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Influence of dust charge fluctuation and polarization force on radiative condensation instability of magnetized gravitating dusty plasma

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ABSTRACT

The influence of dust charge fluctuation, thermal speed and polarization force due to massive charged dust grains is studied on the radiative condensation instability (RCI) of magnetized self-gravitating astrophysical dusty (complex) plasma. The dynamics of the charged dust and inertialess electrons are considered while the Boltzmann distributed ions are assumed to be thermal. The dusty fluid model is formulated and the general dispersion relations are derived analytically using the plane wave solutions under the long wavelength limits in both the presence and the absence of dust charge fluctuations. The combined effects of polarization force, dust thermal speed, dust charge fluctuation and dust cyclotron frequency are observed on the low frequency wave modes and radiative modified Jeans Instability. The classical criterion of RCI is also derived which remains unaffected due to the presence of these parameters. Numerical calculations have been performed to calculate the growth rate of the system and plotted graphically. We find that dust charge fluctuation, radiative cooling and polarization force have destabilizing while dust thermal speed and dust cyclotron frequency have stabilizing influence on the growth rate of Jeans instability. The results have been applied to understand the radiative cooling process in dusty molecular cloud when both the dust charging and polarization force are dominant.

1. Introduction

The phase transition in a plasma offers the dusty (complex) plasma as an interesting and developing research field. In past few decades, dusty plasma has contributed a lot in plasma research and it became most significant dynamical process in astrophysical plasma, planetary rings, molecular clouds, interstellar media (ISM), comet tails, Q machine, tokamak, laboratory plasma, etc. [1–4]. The wave modes and instabilities in two fluid dusty plasma deal with exciting features in these complex systems [5,6]. Kahlert et al. [7] have recently discussed the dynamics of strongly correlated inhomogeneous plasmas. The various kinds of instabilities observed in complex plasmas leads to several interesting features.

However, in complex plasma the variation in dust charge produces charging current which is responsible for the modifications of the dynamics of dust particles. It arises because of charging currents to the dust grains which depends on the grain surface potential. The static charged dust grains only modifies existing plasma wave spectra, but the dust charge describes a new mode called dust acoustic wave (DAW) mode. Many authors have analyzed the effect of a time dependent dust charge variation on the waves and instabilities in both homogeneous and inhomogeneous plasmas. It is well known that the dust charge in cold clouds ($T < 30$ K), fluctuates between ± 1 and 0. Moreover, in the low density partially ionized H II region ($T \sim 10^4$ K) grains may produce 100 or more charges [8]. There are large numbers of complex plasma systems where dust charge fluctuation occurs due to different plasma processes. In this direction, Varma et al. [9] have discussed the electrostatic oscillations in the presence of grain charge perturbations and the collective features in dusty plasma. Shukla and Silin [10] have observed dust ion acoustic wave (DIAW) mode in dusty plasma with negatively charged stationary dust grains.

In Verheest and Meuris [11] work, they have observed whistler-like instability due to dust charge fluctuations in dusty plasma. Mahanta et al. [12] have discussed the dynamics of a magnetized gravitating dusty plasma including the effects of dust charge fluctuations. Tribeche and Zerguini [13] demonstrated current-driven ion-acoustic instability in collisional dusty plasma with charge fluctuations and studied the excitation of DIAW. The effect of radiative cooling on molecular cloud with charged dust grain and dust temperature effects are also discussed in Refs. [14–16]. Li-Ping and Ju-Kui [17] have studied the instability of DAW in inhomo-

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geneous dusty plasmas with non-adiabatic dust charge fluctuation and shown that inhomogeneity, non-thermal ions and non-adiabatic dust charge fluctuation have strongly influence over the oscillation frequency. Schneider et al. [18] have derived dispersion relation of electrostatic waves in a Maxwellian dusty plasma with variable charge on dust particles. Therefore, the consideration of dust charge fluctuation in gravitating, magnetized astrophysical dusty plasma could be important to discuss the complete dynamics of the charged dust particles along with radiative cooling effects.

In addition to this, in inhomogeneous unmagnetized plasma the polarization force acting on a charged dust grain has significant importance in complex plasma. This idea was originally governed by Hamaguchi and Farouki [19], according to which the Debye sheath around the grain is polarized in the presence of external electric field and the charged dust grain experiences polarization force which is given mathematically

$$\boldsymbol{F_P} = -\frac{q_d^2 \nabla \lambda_D}{2\lambda_D^2},$$

where $\lambda_D = \lambda_{Di}/(1+\lambda_{Di}^2/\lambda_{De}^2)^{1/2} = \lambda_{Di}/(1+n_eT_i/n_iT_e)^{1/2}$ is the normalized Debye length ($T_{i(e)}$ is the ion (electron) temperature, $n_{i(e)}$ is the ion (electron) number density). Recently, many authors have predicted their own theoretical model and performed experimental investigations in dusty plasma. Khrapak et al. [20] have included the effect of polarization force of massive dust particles to investigate the modified DAW mode in non-uniform unmagnetized dusty plasma. Mamun et al. [21] have reported the effect of polarization force and dust temperature on shock waves and DAW in strongly coupled dusty plasma (SCDP). Emamuddin and Mamun [22] have studied the influence of positive dust mass on instability in four component magnetodusty plasma in the presence of polarization force. Ashrafi et al. [23] have discussed the role of polarization force in different dusty plasma situations. Sukhinin et al. [24] have investigated the effect of polarization force of dust particles with trapped ions in an external electric field and low density dusty plasma. Asaduzzaman et al. [25] have derived modified dispersion relation of DAW in a non-uniform adiabatic dusty plasma in the presence of polarization force. Pervin et al. [26] have observed the effects of polarization force and fast electrons on DA shock waves in SCDP. Thus, it is one of the important parameter in dusty plasma which can be considered in the present analysis.

Along with this, in our earlier studies [27,28] the effects of polarization force, magnetic field and radiative condensation are studied on the combined Jeans and RCI of self-gravitating dusty plasma. Shukla and Sandberg [29] have also investigated the RCI in a self-gravitating astrophysical dusty plasma but they have not considered the effects of polarization force and dust charge fluctuations. Shadmehri and Dib [30] have also analyzed the magnetothermal condensation modes including the charged dust particles and found that growth rate of condensation modes increases with the electrical charge of the dust particles. In this work, effects of dust charge fluctuation and polarization force were not considered. Thus so far, none of the authors have considered the effects of polarization force, dust charge variation and dust thermal speed on the RCI of self-gravitating magnetized dusty plasma. In many dusty plasma situations, the simultaneous presence of dust charge variation and polarization force are ubiquitous with non-thermal electrons. Therefore in this work, we have considered the combined effects of polarization force, dust charge fluctuations, dust thermal speed and magnetic field on the gravitational instability and RCI of dusty plasmas. The results have been applied in understanding the formation of dense dusty molecular clouds using the appropriate physical parameters.

2. Formulation of the problem

Let us consider an inhomogeneous, self-gravitating, magnetodusty plasma consisting of negatively charged uniform sized (a) dust grain with Boltzmann distributed thermal ions and non-thermal electrons. The plasma is embedded in uniform magnetic field $\boldsymbol{B} = B_0\hat{\boldsymbol{z}}$. The electron temperature perturbations with radiative effects are taken into account. The dust charge fluctuates around the grain surface which provides necessary electron and ion current as a function of surface grain potential. The dust charge fluctuation has significant role in the self-gravitating dusty plasma. We may consider their influence under the limitations when the time scale of dust charge fluctuation is comparable to the time scale of DAW propagation i.e. $\tau_c \sim \tau_a$ (where $\tau_c = \Omega_c^{-1}$ is the grain charge fluctuation time scale and $\tau_a = (kc_s)^{-1}$ is the DAW propagation time scale) [15]. If the dust charge fluctuation is not present then the charge neutrality condition becomes $n_{i0} = n_{e0} + z_{d0}n_{d0}$, where n_{j0} $(j = e, i, d)$ and z_{d0} represent the unperturbed number densities of the plasma species and the equilibrium number of charges residing on the negative charged dust grains respectively.

The fluid model which describes the propagation of DAW and DIAW is appropriate to discuss the low frequency waves ($\omega \ll kv_{te}, kv_{ti}$) and linear instability in an ideal dusty plasma. At the slow dust time scale, the ion densities are expressed by Maxwell–Boltzmann relation

$$n_i = n_{io}\exp\left(-\frac{e\phi}{T_i}\right). \tag{1}$$

The dynamic of inertialess electrons are expressed as

$$-\nabla p_e + en_e\nabla\phi = 0, \tag{2}$$

where $p_e = n_eT_e$ is the electron thermal pressure, $T_{e(i)}$, e, ϕ denote the electron (ion) temperature, electron charge, electrostatic potential. The energy transport equation modified by electron thermal conductivity and radiative heat loss function $L(n_e, T_e) = F_c - F_H$ (where F_c and F_H are the cooling and heating functions respectively) is given by

$$\left(\frac{3}{2}\right)n_e\frac{\partial T_e}{\partial t} + p_e\nabla.\boldsymbol{v_e} = \chi_e\nabla^2T_e - L(n_e, T_e), \tag{3}$$

where χ_e and $L(n_e, T_e)$ refer to the electron thermal conductivity and density-temperature dependent radiative heat-loss function respectively. For a typical plasma with $T_e \le 4.47\times10^4$ K, the electron thermal conductivity approaches to $\chi_e = 2.5\times10^3\sqrt{T_e}$, whereas it reaches to $\chi_e = 1.24\times10^{-6}T_e^{5/2}$ for a plasma with $T_e > 4.47\times10^4$ K [31].

In the steady state of the plasma the thermal equilibrium of the electron is described by the following relation

$$L_0(n_{e0}, T_{e0}) + \chi_e\nabla^2T_{e0} = 0. \tag{4}$$

The dynamics of massive dust grains ($m_dn_d \gg m_in_i \gg m_en_e$) are assumed to be modified by the gravitational force, thermal force and polarization force produced due to the presence of external electric field. The contribution of self-gravitational force of massive dust grains in the presence of dust charge fluctuation is considered under the limitations when τ_c is comparable to dust free fall time scale $t_f(=1/\sqrt{4\pi Gm_dn_{d0}})$. In the equilibrium, the pressure gradient has tendency to balance the gradient of self-gravitating potential. At the same time, the presence of magnetic field and dust thermal force contribute to the different possible low-frequency dust modes. The presence of external electric field causes deformation in the sheath around the dust grain which provides the polarization force. In Ref. [19], it is demonstrated that the total force acting on a small charged dust grain in a non-uniform