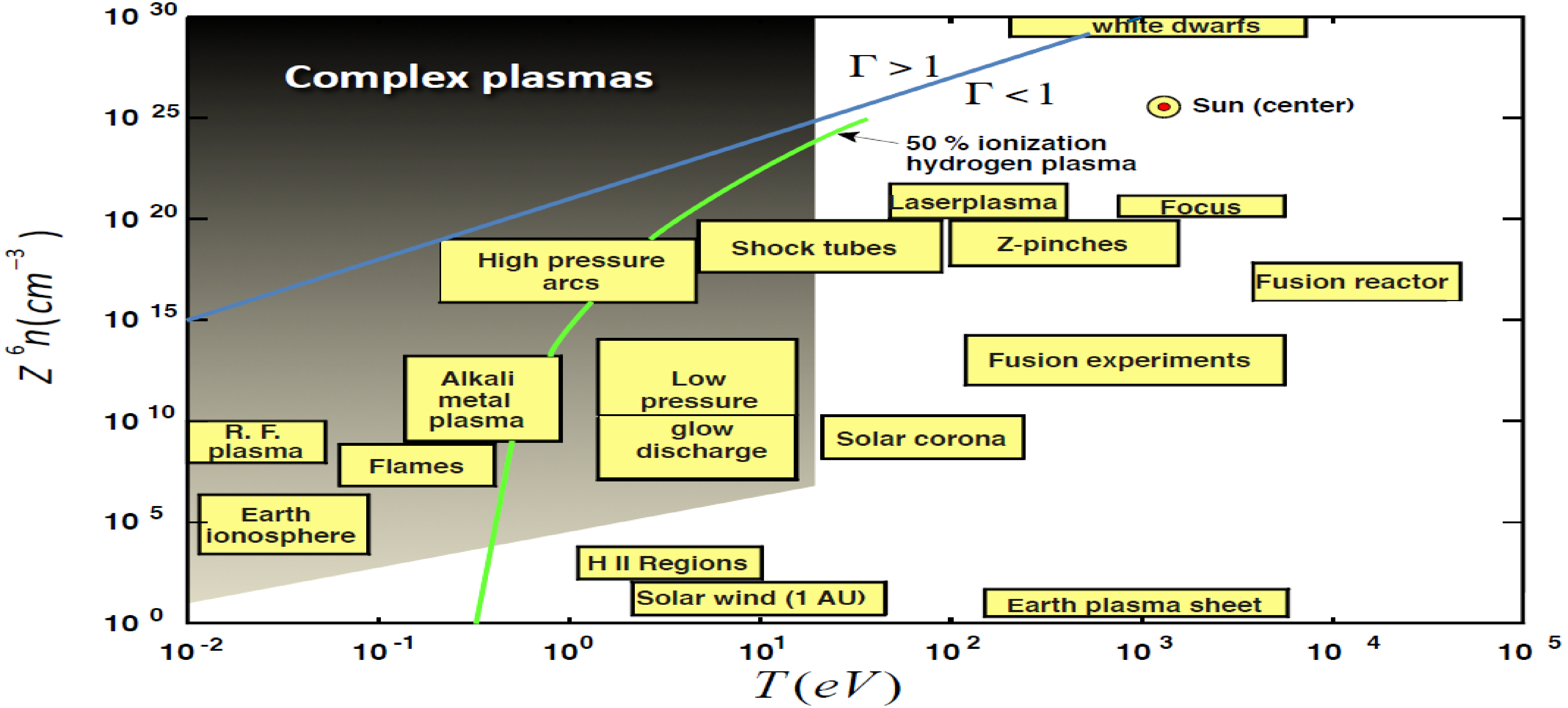


$\Gamma < 1$
"gas"

1.6 Classifications of Plasmas

西安交通大學
XI'AN JIAOTONG UNIVERSITY

$$\Gamma \equiv \frac{(Ze)^2}{kT} n^{1/3}$$



1.7 Yukawa Systems

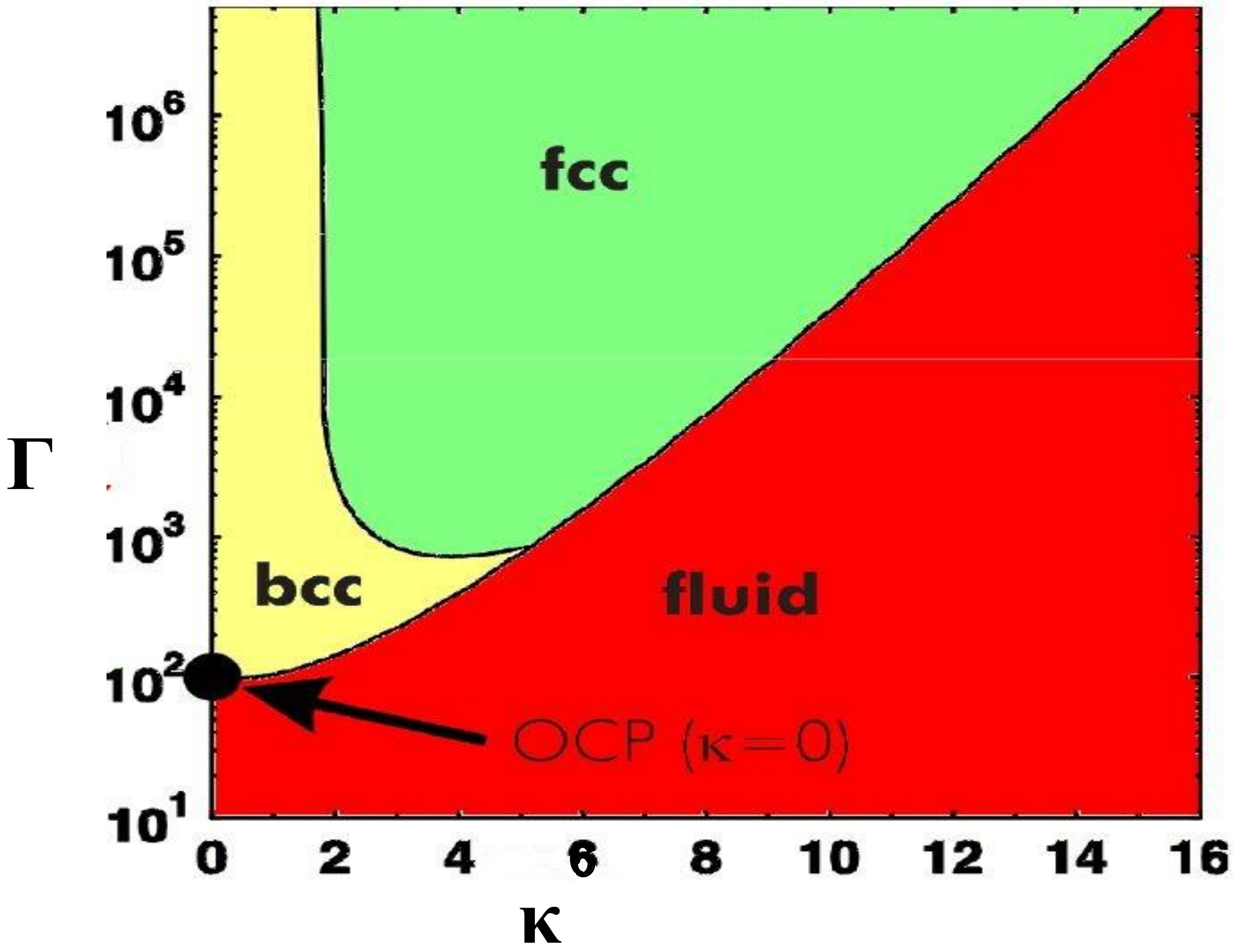
西安交通大学 XI'AN JIAOTONG UNIVERSITY

Debye Screening Parameter

$$\kappa = \frac{a_{ws}}{\lambda_D}$$

$$a_{ws} = (3/4n\pi)^{-1/3}$$

$$\lambda_D = \left(\frac{\varepsilon_o K T_e}{ne^2}\right)^{\frac{1}{2}}$$



西安交通大學 XI'AN JIAOTONG UNIVERSITY

1.8 Summary of dominant forces in dusty plasmas

Force	Origin	Size dependence
Weight	Gravity	a^3
Neutral drag	Streaming neutrals	a^2
Ion drag	Streaming ions	a^2
Thermophoretic	Temperature gradient	a^2
Electric	Electric field	a^1
Magnetic	Magnetic field	a^1

These forces give rise to the majority of the phenomena observed in laboratory and microgravity dusty plasma experiments

a = dust grain radius

1.9 Share viscosity

Shear viscosity

- Viscosity is the material property which relates the viscous stresses in a material to the rate of change of a deformation
- It is a thermophysical properties of fluids, describes the flow and damping of waves
- The viscosity process depends on the mass, temperature, Debye shielding, velocities of particles and external Forces (electric and magnetic)

Application of viscosity

- Shear viscosity plays an essential role physics of plasmas, physics of polymers, medical, semiconductor and chemical industry, environmental safety, space plasma. etc.,

Shear viscosity in DPs

i. Determines energy dissipation (stopping power)
ii. It predict collective modes of Complex dusty plasmas
iii. Characterizes system dynamics as waves, instabilities, vortices
iv. modifies the phase transition and heating

1.10 Diffusion Motion

西安交通大學
XI'AN JIAOTONG UNIVERSITY

What is Diffusion ?

- Diffusion characterized the motion of particles in the gas and liquid regimes
- In diffusion molecules or particles migrate from a high concentration region toward a low concentration region in liquids and gas above the absolute temperature
- The rate of the diffusion process depends on the mass, temperature and viscosity of the particles and external Forces (electric and magnetic

Application of Diffusion Processes

- Diffusion plays an essential role in exploring the dynamical properties in various disciplines of chemistry, physics, and biology

Diffusion in DPs

i. Determines energy dissipation (stopping power)

ii. Characterizes system dynamics as waves, instabilities, vortices

iii. modifies the phase transition and heating

Role of External Electric Field

- Changes in **structural**, **dynamics** and **transport properties** of various fluids under external electromagnetic forces are significant for **physics, chemistry, and biological sciences.**
- Under the action of an electric field, fluids are often known as **electro-rheological fluids (ERFs).**
- **Transport properties** were enhanced in ERFs for the application of the external electric field (EEF).

Electric Field in CPs

- EEF effect the static and dynamics properties, shape and structure, waves and instability etc.
- EEF cause the plasma flow and changes interaction between particles
- Dust particles are polarized and changes their phases

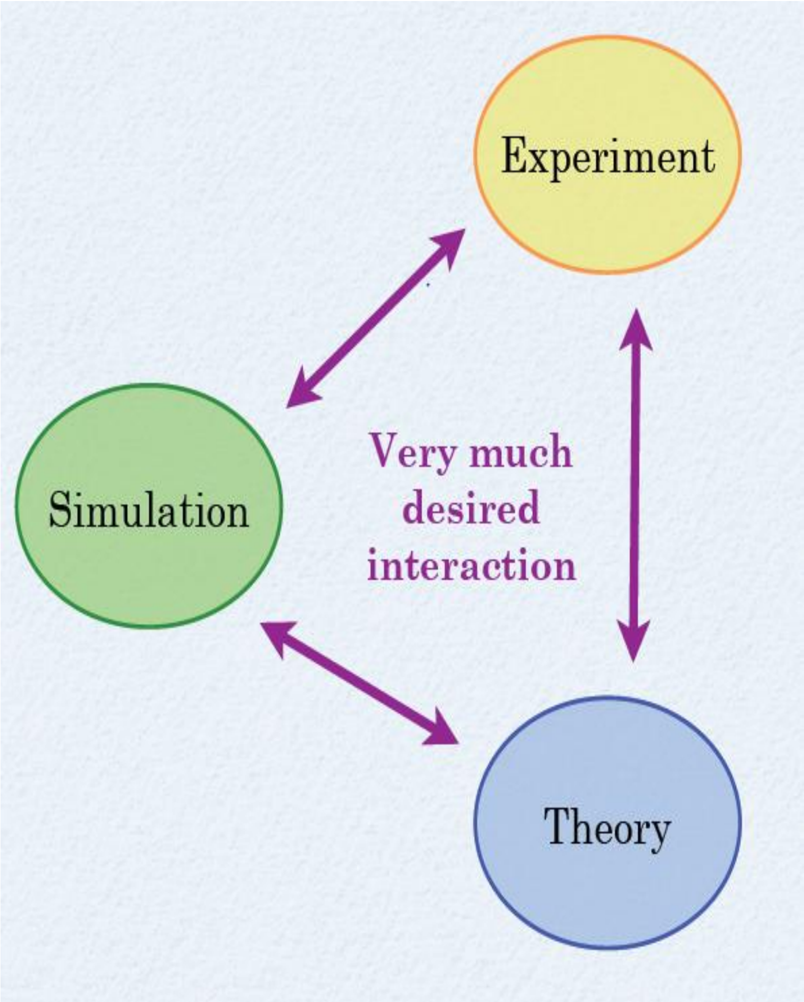
Application of ERFs

- The Conventional ERFs are used for **vibration control** in smart material, **control of ultrasonic transmissions** and sound transmission with low losses, Hydraulics

Possible Applications of EEF in CPs

- Precise tailoring materials
- Can play a significant role in modeled new smart materials

2.0 Computer Simulations



Simulations are useful

- for checking theoretical results
- for cases where no theoretical results are available
- for understanding experimental observations

Simulations allow:

- identification of important processes
- visualization of the system
- Most dramatic advance of resources is experienced in the field of simulations

2.1 Molecular Dynamics Simulations (MDS)

西安交通大學
XI'AN JIAOTONG UNIVERSITY

Equilibrium MDS VS Non-Equilibrium MDS

Equilibrium MDS

- It determine the transport coefficients with out using the effects of internal and external perturbations.
- From the computational point of view it is an expensive technique in terms of time.
- It Strongly depends upon size of system.
- At a time one property measurement is possible

Non-Equilibrium MDS

In Nonequilibrium molecular dynamics (NEMD) techniques

- Perturb the system and measure response
- to study the dusty plasmas under the various types of flow field strengths
- fast computational power.
- It Weakly depends on the size of the system
- All basic transport properties can be calculated at the same time.

Model of Molecular Dynamics Simulation

- Electric potential is the sum of Yukawa (Screened Coulomb) potential and potential induced due to external electric field

- $\Phi(\mathbf{r},\theta) = \frac{Q^2}{4\pi\epsilon_o}\frac{e^{-\mathbf{r}/\lambda_D}}{\mathbf{r}} - E(\mathbf{r}_x cos\theta_1 + \mathbf{r}_y cos\theta_2 + \mathbf{r}_z cos\theta_3)$

Q^2 is charge on dust particles
r distance between two interacting particles
ϵ_0 is the permittivity of free space
λ_D is Debye length

$$\mathbf{E}_{xy} = (\mathbf{E}_x, \mathbf{E}_y, 0) = E(\mathbf{r}_x cos\theta_1 + \mathbf{r}_y cos\theta_2)$$
$$\mathbf{E}_z = (0, 0, \mathbf{E}_z) = E(\mathbf{r}_z cos\theta_3)$$

- E strength of the external electric field
- θ_1, θ_2 and θ_3 are different and correspond to electric field directions
- **r** is the vector for the respective directions along simulation box

Normalization of external electric Field

$$\tilde{E} = e\lambda_D E_{xy}/T$$

and

$$E^* = e\lambda_D E_z/T$$

- $\bar{E}$ is the strength of the EEF on each particle i,
- κ is Debye screening parameters (κ=1/λ_D).
- T is system temperature

Total Force

$$m\boldsymbol{a} = -\frac{\partial\Phi(r)}{\partial r} + QE(\hat{r}_x cos\theta_1 + \hat{r}_y cos\theta_2 + \hat{r}_z cos\theta_3)$$

西安交通大學
XI'AN JIAOTONG UNIVERSITY

Coefficients of share viscosity

- Coefficients of share viscosity is investigated using standard GK expression given as

$$\eta = \frac{1}{Vk_BT}\int_0^\infty Z_\eta(t)dt \qquad Z_\eta(t) = \langle P^{xy}(t)P^{xy}(0)\rangle$$

- V is the volume of the system
- k_B is the Boltzmann constant
- T is the absolute temperature of the systems
- $Z_\eta(t)$ is the stress autocorrelation function (SACF), angular bracket is microcanonical ensemble

$$p^{xy} = \sum_{i=1}^{N}\left[mv_{ix}v_{iy} - \frac{1}{2}\sum_{i\neq j}^{N}\frac{x_{ij}y_{ij}}{r_{ij}}\frac{\partial\phi_{ij}}{\partial r_{ij}}\right]$$

- N is number of dust particles
- m and v is the mass and velocity of i^{th} and j^{th} dust particles
- $r_{ij} = |r| = r_i - r_j = |(x_{ij}, y_{ij})|$ is the position vector between two particles i and j.
- last term represents the forces originating from Yukawa potential.

Green-Kubo relation for self-diffusion coefficient (SDC)

$$SDC = \frac{1}{3N}\int_0^\infty Z(t)dt$$

- $Z(t)$ is velocity autocorrelation function (VACF)

$$Z(t) = \langle V_j(t).V_j(0)\rangle.$$

- V is the velocity of particle at time (t) and (0)

Lattice Correlation function

The density of matter can be calculated at any point by

$\rho(\mathbf{r}) = \sum_{j=1}^{N}\delta(\mathbf{r}-\mathbf{r}_j).$

Particles lattice correlation function can be calculated through Fourier transform

$\boldsymbol{\psi}(\mathbf{k}) = \frac{1}{N}\sum_{i=1}^{N}\exp(-i\mathbf{k}.\mathbf{r}_j).$

k is the reciprocal lattice vector, $\mathbf{k} = 2\pi/(1, -1, 1)l$ for face-centered cubic lattice and l is edge length

3.1 Effect of EEF on share viscosity obtained using MDS at $\kappa = 0.5$

西安交通大學
XI'AN JIAOTONG UNIVERSITY

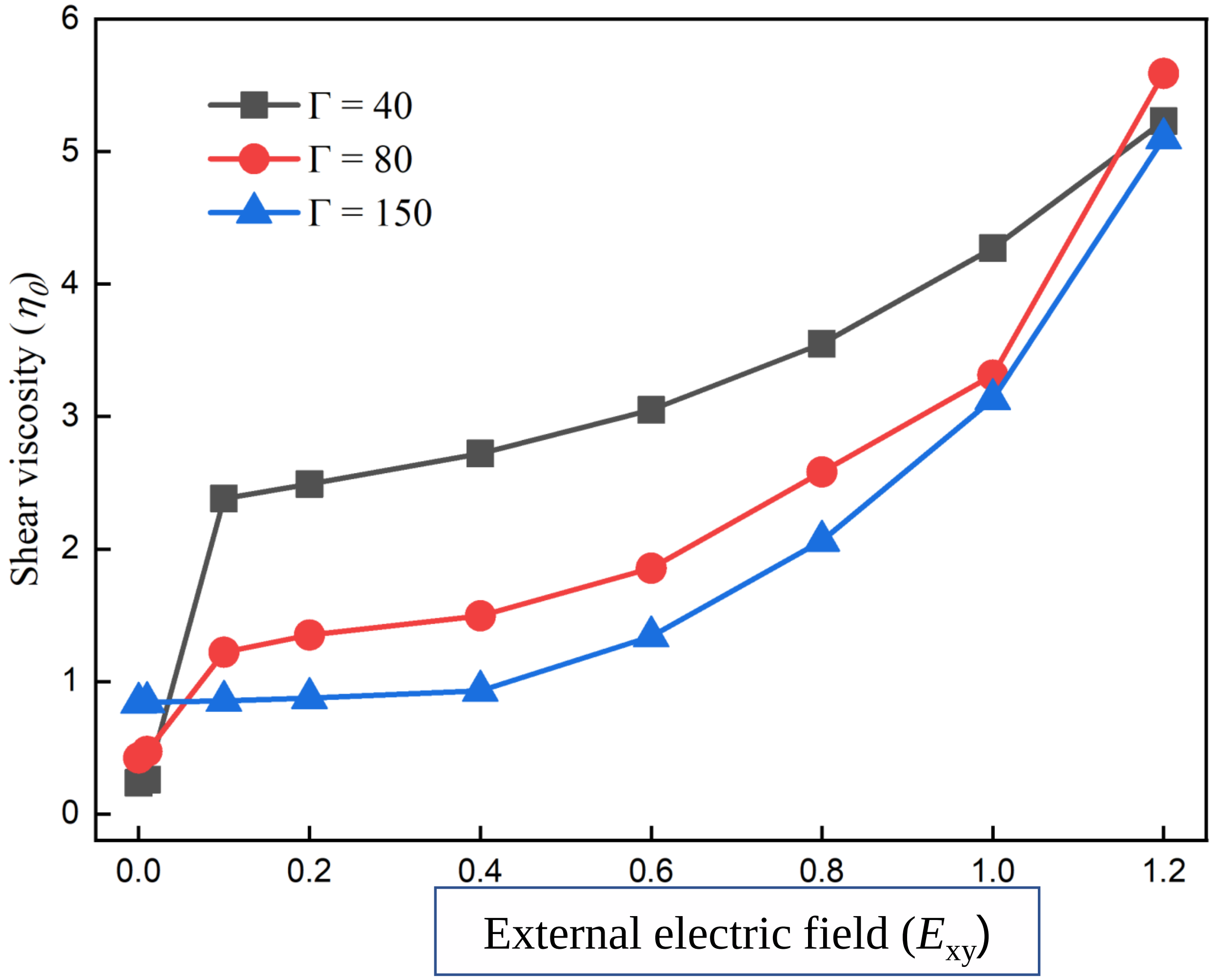


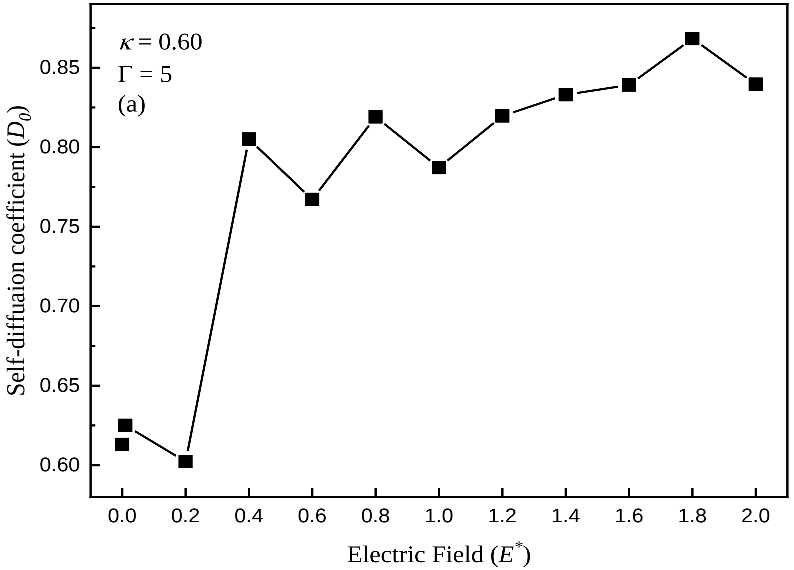
FIG. 1. Effect of external electric field on share viscosity (normalized with plasma frequency) for 3D strongly coupled dusty complex plasmas at three different values of plasma Coulomb coupling (Γ =40, 80 and 150), constant Debye screening (κ =0.5) and the number of particles (N =500).

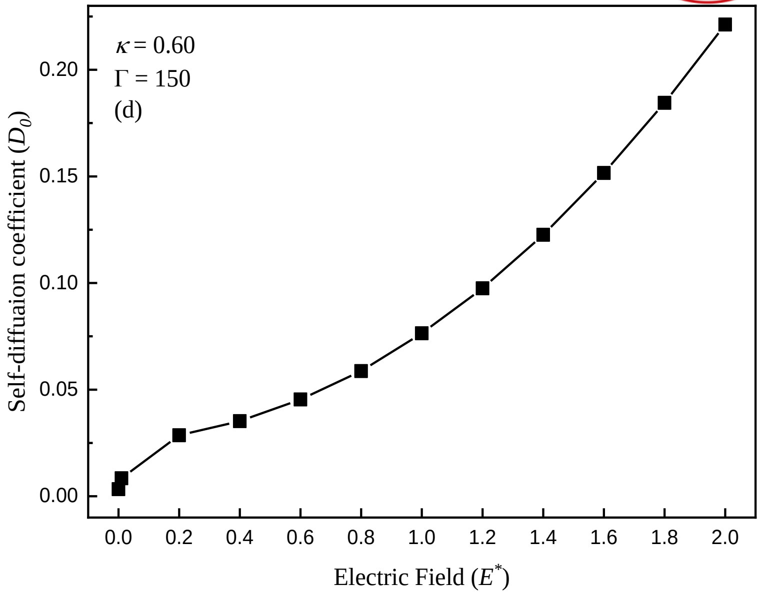
Coulomb Coupling Parameter

$$\Gamma = \frac{Q^2}{4\pi\varepsilon_0 m a k_B T}$$

$$\Gamma = \frac{1}{T} = \frac{1}{\text{Temperature}}$$

3.2 Effect of Electric Field on Self-diffusion for SCCPs for κ=0.6





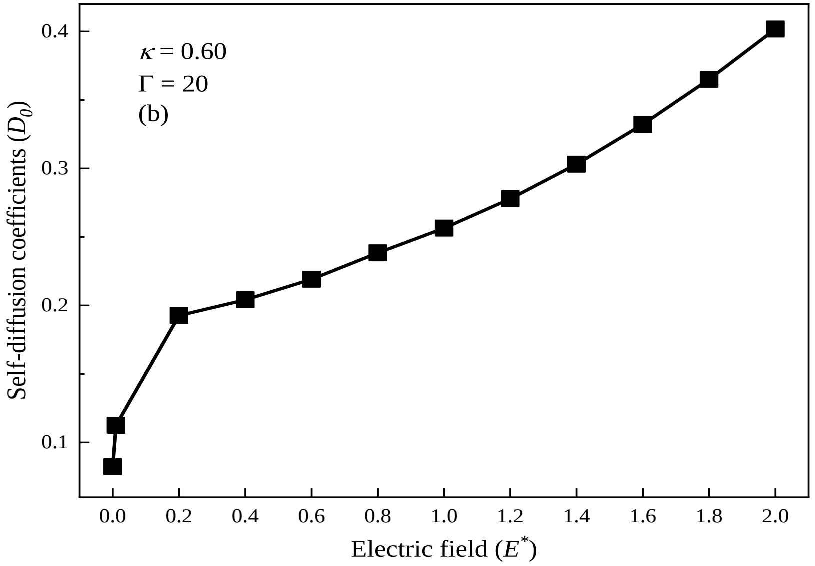
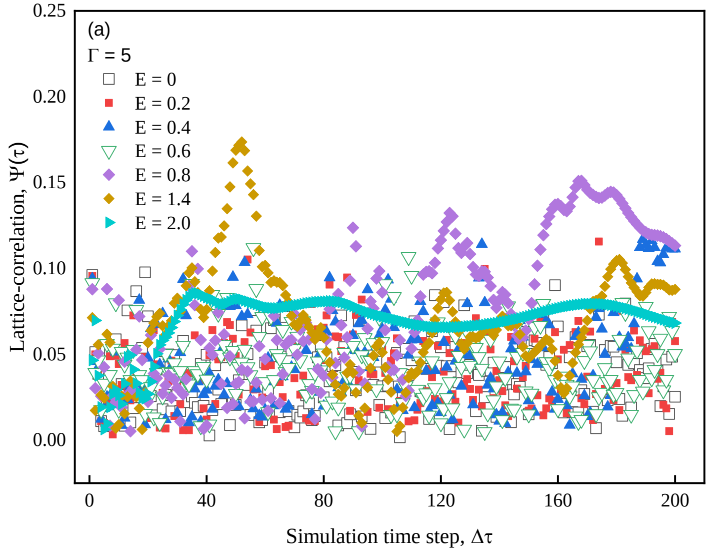
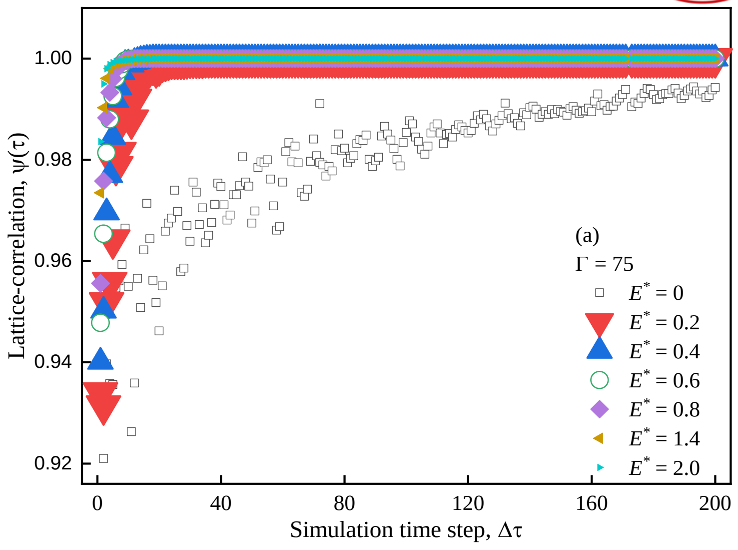


Figure 2. Self-diffusion coefficients as function of external electric field (E^*) for three dimensional strongly coupled complex plasmas at κ=0.6 and N =500, (a) Γ =5, (b) Γ= 20 and (c) Γ = 150

Effect of Electric Field on Self-diffusion in DPs





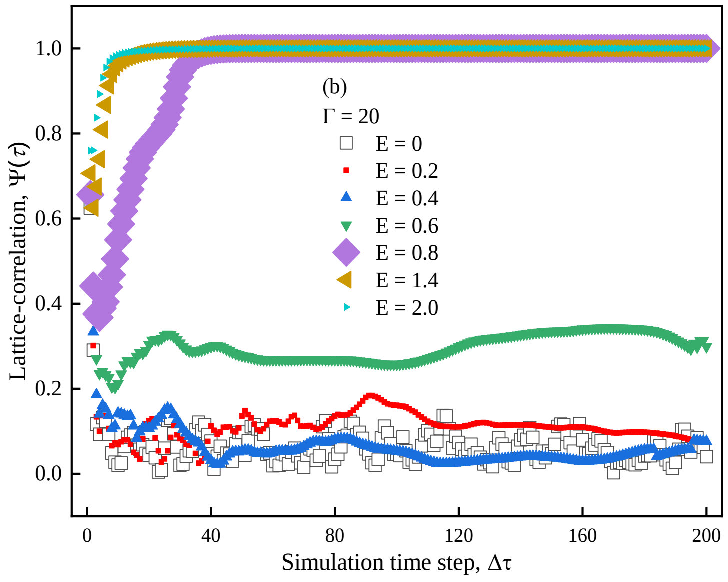


Figure 3. Effect of external electric field on structure of three-dimensional SCCPs for three different states Γ =5, 20 and 75 at κ =0.6 and N =500

4 Conclusions

西安交通大學 XI'AN JIAOTONG UNIVERSITY

1) EMD Simulations are performed for measurement of effect of external electric field on **share viscosity, Self-diffusion coefficients** and structure of 3D strongly coupled complex (dusty) plasmas (SCCPs) used Green-Kubo relation and lattice correlation function
2) Share viscosity (η) increases with increasing external electric field strength ($\mathbf{E}_{xy}$) and plasma coulomb coupling (Γ) and decreases with Debye screening strength (κ)
3) The Self-Diffusion Coefficients (D_0) are increases with increasing electric field ($\mathbf{E}_z$) and κ , decrees with increasing Γ.
4) SCCPs goes under phase transition under influence of external electric field ($\mathbf{E}_z$), nonideal gas-liquid and liquid-solid like states depends on strength of external electric field and plasma parameters
5) Lower value of plasma Coulomb coupling (Γ=5) electric field does not effect significantly, for intermediate value of Γ=20 sufficiently higher electric field strength is need to convert liquids to solid/crystalline state of CPs, further at higher value Γ=75, low strength is enough for condensation of CPs
6) The simulations outcomes are found consistence with electrorheological complex plasmas, conventional electrorheological fluids and ionic liquids under the action of external electric field
7) The presented EMD Simulation techniques is found more comparable performance and has an advantage that it can be used to explore the behavior of thermophysical properties of whole range of plasmas parameters for the external electric field
8) We think; this work will help to understand the static, dynamics and thermophysical properties of micro sized charged dust particles in typical plasma background for the external electric field.

THANK YOU FOR YOUR ATTENTION

Email: asif_shakoori@yahoo.com
Phone:008613201858537

—— 老师，您辛苦了 ——