Kinetic and Hydrodynamic Modes of Propagation in Strongly Coupled Dusty Plasma with Radiative Effects

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Abstract. The polarization force and the charge-gradient force effects in strongly coupled dusty plasma along with the effects of viscosity are studied using theoretical techniques. The strongly coupled dusty medium is suitably described by the simplified phenomenological fluid model. The plasma model is considered to compose of Maxwellian distribution of ions and radiative electrons along with comparatively massive dust grains. With the Generalized Hydrodynamic (GHD) fluid model, the dispersion relation is deduced and the collective properties of the medium are discussed. The viscoelastic and low frequency modes of the waves derived from the dispersion relation and the instabilities of the plasma are inspected in detail to understand the hydrodynamic mode of propagation and the kinetic mode of propagation.

I INTRODUCTION

Electron ion plasmas with charged dust grains of micron-size is said to be strongly coupled dusty plasmas (SCDP) if the coupling parameter $\Gamma>1$.The coupling parameter is the ratio of the average coulomb interaction energy between the particles and their average thermal energy[1].In the astrophysical realm the interior of neutron stars, white dwarfs and some heavy planets have strongly coupled matter [2]. Strongly coupled plasmas are also seen in industrial applications like laser implosion experiments with Γ value reaching as high as 100 [3].Below the critical level(Γ_c) it behaves as viscoelastic fluid with properties of viscosity and elasticity[4].The visco-elastic medium can be suitably described by a generalized hydrodynamic (GHD) model [5].This model was successfully adopted earlier by Kaw et al. to study the transverseshear waves supported by the strongly coupled dusty plasma medium [6, 7].The investigations of instabilities and wave modes of SCDP require the understanding of gravitational instability and radiative condensational instability. Industy plasma, some plasma components such as electrons can gather on the dust grainswhich are very large as compared to the other components andcan cause a variation in the charge on the dust grainKhrapak et al[8].had proposed that if the dust charge is not constant then there acts a force termed as charge gradient force. Later the work was carried further and the influence of a charge-gradient force, which arises due to the variations of the particulate charge in response to external perturbations, was investigated and documented by Khrapak et al[9]. In this paper we focus our investigation on the effect of the charge-gradient force, polarization force and the gravitational instability simultaneously along with radiative electrons in SCDP system.

II GOVERNING EQUATIONS

Generalized hydrodynamic model (GHD) is utilized to describe this multicomponent strongly coupled dusty plasma system. Wave modes subject to hydrodynamic limit and the kinetic limit of such a plasma model is investigated in this study where the ion number density can be defined by Maxwellian distribution as follows

$$N_i = N_{i0} \exp(-e\phi / T_i) \tag{1}$$

The electron' distribution function outlines radiative effects as it departs from normal Maxwellian distribution. The electrons are regarded as inertialess and with finite thermal conductivity. The energy transfer equation is adapted to accommodate the functions of heat loss that depends upon temperature and density in order to analyze the radiative effect of electrons. The equations related to the electron dynamics is given as

$$0 = eN_e \nabla\phi - \nabla p_e \quad (2) \qquad \frac{3N_e}{2}\frac{\partial T_e}{\partial t} + p_e \nabla \boldsymbol{v}_e = \chi_e \nabla^2 T_e - L\left(N_e, T_e\right) \quad (3) \qquad \frac{\partial N_e}{\partial t} + \nabla\cdot\left(n_e \boldsymbol{v}_e\right) = 0 \quad (4)$$

where $L\left(N_e, T_e\right)$ is the function for radiative loss of heat, $p_e = n_e T_e$ is the electron pressure and χ_e is the electron thermal conductivity. The dust dynamics are given in the continuity (5) and momentum equations (6)

$$\frac{\partial N_d}{\partial t} + \nabla.\left(N_d \boldsymbol{v}_d\right) = 0 \quad (5)$$

$$\left(1+\tau_m \frac{\partial}{\partial t}\right)\left[\frac{\partial \boldsymbol{v}_d}{\partial t} + \boldsymbol{v}_d \nabla \boldsymbol{v}_d + \nabla\psi + \frac{q_d \nabla\phi(1-\Re_p)}{m_d} + \frac{V_{Td}^2 \nabla N_d}{N_d} - \frac{q_d \nabla q_d}{\lambda_D m_d}\right] = \frac{\eta \nabla^2 \boldsymbol{v}_d}{m_d N_d} + \left(\frac{\nu + \eta/3}{m_d N_d}\right)\nabla^2 \boldsymbol{v}_d \quad (6)$$

where $\boldsymbol{v}_d$ is the fluid velocity of the dust, m_d is the dust grain mass, N_d is the number density of dust, e is the magnitude of charge, Z_d gives the number of charges accumulating on the dust grain, $\Re_p$ is the dust polarization force parameter. In Eq. (6) $\left(1+\tau_m \partial/\partial t\right)$ is referred to as the Frenkel's term which represents the viscoelastic operator with viscoelastic relaxation time τ_m and η is the longitudinal viscosity coefficient. The expression $\nabla^2\psi = 4\pi G m_d N_d$ gives definition of the gravitational potential ψ, where G is gravitational potential. The Poisson's equation is represented as $\nabla^2\phi = -4\pi\left(eN_i - eN_e + N_d Z_d\right)$

III DISPERSION RELATION AND DISCUSSION

The plasma variables $\left(\boldsymbol{v}_d, q_d, \psi, \phi \ and \ N_{e,i,d}\right)$ can be assumed as $g = g_0 + g_1$, with g_0 represented as the equilibrium part and g_1 is represented as the perturbed part of first order where the equilibrium part of gravitational potential, electrostatic potential and dust velocity is assumed to be zero. The linearized perturbed equations obtained by Fourier analysis of Eqs. (1) – (6) are used to get the dispersion relation.For simplification and further discussion we substitute $-i\omega = \sigma$

$$\left[\sigma^2 + \frac{V_c^2 \sigma}{(1+\tau_m\sigma)}k^2 + k^2 V_{Td}^2 - \omega_{Jd}^2\right]\left[\frac{1}{\lambda_{Di}^2}\left(1+\frac{J_0 N_{d0}}{\Omega_{ch} N_{i0}}\right) + \frac{1}{\lambda_{De}^2}\left(1+\frac{J_0 N_{d0}}{\Omega_{ch} N_{e0}}\right)\Re_{rad}\right] + \omega_{pd}^2 k^2\left[(1-\Re_p) + \frac{J_0}{\lambda_D \Omega_{ch}}\frac{e}{T_{i0}} + \frac{J_0}{\lambda_D \Omega_{ch}}\frac{e}{T_{e0}}\Re_{rad}\right] = 0 \quad (7)$$

where $\omega_{Jd} = \left(4\pi G m_d N_{do}\right)^{1/2}$ is the dust Jeans frequency, $\omega_{pd} = \left(4\pi Z_d^2 e^2 N_{d0}/m_d\right)^{1/2}$ is the dust plasma frequency, $V_c = \left[\left(\nu + 4\eta/3\right)/m_d N_{d0}\right]^{1/2}$ is the compressional wave velocity of the medium, $\lambda_{di(e)} = \left(T_{i(e)}/4\pi e^2 N_{i(e)o}\right)^{1/2}$ is the dust Debye length, $\Re_{rad} = (L_{Te} + \chi_e k^2/N_{e0} - 3i\omega/2)/(L_{Te} + \chi_e k^2/N_{e0} - L_{Ne} - 5i\omega/2)$ is the radiative cooling parameter and the dust charge number $Z_1 = -J_0/\Omega_{ch}\left(e\phi_1/T_{e0} + e\phi_1\wp_{rad}/T_{e0}\right)$.

The modified dispersion relation in eq. (7) describes the modifications in the SCDP system due to the overall effect of viscosity and elasticity, polarization and charge gradient force, and the radiative cooling effect.In absence of the charge-gradient force the dispersion relation becomes similar to the expression given by Sharma [10] without the dust cyclotron term in that case. In the next section the discussion of the dispersion relation given by Eq. (7) is given in two regimes as kinetic regime and hydrodynamic regime.

The expression for the dispersion relation given by Eq. (7) puts forthtwo ranges of wave modes, weakly coupled hydrodynamic regimeand strongly coupled kinetic regime.

1. Hydrodynamic regime ($\sigma\tau_m << 1$)

Taking $\left(\sigma\tau_m << 1\right)$ to obtain the low frequency range of dusty plasma medium with the strongly coupled effect the dispersion relation given by Eq. (7) becomes

$$\left(\sigma^2 + V_c^2\sigma k^2 + k^2V_{Td}^2 - \omega_{Jd}^2\right)\zeta + \omega_{pd}^2 k^2 \Re_{com} = 0 \tag{8}$$

For simplicity $\Re_{com} = 1 - \Re_p + J_0 e/\lambda_D\Omega_{ch}T_{i0} + J_0 e\Re_{rad}/\lambda_D\Omega_{ch}T_{e0}$ is considered along with $\zeta = 1/\lambda_{Di}^2\left(1 + J_0N_{d0}/\Omega_{ch}N_{i0}\right) + 1/\lambda_{De}^2\left(1 + J_0n_{d0}/\Omega_{ch}N_{e0}\right)\Re_{rad}$.The expression for the dispersion relation in Eq. (8) reflects theJeans instability in the low frequency range with dust polarization force, charge gradient force and radiative effect coupled together. If we exclude the effect of self-gravitation, radiative electron, strong coupling and viscoelastic effect then the Eq. (8) resembles the dispersionrelation deduced by Khrapak et al.[8]. The Jeans instability criteria is

$$k^2V_{Td}^2 + \left(\omega_{pd}^2 k^2\Re_{com}/\zeta\right) < \omega_{Jd}^2 \tag{9}$$

A close examination of eq. (9) impliesthat the gravitational instability is affected by the radiative effect, charge gradient force and strong coupling effects in hydrodynamic regime.

2. Kinetic regime ($\sigma\tau_m >> 1$)

Further, the dispersion relation (7) in the kinetic range with $\sigma\tau_m \gg 1$ is written as

$$\left[\sigma^2 + (V_c^2k^2/\tau_m) + k^2V_{Td}^2 - \omega_{Jd}^2\right]\zeta + \omega_{pd}^2 k^2\Re_{com} = 0 \tag{10}$$

The net effect of forces such as polarization and charge gradient forces, influence of strong coupling and self-gravitation is modifying the dispersion relation of the SCDP. The quadratic equation (10) reduces to the equation that shows the kinetic modes in Sharma [10]. If the roots of the equation are derived, it gives a positive root stressing the implication that the system will be unstable.

$$\sigma = \pm(V_c^2k^2/\tau_m + k^2V_{Td}^2 - \omega_{Jd}^2 + \omega_{pd}^2k^2\Re_{com}/\zeta)^{1/2} \tag{11}$$

The constant term of the Eq. (10) can be used to find the Jeans instability condition as

$$V_c^2k^2/\tau_m + k^2V_{Td}^2 + \omega_{pd}^2k^2\Re_{com}/\zeta < \omega_{Jd}^2 \tag{12}$$

The charge gradient force and the polarization force effect, coupled with the radiative effect and the memory relaxation parameter modifiesthe dispersion relation and gives equation (12) which is modified Jeans condition for the strongly coupled kinetic regime. The criterion of Jeans instability is changed in the kinetic regime but in the hydrodynamic regime the Jeans instability condition is unaffected

IV NUMERICAL DISCUSSION

For a graphical representation ofthe dispersion relations we usethe following dimensionless parameters.

$$\sigma^* = \frac{\sigma}{\omega_{pd}}, k^* = k\,\lambda_D, V_c^{*2} = \frac{\nu + 4\eta/3}{m_d N_{d0}\lambda_{Di}^2\omega_{pd}}, \tau_m^* = \tau_m\omega_{pd},\ \omega_{Jd}^* = \frac{\omega_{Jd}}{\omega_{pd}},\ \lambda_{Di(e)}^* = \frac{\lambda_{Di(e)}}{\lambda_D}, V_{td}^* = \frac{V_{td}}{\lambda_D\omega_{pd}}.$$

$$\Re_{rad}^* = 2.0,\ \lambda_{Di(e)}^* = 0.1,\ k^* = 0 - 1.4, V_c^* = 0.5, \tau_m^* = 1.0,\ \omega_{Jd}^* = 0.4,\ V_{td}^* = 0.3,\ ,\Re_p = 0.5.$$

For the Figs. 1and 2, we have chosen the constant dimensionless parameters.From the curves we observe that there is a destabilizing effect due to radiative condensational instability and stabilizing effect due to the presence of the charge gradient along with the polarization force.As the wave number increases from zero to the greater values, the growth rate of the gravitational instability decreases. But as the charge gradient force decreases the growth rate of the instability gradually decreases since the charge gradient force neutralizes the effect of the polarization force and the radiative cooling of the electron. It implies that the charge gradient force alters gravitational collapse.

In Fig. 2 along with all the other parameters from the Fig. 1we have taken the memory parameter in the kinetic regime. The solid line with the stars as markers shows the effect of the charge gradient force in the absence of radiative instability and the dotted line of the respectivecolour represents the system with the presence of the radiative effect. The curve shows that the charge gradient force and the viscoelastic effect damp the excited system and stabilizes it, suppressing the growth of the instability in the strongly coupled dusty plasma. The gravitational collapse and radiative condensation are leading to the fragmentation and cloud formation especially if the cooling time taken is very short. When we compare curves of the two regimes, it is clearly evident that the strongcoupling has literally no effect on the criterion of Jeans instability in the hydrodynamic regime while the condition of Jeans instability changes such that the separation between the curves is reduced inkinetic regime. The kinetic mode shows greater stability.

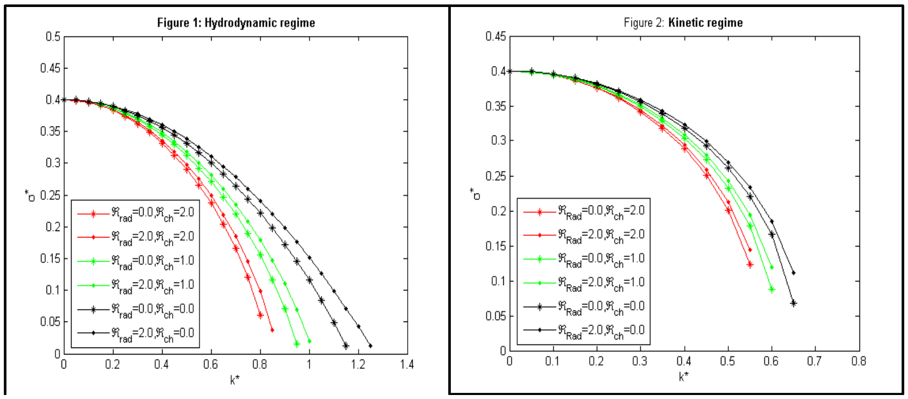

Figure: The dimensionless growth rate of gravitational instability σ^* against the dimensionless wave number k^* in (Fig.1) Hydrodynamic mode and (Fig.2) Kineticmode of SCDP for different values of charge gradient force and radiative cooling parameter $\Re^*_{rad}$

VI CONCLUSION

The investigation on the effect of the charge gradient force, polarization force, viscoelastic modes and Jeans modes in SCDP using the GHD model showed modification in the dispersion relation and it can be noted that the Jeans instability is the kinetic regime depends upon the polarization parameter, strongly coupling parameter and radiative cooling. Though polarization force is destabilizing, the charge gradient force tends to stabilize the system and the excited modes are damped. The results of the present study can be useful to explain the astrophysical phenomena taking place in the interstellar medium and in laboratory plasmas or in industrial applications where the SCDP is utilized for plasma processing.

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