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Jeans-Alfvén instability in quantum dusty magnetoplasmas

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The Jeans instability is examined in quantum dusty magnetoplasmas due to low-frequency magnetosonic perturbations. The fluid model consisting of the momentum balance equation for quantum plasmas, Poisson's equation for the gravitational potential and Maxwell's equations for electromagnetic magnetosonic perturbations is solved. The numerical analysis elaborates the significant contribution of magnetic field, electron number density and variable dust mass to the Jeans instability.

Key words: astrophysical plasmas, dusty plasmas, magnetized plasmas

1. Introduction

From the beginning of life, astrophysical objects have been a great source of learning. With the passage of time, the thirst for knowledge of the mechanisms that take place in these objects has led human beings to explore the universe from different angles. The interest in knowledge concerning different aspects has led to different disciplines of research. One such research field is plasma physics. The plasma physicists have made their highest priority the understanding of the formation of astrophysical objects. Sir James Jeans developed his theory to explain the collapse of mass into giant astro-objects. Accordingly, the dusty plasma is marginally stable, in the sense of self-gravitational collapse, to all of the density perturbations which satisfy the criteria of the Jeans length. The scale of the Jeans length is extremely large, at astrophysical length scales. Such density perturbations are multidisciplined and may lead to gravitational collapse. These perturbations fall into two major categories which are low-frequency electrostatic and electromagnetic in nature. Examples of the prior case are dust lower hybrid waves, dust acoustic and dust ion acoustic waves and of the latter are Alfvén and magnetosonic waves. The corresponding instability can describe the Jeans instability present in the literature (Verheest *et al.* 1997).

A new type of longitudinal oscillation propagating in the direction perpendicular to the external magnetic field B_0 is possible due to the restoring force of the magnetic

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field (magnetic pressure) and these are known as magnetoacoustic, magnetosonic or simply compressional waves. These waves involve compression and rarefaction of the magnetic lines of force as well as the plasma. The magnetosonic waves grow due to the mixing of Alfvén wave phases. The amplitude of the Alfvén pulse generates the magnetosonic waves (Nakariakov, Roberts & Murawshi 1997). For cold plasmas, where the gyro-radius of the ions tends to zero, Adlam & Allen (1958), Gardner *et al.* (1958) and Sagdeev (1958) pointed out the dispersive propagation of waves even perpendicular to the external magnetic field due to the contribution of the finite inertia of the electrons (Kennel & Sagdeev 1967). The magnetosonic waves are low-frequency electromagnetic waves at a frequency well below the ion-cyclotron frequency, propagating along the direction perpendicular to the magnetic field. The magnetosonic waves are fundamental electromagnetic modes that exist in the laboratory as well as in space plasmas and can be taken as an effective tool for the diagnosis of materials. Salimullah *et al.* (2003), Shukla & Stenflo (2006), Schunk & Nagy (2009) discussed the comparison between the gravitational and electromagnetic forces on plasma charge carriers. Field (1965), Salahuddin & Shah (2004), Shaikh, Khan & Bhatia (2008), Tsintsadze *et al.* (2008), Prajapati & Chhajlani (2010, 2011), Prajapati *et al.* (2012) and Pensia *et al.* (2011) discussed the Jeans instability in the classical regime and at the quantum scales this subject has also been the focus of the eminent scientists Ren *et al.* (2009), Salimullah *et al.* (2009), Jamil *et al.* (2014), Sharma, Jain & Prajapati (2016). The quantum plasmas are usually described by the Fermi degenerate pressure and tunnelling potential of charge carriers. To the best knowledge of the authors, the compressional electromagnetic perturbations for the Jeans instability could not be more attractive to plasma researchers. In this paper we investigate the Jeans instability in the presence of low-frequency electromagnetic compressional perturbations in a quantum plasma system composed of electrons, ions and micron-sized negatively charged dust particulates. The objective of our studies is to investigate how the mechanism of Jeans instability would be altered due to quantum effects for low-frequency electromagnetic propagation.

The plan of the paper is as follows. In § 2, the quantum hydrodynamic fluid equations and Poisson's equation of gravitation are solved for the perturbed electromagnetic and gravitational fields in order to derive the dispersion law for the uniform quantum dusty magnetoplasma. Finally, a numerical analysis of the Alfvén Jeans instability is depicted in graphical representation and a summery of the results is presented in § 3.

2. Mathematical model of the problem

An infinitely extended dense homogeneous quantum plasma composed of electrons, ions and negatively charged dust grains is considered. The plasma system is assumed to be embedded in an ambient static magnetic field $B_0 \parallel z$ in a Cartesian coordinate system. The charge quasi-neutrality condition is satisfied at equilibrium, that is, $n_{e0} + (q_d/e)n_{d0} = n_{i0}$, where n_{j0} is the equilibrium number density of the jth species, j = electrons, ions or dust, q_d is the average charge on a dust grain and e is the electronic charge. Here, magnetosonic waves are studied that propagate along the x-axis, perpendicular to the static magnetic field. All wave quantities will depend only on x and time t. The governing equations of the electromagnetic waves include the degenerate pressure with non-zero thermal effects, the tunnelling potential and the gravitational potential. A small amplitude of oscillations is the matter of interest, thus a system of linearized equations is used. At equilibrium, the plasma is assumed to have null zeroth-order velocities of the jth species. The microscopic state of a quantum dusty plasma is governed by the following linearized set of quantum hydrodynamic and Maxwell equations:

$$m_j n_{j0}\left(\frac{\partial \boldsymbol{v}_{j1}}{\partial t}\right) = n_{j0}q_j\left(\boldsymbol{E}_1 + \frac{1}{c}\boldsymbol{v}_{j1}\times\boldsymbol{B}_0\right) - \nabla p_j + \frac{\hbar^2}{4m_j}\nabla(\nabla^2 n_{j1}) - m_j n_{j0}\nabla\psi_1 \tag{2.1}$$

$$\frac{\partial n_{j1}}{\partial t} + n_{j0}(\nabla\cdot\boldsymbol{v}_{j1}) = 0 \tag{2.2}$$

$$\nabla\times\boldsymbol{E}_1 = -\frac{1}{c}\frac{\partial \boldsymbol{B}_1}{\partial t} \tag{2.3}$$

$$\nabla\times\boldsymbol{B}_1 = \frac{1}{c}\frac{\partial \boldsymbol{E}_1}{\partial t} + \frac{4\pi}{c}\boldsymbol{J}_1. \tag{2.4}$$

The symbols used here q_j, m_j, v_{j1}, $n_{j(0,1)}$, $\boldsymbol{B}_1$, ψ_1, E_1, J_1 are charge, mass, perturbed speed for the jth species, equilibrium and perturbed number density, perturbed magnetic field and gravitational potential, perturbed electric field and perturbed current density respectively. The relationship between the Fermi pressure and the number density of the jth species is defined as $p_j = (m_j v_{Fj}^2 n_{j1}^3/3n_{j0}^2)$, where $v_{Fj}^2 = (6/5)(k_B T_{Fj}/m_j)\{1 + (5/12)\pi^2(T_j/T_{Fj})^2\}$, k_B is the Boltzmann constant, T_j is the thermal temperature, $T_{Fj} = (\hbar^2(3\pi^2 n_{j0})^{2/3}/2m_j)$ is the Fermi temperature while $\hbar = (h/2\pi)$. The Poisson equation satisfying the perturbed gravitation potential ψ_1 for the massive dust grains is

$$\nabla^2\psi_1 = 4\pi G m_{d0} n_{d1}, \tag{2.5}$$

where G is the universal gravitational constant and the subscript 1 indicates the perturbed quantities. Taking Fourier transformations of the linearized equations (2.1), (2.2) and performing some straightforward calculations provide the fluid velocities of the jth species as a linear combination of the components of the wave electric field and the gravitational potential:

$$v_{j1x} = \frac{1}{\omega^2 - v_{Fj}^{\prime 2}k^2 - \omega_{cj}^2}\left[\frac{\mathrm{i}\omega q_j}{m_j}E_{1x} - \frac{q_j\omega_{cj}}{m_j}E_{1y} + \omega k\psi_1\right] \tag{2.6}$$

$$v_{j1y} = \frac{1}{\omega^2 - v_{Fj}^{\prime 2}k^2 - \omega_{cj}^2}\left[\frac{q_j\omega_{cj}}{m_j}E_{1x} + \frac{\mathrm{i}q_j(\omega^2 - v_{Fj}^{\prime 2}k^2)}{m_j\omega}E_{1y} - \mathrm{i}\omega_{cj}k\psi_1\right] \tag{2.7}$$

$$v_{j1z} = \frac{\mathrm{i}q_j}{m_j\omega}E_{1z}. \tag{2.8}$$

Here $v_{Fj}^{\prime 2} = v_{Fj}^2 + H^2k^2$ is combined effect due to Fermi pressure and Bohm potential where $H = (\hbar/2m_j)$, while ω is perturbation frequency, k is wavevector and i is iota. Solving Maxwell's curl equations (2.3), (2.4) of the fields of the electromagnetic wave,

$$\left[-\boldsymbol{k}\boldsymbol{k}\cdot\boldsymbol{E}_1 + k^2\boldsymbol{E}_1 - \frac{\omega^2}{c^2}\boldsymbol{E}_1\right] = \frac{4\pi\mathrm{i}\omega}{c^2}\boldsymbol{J}_1. \tag{2.9}$$

Here, $\boldsymbol{J}_1 = \sum_{j=e,i,d}[q_j n_{j0}\boldsymbol{v}_{j1}]$ is the perturbation current density of the jth species in response to a small field of the electromagnetic wave and c is speed of light. The subscripts of summation e, i, d are for electrons, ions and dust fluid, respectively. The velocity components from (2.6) to (2.8), are used to attain the corresponding components of current densities that yields (2.9) and, in turn, the

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following simultaneous equations

$$\left\{1-\sum_j \frac{\omega_{pj}^2}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\right\}\omega E_{1x}-\sum_j \frac{\omega_{pj}^2\omega_{cj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\mathrm{i}E_{1y} + \sum_j \frac{\omega_{pj}\omega_{Jj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\frac{\mathrm{i}}{\sqrt{G}}\omega k\psi_1=0 \tag{2.10}$$

$$\sum_j \frac{\omega_{pj}^2\omega_{cj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\omega E_{1x}-\left\{\omega^2-c^2k^2-\sum_j \frac{\omega_{pj}^2(\omega^2-v_{Fj}'^2k^2)}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\right\}\mathrm{i}E_{1y} - \sum_j \frac{\omega_{pj}\omega_{Jj}\omega_{cj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\frac{\mathrm{i}\omega k\psi_1}{\sqrt{G}}=0 \tag{2.11}$$

$$\left(\omega^2-c^2k^2-\sum_j \omega_{pj}^2\right)E_{1z}=0 \tag{2.12}$$

similarly solving (2.5), we obtain

$$\sum_j \frac{\omega\omega_{pj}\omega_{Jj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}E_{1x}+\sum_j \frac{\mathrm{i}\omega_{pj}\omega_{cj}\omega_{Jj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}E_{1y} + \left\{-1-\sum \frac{\omega_{Jj}^2}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\right\}\frac{\mathrm{i}\omega k}{\sqrt{G}}\psi_1=0, \tag{2.13}$$

where $\omega_{pj}=\sqrt{4\pi n_{0j}q_j^2/m_j}$, $\omega_{Jj}=\sqrt{4\pi G m_j n_{j0}}$, $\omega_{cj}=(q_jB_0/m_jc)$ are the plasma frequency, gravitational frequency and cyclotron frequency of the jth species. For (2.10)–(2.13), the components of the electric fields of the electromagnetic wave and the gravitational field will form a fourth-order matrix for the equation of dispersion containing the field force of gravitation in addition to the electromagnetic field.

$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} & D_{x\psi} \\ D_{yx} & D_{yy} & D_{yz} & D_{y\psi} \\ D_{zx} & D_{zy} & D_{zz} & D_{z\psi} \\ D_{\psi x} & D_{\psi y} & D_{\psi z} & D_{\psi\psi} \end{bmatrix}\begin{bmatrix} \omega E_{1x} \\ -\mathrm{i}E_{1y} \\ E_{1z} \\ \dfrac{\mathrm{i}\omega k}{\sqrt{G}}\psi_1 \end{bmatrix}=0, \tag{2.14}$$

where the elements of dispersion matrix are

$$\left.\begin{array}{c} D_{xx}=1-\sum_j \dfrac{\omega_{pj}^2}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}, \quad D_{xy}=D_{yx}=\sum_j \dfrac{\omega_{pj}^2\omega_{cj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}, \\ D_{x\psi}=D_{\psi x}=\sum_j \dfrac{\omega_{pj}\omega_{Jj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2} \\ D_{yy}=\omega^2-c^2k^2-\sum_j \dfrac{\omega_{pj}^2(\omega^2-v_{Fj}'^2k^2)}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}, \quad D_{y\psi}=D_{\psi y}=-\sum_j \dfrac{\omega_{pj}\omega_{Jj}\omega_{cj}}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2} \\ D_{zz}=\left(\omega^2-c^2k^2-\sum_j \omega_{pj}^2\right), \quad D_{\psi\psi}=\left\{-1-\sum_j \dfrac{\omega_{Jj}^2}{\omega^2-v_{Fj}'^2k^2-\omega_{cj}^2}\right\} \\ D_{xz}=D_{zx}=D_{yz}=D_{zy}=D_{\psi z}=D_{z\psi}=0. \end{array}\right\} \tag{2.15}$$

The summation is expanded over electrons (e), ions (i) and dust (d) species. Furthermore, the condition of a low-frequency wave, $\omega^2 \ll v_{Fe}^{\prime 2}k^2 \ll \omega_{ce}^2$, $\omega^2 \ll \omega_{cd}^2, \omega_{ci}^2$, $\omega^2 \ll \omega_{Jd}^2$ is applied in order to gain the simple expressions. The quantum effects of the ions and dust are ignored in comparison with the electrons due to their higher masses. The gravitational effects of the dust are dominant over the electrons and ions due to the same reason of higher mass. Furthermore, for dense plasmas, $(\omega_{pe}^2/\omega_{ce}^2) \ll (\omega_{pi}^2/\omega_{ci}^2)$, $(c^2/v_A^2) = (\omega_{pd}^2/\omega_{cd}^2) + (\omega_{pi}^2/\omega_{ci}^2)$ where $v_A = (B^2/4\pi(n_{i0}m_i + n_{d0}m_d))^{1/2}$ is the Alfvén speed associated with the ion and dust species. Hence the values of the D components become

$$\left.\begin{aligned} D_{xx} = \frac{c^2}{v_A^2}, \quad D_{xy} = D_{yx} = 0, \quad D_{x\psi} = D_{\psi x} = -\frac{\omega_{Pd}\omega_{Jd}}{\omega_{cd}^2}, \\ D_{yy} = \omega^2\frac{c^2}{v_A^2} - c^2k^2 - \frac{\omega_{pe}^2 v_{Fj}^{\prime 2}k^2}{\omega_{ce}^2}, \quad D_{y\psi} = D_{\psi y} = -\frac{\omega_{Pd}\omega_{Jd}}{\omega_{cd}}, \quad D_{\psi\psi} = -1. \end{aligned}\right\} \tag{2.16}$$

Equation (2.14) is the generalized dielectric tensor introduced in such a way as to make clear the distinction and relationship between the O and X mode dielectric functions with quantum effects of the electrons and the gravitational effects of the dust species. The dispersion relation of linear magnetosonic waves is obtained after decoupling of these modes. Hence, using (2.16), the solution of (2.14) leads to the dispersion relation containing the gravitational effects in addition to the quantum effects that arise from the degenerate pressure and quantum tunnelling described by the Bohm term

$$\omega^2 = v_A^2k^2 + \delta_e v_{Fj}^{\prime 2}k^2 - \delta_d\omega_{Jd}^2\left(1 - \delta_d\frac{\omega_{Jd}^2}{\omega_{cd}^2}\right). \tag{2.17}$$

Here, $\delta_{e,d} = (n_{0(e,d)}m_{(e,d)}/(n_{0i}m_i + n_{0d}m_d))$. The dispersion relation '(2.17)' describes the sound-like nature of magnetosonic waves perturbed due to quantum, electromagnetic and gravitational forces. The threshold value of the wavevector k for the Jeans instability is $k_J = \sqrt{\delta_d\omega_{Jd}^2/((v_A^2 + \delta_e v_{Fj}^{\prime 2})(1 + \delta_d\omega_{Jd}^2/\omega_{cd}^2))}$ while the Jeans length is defined as $\lambda_J = (2\pi/k_J)$. The basic parameters for the coupling of magnetosonic and gravitational modes are the corresponding time scales. Owing to the comparable scales, the gravitational instability is opposed by the magnetosonic perturbations and hence resists the gravitational squeezing. Henceforth, the resultant Jeans–Alfvén mode propagates with the magnetoacoustic speed which is the equivalent speed of the Alfvén and sound speeds in quantum plasmas. The sound speed is represented by the Fermi temperature of the electrons and the sum of the masses of ions and dust (Verheest *et al.* 1997).

3. Graphical analysis and discussion

From (2.17) the curves of frequency versus wavenumber are obtained for small amplitude magnetosonic waves propagating perpendicular to the magnetic field in a quantum plasma consisting of electrons, ions and dust species. The typical parameters are defined in the cgs system of measurements (Jamil *et al.* 2014; Sharma *et al.* 2016), $c = 3 \times 10^{10}$ cm s^{-1}, $G = 6.67 \times 10^{-8}$ cm^3 gm^{-1} s^{-2}, $m_e = 9.1 \times 10^{-28}$ gm, $m_i = 1.67 \times 10^{-24}$ gm, $m_d/m_i = (1.0\text{–}1.3) \times 10^9$, $e = 4.8 \times 10^{-10}$ statcoulomb, $\hbar = 1.05 \times 10^{-27}$ erg s, $k_B = 1.38 \times 10^{-16}$ erg k^{-1}, $T_e = 10^2$ k, $B_0 = 1 \times 10^8\text{–}1.2 \times 10^{10}$ G,

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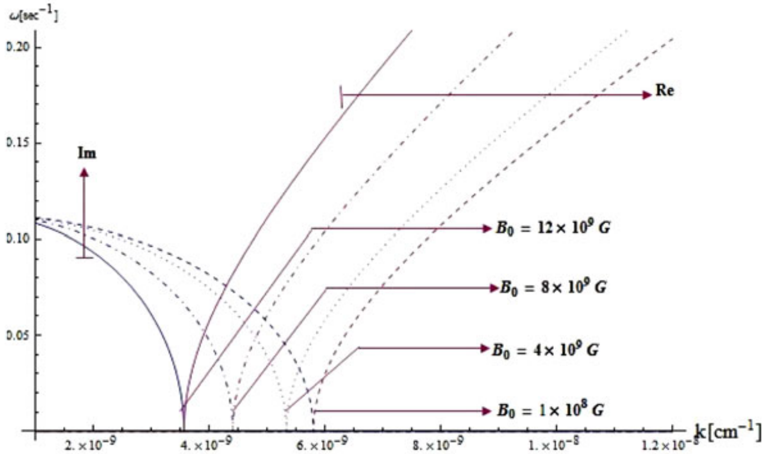

FIGURE 1. Relationship of (Im ω, Re ω) versus k with varying magnetic field, $B_0 = 0.1 \times 10^9$ G (dashed curve), $B_0 = 4.0 \times 10^9$ G (dotted curve), $B_0 = 8.0 \times 10^9$ G (dashed-dotted curve), $B_0 = 1.2 \times 10^{10}$ G (solid curve).

$n_{0i} = 1.001 \times 10^{27}$ cm^{-3}, $n_{0e} = (0.7\text{–}1.0) \times 10^{27}$ cm^{-3}, $n_{0d} = 10^{-8} n_{0i}$, $q_d = z_d e$ statcoulomb, $z_d = (n_{0i} - n_{0e})/n_{0d}$.

Figure 1 shows the gravitational stability with varying magnetic field. The imaginary part shows the instability whereas the real part describes the wave structure. At $B_0 = 1 \times 10^8$ G, the threshold value of the wavevector is $k \simeq 6.0 \times 10^{-9}$ cm^{-1}. Increasing k tends to decrease the rate of instability due to the competition between the gravitational and magnetosonic effects in quantum magnetoplasmas. On increasing the external magnetic field, the threshold value of k decreases significantly and reduces the spectrum of magnetosonic waves which stabilize the gravitational collapse. The increasing magnetic field decreases the gravitational collapse with a higher rate. Physically, the increasing magnetic field minimizes the gyro-radius, and hence B_0 contributes less to the stability of gravitational collapse. As for Re ω, the phase speed gains its highest value at the highest magnetic field. With a strong magnetic field the phase velocity and group velocity are higher than the velocities with a week magnetic field, however, with a small field, the velocities are minutely affected. Figure 2 shows the effect of varying the dust mass on the Jeans stability as variation of dust particle size is a natural mechanism. With higher dust inertia, the Jeans instability decreases with a small rate. The width of the electromagnetic spectrum increases with increasing the mass of the dust species. The phase speed and group speed of the magnetosonic waves are not significantly effected with increasing the inertia of the dust particles. Figure 3, elaborates the effect of the number density of quantized electrons in neutralized dusty plasmas. Increasing the number density of electrons stabilizes the gravitational collapse with a higher rate. The true spirit of the variable electron number density makes its contribution through the dust charge number z_d. In other words, maintaining quasi-neutrality, the variation of the electron number density modifies the dust charge and therefore has an effect over the Jeans instability. Physically, the potential of the dust particle stabilizes the gravitational instability with a higher rate.

In summary, the study of the Jeans instability (for uniform quantum dusty magnetoplasmas) in self-gravitating astrophysical high density objects and their

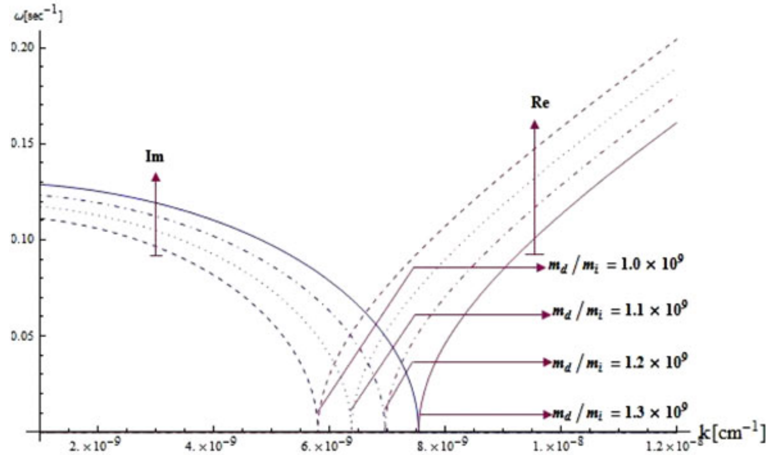

FIGURE 2. Relationship of (Im ω, Re ω) versus k with variable dust mass $m_d/m_i = 1.0 \times 10^9$ (solid curve), $m_d/m_i = 1.1 \times 10^9$ (dashed-dotted curve), $m_d/m_i = 1.2 \times 10^9$ (dotted curve), $m_d/m_i = 1.3 \times 10^9$ (dashed curve).

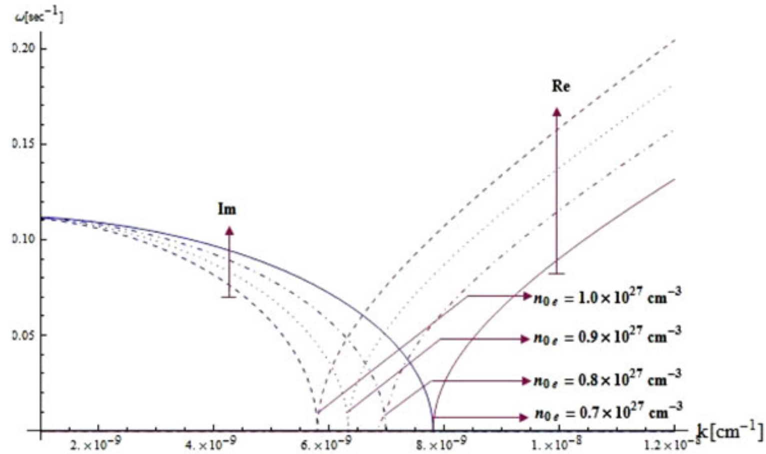

FIGURE 3. Relationship of (Im ω, Re ω) versus k with varying magnetic field, $n_{0e} = 1.0 \times 10^{27}$ cm^{-3} (dashed curve), $n_{0e} = 0.9 \times 10^{27}$ cm^{-3} (dotted curve), $n_{0e} = 0.8 \times 10^{27}$ cm^{-3} (dashed-dotted curve), $n_{0e} = 0.7 \times 10^{27}$ cm^{-3} (solid curve).

environments is presented. The multifluid model for quantum plasmas in the presence of a uniform external magnetic field which is composed of Poisson's equation of the gravitational potential, momentum balance and Maxwell's equations for electromagnetic perturbations have been employed to derive a generalized dispersion matrix of the fourth order. The solution of the dispersion matrix lead to the linear dispersion relation of a magnetosonic wave in a self-gravitating plasma with the quantum effects arising through the Fermi degenerate pressure as well as the tunnelling potential. The numerical study is presented with different variable parameters. It is found that the magnetic field, variable dust mass and electron number density play significant roles in the Jeans instability. In all of the figures, the value of k (cm^{-1}) at which ω (s^{-1}) becomes zero is known as the threshold value. For example, in figure 1, the threshold value at $B_0 = 10^8$ G is $k = 6.0 \times 10^{-9}$ cm^{-1}. On increasing B_0, the threshold value comes into being at smaller values of k. Similar or different trends are observed for different variable parameters. Henceforth, the results of our studies at quantum scales may be useful in understanding the collapse of self-gravitating dusty plasma systems.

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