Collisional Effect on Gravitational Instability in the Presence of Dust Polarization and Charge Gradient Force

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Abstract. The analytical investigation of the effect of collisions on the Jeans instability in dusty plasma is carried out to observe the effect of the simultaneous presence of polarization force and charge gradient force on the dust particles. The dispersion relation, the instability growth rate and the graphical analysis shows that the combined effect of the charge gradient force, dust polarization force and collisions moves the system towards stabilization.

INTRODUCTION

Complex plasmas with ions, electrons, and dust particles, develop instabilities due to the dust-neutral, ion-neutral and dust-neutral collisions [1]. Jeans gravitational instability could be a reason for the collapse of uncharged clouds of extended mass to form massive astrophysical bodies [2] or condensed crystals in case of laboratory plasma [3]. For charged dust particles, different forces such as the electrostatic force, the polarization force, the charge gradient force etc. become significant leading to deviations and modifications which can be interesting and intriguing in the dust dynamics [4]. The recent trends in research, describe that the self-gravitational effect caused by the presence of dust grains of high masses brings about Jeans type modification of the electrostatic [5, 6] and electromagnetic modes [7-9] found in the multicomponent dusty plasma. Several authors have documented the effect of self-gravitation of the dust grains and the resultant modification of the waves that propagate in collision less dusty plasma [10]. Some sites of astrophysical plasma exhibit highly collisional behavior, as in dark molecular clouds and in case of laboratory experiments with gas discharge where the frequency of ion-neutral collisions stands in the range of 10\textsuperscript{5}-10\textsuperscript{7} [11]. So, it is crucial to study the self-gravitating collisional dusty plasma with the effect of polarization force and charge gradient force. Shukla and Verheest [12] have treated the electrostatic, gravitational and the drag forces simultaneously and found new classes of instabilities of dissipative nature while Abbasi and Rashidian Vaziri [10] combined the effect of polarization force and collisional effect on Jeans instability in dusty plasma in their work. Khrapak et al. [13] have examined the propagation of low frequency dust acoustic waves in the presence of polarization force. Moreover, Khrapak and Khrapak [14] investigated the effect of charge gradient force on dust acoustic wave. In this proposed paper, the effect of dust neutral collisions along with the charge gradient force and polarization force on Jeans instability is investigated.

MODEL EQUATIONS AND DISPERSION RELATIONS

A system of inhomogeneous unmagnetized dusty plasma with Maxwellian ion and electron distribution and self-gravitating polarized dust grains with negative charge is considered. We consider all dust particles are of the same size, same mass and equal charge. We use the three-fluid model to describe the system and the basic set of three fluid equations which are linearized considering the first order perturbation of each variable. The perturbation invariables can be defined as $\xi = \xi_0 + \partial \xi$, here $\xi_0$ is the symbol for unperturbed quantity, while $\partial \xi$ for the perturbed quantity.
The symbol $\xi$ stands for the velocity, density, charge, state temperature and potential. The equations for gravitational dusty fluid are given by

$$\frac{\partial \delta n_d}{\partial t} + n_{d0} \nabla U_d = 0$$  \hspace{1cm} (1)$$

$$\frac{\partial U_d}{\partial t} = -\frac{Q \nabla \Phi}{m_d} + \frac{F_{\text{eff}}}{m_d} - \nu_d \delta U_d - \nabla \delta \psi$$  \hspace{1cm} (2)$$

The parameter $F_{\text{eff}}$ represents the effective force due to the polarization of dust and due to the gradient of charge generated onto the dust surface i.e. $F_{\text{eff}} = F_p + F_q$. The dust polarization force is defined as $F_p = -R_{\text{pol}} Q \nabla \phi$ with $R_{\text{pol}} = (-a T_e z / 16 \pi e_0 \lambda_e T_e) \nabla \phi$ and the dust charge gradient force is $F_q = -R_{\text{ch}} Q \nabla \phi$ with $R_{\text{ch}} = (a T_e z Q / 4 \pi e_0 \lambda_e T_e (1 + z)) \nabla \phi$. However, the first term in the left-hand side of Eq. (2) represents the electrostatic force; the second gives the effective force caused by the phenomena of polarization of dust and the charge gradient developed on the dust surface. Third term gives the collisional force due to the phenomena of dust neutral collisions. The last term in the equation is responsible for the self-gravitational force of the dust.

The Poisson’s equation for self-gravitational and electrostatic potential is

$$\nabla^2 \bar{\psi} = 4 \pi G m_d \delta n_d$$  \hspace{1cm} (3)$$

$$\nabla^2 \bar{\phi} = 4 \pi e \left( \delta n_e - \delta n_i + Z_d \delta n_d \right)$$  \hspace{1cm} (4)$$

The equation for the charge variation of dust is

$$\frac{1}{\Omega_{\text{ch}}} \frac{\partial \delta Z_d}{\partial t} + \delta Z_d = R_e \left( \frac{\delta n_i}{n_{i0}} - \frac{\delta n_e}{n_{e0}} \right)$$  \hspace{1cm} (5)$$

where

$$R_e = J_0 / \Omega_{\text{ch}}$$ and $\delta Z_d = R_e \left( \delta n_i / n_{i0} - \delta n_e / n_{e0} \right)$

The electron and ion follow the Maxwellian distribution so the perturbed densities of electrons and ions can be obtained as

$$\delta n_i = -n_{i0} e \phi / k_B T_i \text{ and } \delta n_e = n_{e0} e \phi / k_B T_e$$  \hspace{1cm} (6)$$

However, using the plane wave analysis, and assuming all the perturbed quantities like velocity and both the potentials can be expressed as $U_{ik} = \phi = \psi \equiv \exp(ik \cdot r - i\omega t)$ where $\omega$ represents the frequency of perturbation, and $k$ is the wave number. Moreover, from Eq. (2) we can get a relation for perturbed dust density using Eqs. (1), (3) and (4) as

$$m_d \left( \omega^2 + i \omega v_d - \omega_{ld}^2 \right) \delta n_d = -q_{d0} n_{d0} k^2 \left( 1 + R_{\text{eff}} \right) \delta \phi$$  \hspace{1cm} (7)$$

where $R_{\text{eff}} = R_{\text{pol}} + R_{\text{ch}}$

Now, with the obtained expression for the dust density, the electron and ion density we can calculate the effective potential generated using Poisson’s equation since, the presence of the polarization force and charge gradient force affects the dispersion properties of the propagating wave in the self-gravitating dusty plasma. Accordingly, putting the values of $\delta n_i$, $\delta n_e$ and $\delta n_d$ into Poisson’s equation, we derive the dispersion relation as (using $-i \omega = \sigma$)

$$\left( \sigma^2 + \sigma v_d - \omega_{ld}^2 \right) \left( 1 + R_e \frac{n_{d0}}{n_{i0}} \right) = -k^2 \omega_{pl}^2 \lambda_D^2 \left( 1 + R_{\text{eff}} \right)$$  \hspace{1cm} (8)$$
where, $\lambda_{D}(e) = (1 + \frac{4\pi e^2 n_{e0}}{m_{e0}})^{1/2}$ is the dust Debye length and $\omega_{pd} = \left(\frac{4\pi Z^2 e^2 n_{d0}/n_{0}}{m_{p}}\right)^{1/2}$ is the dust plasma frequency and $\omega_{d} = \left(\frac{4\pi Ge_{b}n_{d0}}{m_{d}}\right)^{1/2}$ is the dust Jeans frequency. Equation (8) shows the dispersion relation for modified low frequency wave modes in dusty plasma with the modifications observed can be attributed to polarization force and charge gradient force collisional dusty plasma.

NUMERICAL ANALYSIS

In order to recognize the effect of dust neutral collisions on the growth rate of gravitational instability in the presence of dust polarization force and dust charge gradient force, we perform numerical calculations of the general dispersion relation. For numerical calculations we normalize the dispersion relation given by Eq. (8)

$$\sigma^2 + \sigma^* V_d^* + 1 + k_D^* \omega^2_{pd} (1 + R_{pol} + R_{ch}) (1 + R_c \left(\frac{n_{d0}}{n_0}\right)) = 0$$

where $\sigma^* = \frac{\sigma}{\omega_D}$, $V_d^* = \frac{V_d}{\omega_D}$, $k^* = k \lambda_D$, $\omega^*_{pd} = \frac{\omega_{pd}}{\omega_D}$

In order to watch over the influence of overall effective force on the dust grains, we focus on the effect of variation of the charge gradient force which in turn shows the changes in $R_{eff}$.

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FIGURE: The dimensionless growth rate of gravitational instability versus the dimensionless wave number for different charge gradient force in (Figure 1) and (Figure 2) with variations in dust collisional frequency.

The (1) clearly shows that the increase of charge gradient force decreases the growth rate of instability and hence the system will move towards stabilization. In a similar way, figure (2) displays the effect of charge gradient force in presence of collisions and in absence of collisions. The upper curves are portraying the collision less plasma while the lower ones are portraying the effect of collisions with charge gradient force. The lower peak values obtained from the graphical representation show that

- In the presence of collisions, the plasma system of gravitating particles is more stable.
- Depending on the collision frequency, the peak values of the plots decrease for increasing collision frequencies. The system becomes more stable.
- Along with the increasing collision frequencies, the charge gradient force also helps the gravitating dusty plasma system to be more stabilized.

CONCLUSIONS

The work presents the effect of the collisional force on self-gravitational instability in the presence of charge gradient force and polarization force of dust grains. Collisions and charge gradient force together decrease the
growth rate of the Jeans mode. The results are relevant in case of fragmentation and condensation of dark molecular clouds and can also be useful to understand the astrophysical phenomena reported by observations carried out in the interstellar medium. For laboratory experiments and their industrial applications, these results would be beneficial especially when aggravated dust grain condensation takes place and essentially requires minimization.

REFERENCES