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Effect of Bohm potential on magnetohydrodynamic wave propagation in dense quantum fluid plasma

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Abstract

In this paper we have investigated the simultaneous effects of Bohm potential and electron spin on the low frequency magnetohydrodynamic (MHD) wave propagation in dense Fermi degenerate quantum plasma. The elementary ideal about quantum collision process in quantum plasma is also discussed. The quantum magnetohydrodynamic (QMHD) model is modified and a general dispersion relation is obtained using the plane wave approximation for the considered system. This dispersion relation is reduced for the parallel and perpendicular modes of propagations. We find that the quantum Bohm potential is coupled with the Alfven mode in perpendicular propagation but in the parallel mode of propagation the dispersion relation is unaffected due to the presence of magnetic field. From the curves we find that increase in Alfven velocity and sound velocity increases the frequency of the perturbations.

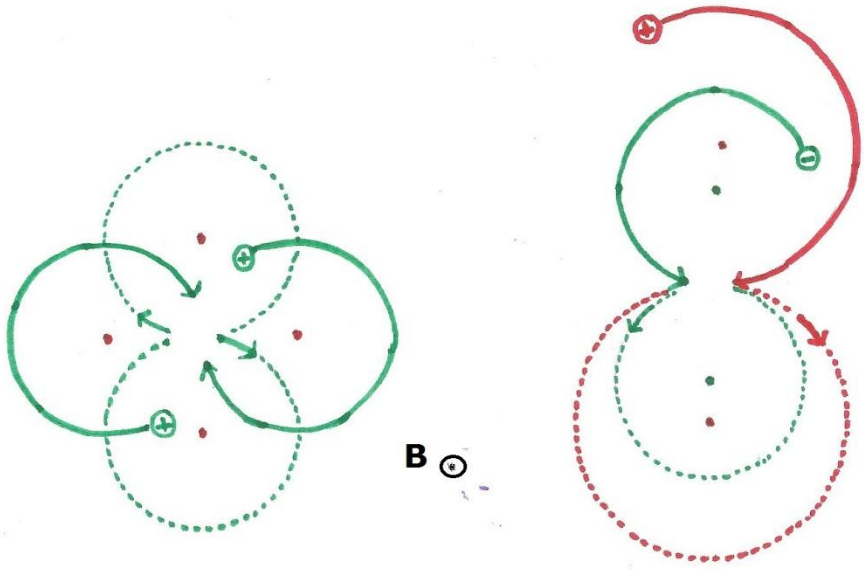
Keywords: *Quantum plasma, MHD wave propagation, Bohm potential, Plane wave approximation, dispersion characteristics*

1 Introduction

The study of quantum plasma has a great interest now day's due to its many significant applications in ultra-small electronic devices, dense astrophysical plasmas, laser fusion plasma and in excitation of linear and nonlinear waves [1-4]. In traditional plasma the magnetohydrodynamic (MHD) fluid model is widely used to discuss wave propagation in hot and cold plasmas. The MHD fluid model is one of the most useful fluid models which focus on the global properties of plasma. In the quantum plasma the de Broglie wavelength of charge carriers are become comparable to the inter-particle distance at extremely low temperature thus one can consider that the overlapping of the neighboring particles [5,6]. The quantum magnetohydrodynamic (QMHD) model derived by Haas [7] including Bohm potential is appropriate to investigate waves and instabilities in quantum plasma. We can consider two significant quantum effects in non-relativistic dense Fermi degenerate quantum fluid plasma. One of this is quantum force produced by density fluctuations, which has its origin called Bohm potential. The second effect is caused by the spin of particles which is considered in the equation of motion. In general in quantum plasma, high density and low temperature are usually considered as the typical plasma environment in which quantum effect occurs. The atmospheres of neutron star and interiors of super dense white dwarf star are assumed to be like a Fermi gas where the number density of plasmas is controlled by Fermi-Dirac distribution rather than the Maxwell-Boltzmann distribution [8-10].
The quantum corrections are obtained in the classical dispersion relations by many authors recently with different assumptions [11]. Prajapati and Chhajlani [12] have investigated the effect of Hall current on the Jeans instability of an infinitely conducting, homogeneous, viscous quantum plasma. Prajapati and Chhajlani [13] have also studied effect of magnetic field on Jeans instability of quantum dusty plasma and applied the results in the formation of white dwarf star. The quantum effects for oblique propagation in magnetosonic waves for electron-positron-ion and dust-electron-ion plasma already studied by Masood and Mushtaq [14] including the contribution of Bohm potential. The effects of electron spin and Bohm potential in oblique propagation of magnetosonic was studied by Felipe [15]. The linear and nonlinear behavior of the slow and fast magnetosonic modes is studied by Mushtaq and Vladimirov [16] using QMHD model.
In this paper we have investigated the simultaneous effects of Bohm potential and spin effect on MHD wave propagation of quantum fluid plasma. The present paper is organized as follows. In Sec. 2, the collision processes in classical and quantum plasmas are discussed. In Sec. 3, the model equations of the problem are formulated and a general dispersion relation is obtained. The results of the problem are discussed in Sec. 4. The present problem is summarized in Sec. 5.

2 Collision processes in classical and quantum plasmas

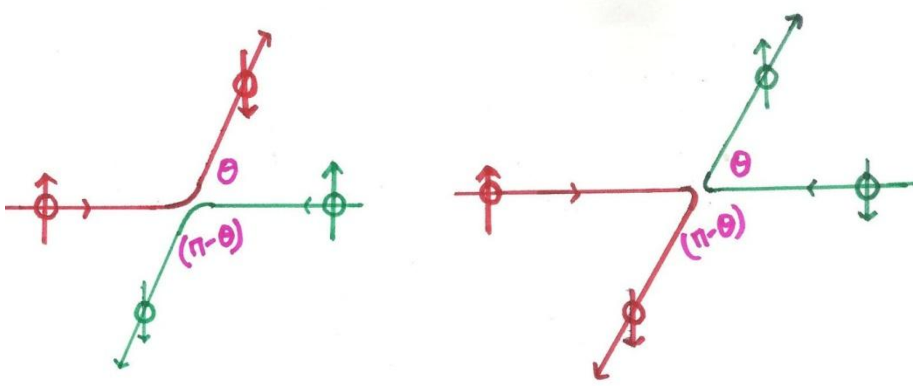
In classical plasma all collisions are coulomb collision. There are two process-collision between like charge particle and collision between unlike charge particle. In case of collision between like charges, simply they interchange their orbits by changing the velocity 90° in direction. The centre of mass of two guiding centers remains stationary and gives rise to very little diffusion as shown in Fig. 1. For collision between unlike charges, after collision velocity are changed 180° in direction i.e. in reversed direction. In the case of collision between unlike charges the guiding centre shift in the same direction.



(a) Collision between like charges (b) Collision between unlike charges

Fig.1: Collision processes between like and unlike charge particles.

The process for changing guiding centre in case of quantum system is quite different than the classical approach. The origin of this difference is due to the presence of Coulomb force and spin force. The like spin tends to oppose each other and unlike spins have tendency to closes each other. We consider all the Fermion particles have half odd integral spin i.e. $\frac{\hbar,}{2},\frac{3\hbar}{2},\frac{5\hbar}{2}$ which obey the Pauli's exclusion principle. In the case of quantum plasma there are five possible collision processes: (i) collision between like charges with same spin, (ii) collision between like charges but opposite spin (iii) collision between opposite charge with same spin, (iv) collision between opposite charge but opposite spin and (v) collision between charged and neutral particles. Quantum mechanically two possible collision processes are described in Fig. 2. This describes the collision between two particles with same spin and having opposite spin. In both the cases after collision the spin are interchanged. We assure that when two electrons move on same path from opposite side, just before collision the direction of electrons are shifted due to the repulsive nature of same spin thud only side by side collisions occur. The scattering angel θ depends on the energy of particle which is related to the strength of magnetic field but for like spin scattering the scattering angel θ is small compared to the unlike scattering.



(a) Same spin (b) Opposite spin

Fig.2: The quantum collision process in two charge particles with same and opposite spins.

3 Model equations of the problem and dispersion relation

Consider a compressible, in-viscid, perfectly conducting fluid immersed in presence of uniform magnetic field **B**(0, 0, B). Thus the continuity equation remains unchanged due to Bohm potential but the momentum equation is modified. The continuity equation and momentum equations for magnetized quantum fluid plasma are as follows [7]

$$\frac{\partial \rho_m}{\partial t}+\nabla.\,(\rho_m\,\mathbf{u})=0, \tag{1}$$

$$\rho_m\frac{\partial \boldsymbol{u}}{\partial t}+\rho_m\,(\mathbf{u}.\nabla)\,\mathbf{u}=-\nabla p+(\mathbf{J}\times\mathbf{B})+\frac{\hbar^2}{2m_e m_i}\,\nabla\left(\frac{\nabla^2\sqrt{\rho_m}}{\sqrt{\rho_m}}\right), \tag{2}$$

where ρ_m is the mass density, $\mathbf{u}$ is the global fluid velocity, $\mathbf{J}$ is the current density, p is the quantum Fermi pressure and $\hbar$ is the Planck's constant divided by 2π. The momentum Eq. (2) has been modified to include non-locality effects, such as tunneling, described by the Bohm potential. These effects arising from density perturbations play an important role for dense and low temperature plasma. This system is closed with an equation of states for the pressure which is written as-

$$\nabla p=C_s^2\ \nabla\rho_m, \tag{3}$$

where $C_s^2=\left(\frac{dp}{d\rho_m}\right)$ is the quantum speed of sound described by [16]

$$C_s^2=v_{ti}^2+\frac{m_i}{m_e}\left(v_{te}^2+\frac{3}{5}v_{Fe}^2\right), \tag{4}$$

where $v_{Fe}=\hbar\frac{(3\pi^2\ n_e)^{\frac{1}{3}}}{m_e}$ is electron Fermi velocity, v_{ti} and v_{te} are the ion and electron thermal velocities, respectively. $v_{tj}=\left(\frac{\pi}{3}\right)^{\frac{1}{3}}\frac{T}{\hbar m_j^{1/3}}$ where T is plasma thermal temperature in energy unit and j= (e, i) electron and ions. Here suffix j is for electron and ion.

The Maxwell's equations for magnetized system are

$$\nabla\times\boldsymbol{B}=\mu_0\,\mathbf{J}, \tag{5}$$

$$\nabla\times\boldsymbol{E}=-\frac{\partial\boldsymbol{B}}{\partial t}, \tag{6}$$

$$\mathbf{E}+\mathbf{u}\times\mathbf{B}=0. \tag{7}$$

Substituting Eqs. (3), (5) (6) and (7) in Eq. (2) then we get

$$\rho_m\frac{\partial \boldsymbol{u}}{\partial t}+\rho_m\,(\mathbf{u}.\nabla)\,\mathbf{u}=-c_s^2\,\nabla\rho_m+\frac{1}{\mu_0}\,(\nabla\times\boldsymbol{B})\times\mathbf{B}+\frac{\hbar^2}{2m_e m_i}\,\nabla\left(\frac{\nabla^2\sqrt{\rho_m}}{\sqrt{\rho_m}}\right). \tag{8}$$

For deducing the dispersion relation we linearize above equations considering small-amplitude variation in each physical quantities with their equilibrium values such as

$$\mathbf{B}(\mathrm{r},\mathrm{t})=\boldsymbol{B}_0+\boldsymbol{B}_1(\mathrm{r},\mathrm{t}), \tag{9}$$

$$\rho_m(\mathrm{r},\mathrm{t})=\rho_{m0}+\rho_{m1}(\mathrm{r},\mathrm{t}), \tag{10}$$

$$\mathbf{u}(\mathrm{r},\mathrm{t})=\boldsymbol{u}_1(\mathrm{r},\mathrm{t}). \tag{11}$$

Thus the linearized form of the above equations will be

$$\frac{\partial\rho_{m1}}{\partial t}+\rho_{m0}(\nabla.\boldsymbol{u}_1)=0. \tag{12}$$

$$\frac{\partial\boldsymbol{B}_1}{\partial t}-\nabla\times(\boldsymbol{u}_1\times\boldsymbol{B}_0)=0. \tag{13}$$

$$\rho_{mo}\frac{\partial\boldsymbol{u}_1}{\partial t}+C_s^2\nabla\rho_{m1}+\frac{1}{\mu_0}\,\boldsymbol{B}_0\times(\nabla\times\boldsymbol{B}_1)-\frac{\hbar^2}{2m_e m_i}\,\nabla\left(\frac{\nabla^2\sqrt{\rho_m}}{\sqrt{\rho_m}}\right)=0. \tag{14}$$

Differentiating Eq. (14) with respect to t and using Eqs. (11) and (13) we get-

$$\frac{\partial^2\boldsymbol{u}_1}{\partial t^2}-C_s^2\,\nabla(\nabla.\boldsymbol{u}_1)+\boldsymbol{V}_A\times[\nabla\times\{\nabla\times(\boldsymbol{u}_1\times\boldsymbol{V}_A)\}]-\frac{\hbar^2}{4m_e m_i\rho_{m0}}\frac{\partial}{\partial t}[\nabla(\nabla^2\,\rho_{m1}]=0, \tag{15}$$

where $V_A=\frac{B_0}{\sqrt{(\mu_0\rho_{m0})}}$ is Alfven velocity.

Now we consider the plane wave solution for Eq. (15) in the form of $\boldsymbol{u}_1(\mathrm{r},\mathrm{t})=\boldsymbol{u}_1\exp\,(i\mathbf{k}.\mathbf{r}-i\omega t)$, where $\mathbf{u}_1$ is the perturbed velocity of fluid, $\mathbf{k}$ is propagation vector, and ω is the plasma frequency. Simply we can replace the operator ∇ by $i\mathbf{k}$ and partial time derivative by $-i\omega$ thus we get

$$-\omega^2\boldsymbol{u}_1+(C_s^2+V_A^2)\,(\mathbf{k}.\boldsymbol{u}_1)\,\mathrm{k}+(\mathbf{k}.\boldsymbol{V}_A)\,[-(\boldsymbol{V}_A.\boldsymbol{u}_1)\,\mathbf{k}+(\boldsymbol{V}_A.\mathbf{k})\boldsymbol{u}_1-(\mathbf{k}.\boldsymbol{u}_1)V_A]+\frac{\hbar^2k^3\omega}{4m_e m_i\rho_{m0}}\rho_{m1}=0. \tag{16}$$

Using simplified form of Eq. (12) $\rho_{m1}=\frac{\rho_{m0}\boldsymbol{k}.\boldsymbol{u}_1}{\omega}$ we get

$$-\omega^2\boldsymbol{u}_1+(C_s^2+V_A^2)\,(\mathbf{k}.\boldsymbol{u}_1)\mathrm{k}+(\mathbf{k}.\boldsymbol{V}_A)\,[-(\boldsymbol{V}_A.\boldsymbol{u}_1)\,\mathrm{k}+(\boldsymbol{V}_A.\mathbf{k})u_1-(\mathbf{k}.\boldsymbol{u}_1)V_A]+\frac{\hbar^2k^3\boldsymbol{k}.\boldsymbol{u}_1}{4m_e m_i}=0 \tag{17}$$

This equation shows the general dispersion relation of magnetized quantum fluid plasma modified due to the presence of quantum corrections. If we ignore the quantum effects then we get the classical dispersion relation of MHD wave propagation. This dispersion relation can be further discussed for two modes of propagations one perpendicular and other parallel to the direction of applied magnetic field.

4 Discussions of the dispersion relation

4.1 Propagation perpendicular to the magnetic field (k⊥B)

In this mode of propagation when wave vector **k** is perpendicular to the magnetic field **B** we have $\mathbf{k}.\boldsymbol{V_A}$=0 and we get two dispersion relations. In the longitudinal wave propagation when $\boldsymbol{u_1}$ is parallel to **k** the phase velocity is given by

$$\frac{\omega}{k}=\left(c_s^2+V_A^2+\frac{\hbar^2k^2}{4m_em_i}\right)^{1/2}. \tag{18}$$

In the case of transverse wave propagation when $\boldsymbol{u_1}$ is perpendicular to **k,** we get the phase velocity

$$\frac{\omega}{k}=\left(\frac{\hbar^2k^2}{4m_em_i}\right)^{1/2}. \tag{19}$$

From the above two dispersion relations it is obvious that in longitudinal wave propagation the dispersion relation is modified by Alfven mode, quantum acoustic speed and Bohm potential. But in transverse propagation Alfven velocity and quantum acoustic speed have not any influence on the dispersion properties. The above shows the coupling of Alfven and acoustic mode.

In below Fig.3 we have plotted the variation of frequency of wave mode versus the wavenumber for various values of Alfven velocity. The parameters are taken for the interior of dense white dwarf star and numerical calculations have been performed using MATLAB code.

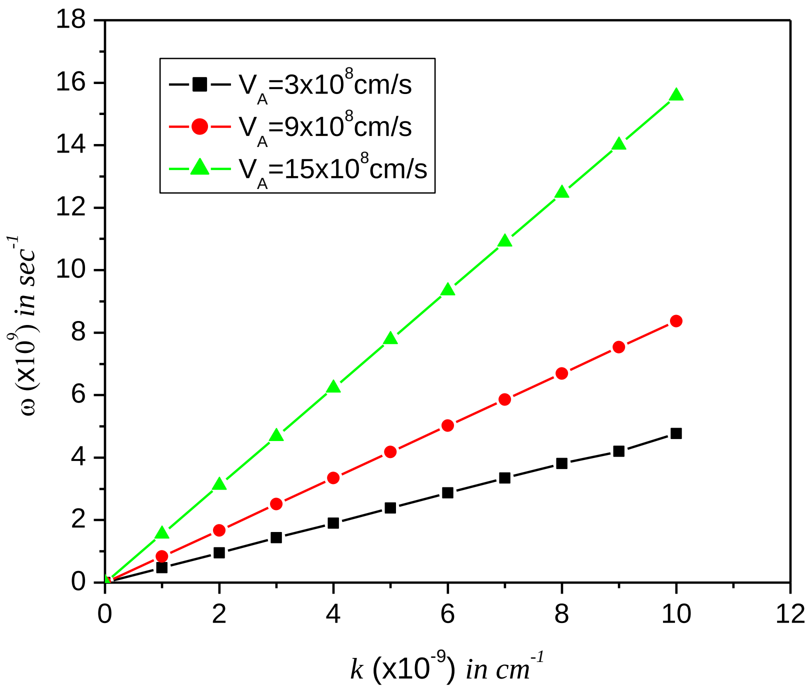


Fig. 3: The frequency of perturbations versus wavenumber for various values of Alfven velocity.

This graph shows that how longitudinal wave propagation is affected with different values of Alfven velocity. The numerical parameters are taken for dense white dwarf star as follows: m_e=9.109× 10^{-28}gm, m_i=12×1.67× 10^{-24}gm, $\hbar$ =1.0546× 10^{-27}erg-sec ρ_m=10^9gm-cm^{-3}, C_s=9.3× 10^8 cm-sec^{-1}, thus $\frac{\hbar^2}{4m_em_i}$=4.574 × 10^{-3} unit with different Alfven velocities as shown in the graph. From the curves it is clear that as we increase wavenumber k, the frequency of oscillations ω also increases. The phase velocity (ω/k) also increases with increase in Alfven velocity in the plasma.

In Fig.4 we have plotted the frequency of oscillations versus wavenumber for various values of quantum acoustic speed. From the curves it is clear that as we increase wavenumber k, the frequency of oscillations ω also increases. The phase velocity (ω/k) also increases with increase in quantum acoustic speed.

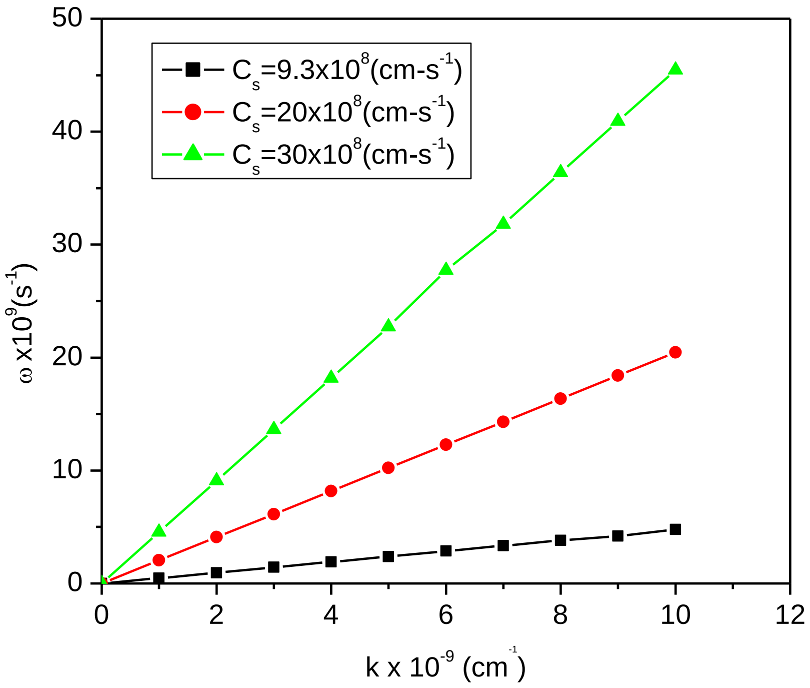


Fig. 4: The frequency of perturbations versus wavenumber for various values of quantum acoustic speed.

4.2 Propagation parallel to the magnetic field (k||B)

In the parallel propagation when wave vector is along the direction of the magnetic field i.e. **k**||**B** , we have $\mathbf{k}.\boldsymbol{V_A} = \boldsymbol{k}\,\boldsymbol{V_A}$ and we get from Eq. (17)

$$(k^2V_A^2 - \omega^2)\boldsymbol{u_1} + \left(\frac{C_s^2}{V_A^2} - 1\right) k^2V_A\,(\boldsymbol{u_1}.\boldsymbol{V_A}) + \frac{\hbar^2 k^3 \boldsymbol{k}.\boldsymbol{u_1}}{4m_e m_i} = 0. \tag{20}$$

In the longitudinal wave propagation when $\boldsymbol{u_1}$ is parallel to **k**. the phase velocity is given by

$$\frac{\omega}{k} = \left(c_s^2 + \frac{\hbar^2 k^2}{4m_e m_i}\right)^{1/2}. \tag{21}$$

The Alfven velocity has not any contribution in this mode. In the case of transverse wave propagation when $\boldsymbol{u_1}$ is perpendicular to **k** we get the phase velocity

$$\frac{\omega}{k} = V_A. \tag{22}$$

In this case we get pure Alfven mode where there is no any effect due to the quantum Bohm potential.

4.3 Quantum MHD wave propagation including electron spin

We now employ this QMHD fluid model only for electron gas. The dynamics of electron is modified due to the contribution of spin force. The continuity equation remains unchanged as in Eq. (1) but momentum Eq. (2) gets modified. Thus the equations are

$$\rho_m \frac{\partial \boldsymbol{u_e}}{\partial t} + \rho_m\,(\mathbf{u_e}.\nabla)\,\mathbf{u_e} = -\boldsymbol{\nabla} p + (\mathbf{J}\times\mathbf{B}) + \frac{\hbar^2}{2m_e m_i}\boldsymbol{\nabla}\left(\frac{\nabla^2\sqrt{\rho_m}}{\sqrt{\rho_m}}\right) + \frac{2\mu_q}{\hbar}\,\mathbf{S}.\boldsymbol{\nabla}\mathrm{B}, \tag{23}$$

where μ_q is elementary magnetic moment of charge 'q'and **S** is spin vector. **B**= (0, 0, $\boldsymbol{B_0}$) is magnetic field vector in z-direction and $\mathbf{u_e}$ is the electron fluid velocity.

The evolution equation for the spin vector is

$$\left(\frac{\partial}{\partial t} + \mathbf{u_e}.\,\nabla\right)\mathbf{S} = \frac{2\mu_q}{\hbar}\,(\mathbf{S}\times\mathbf{B}). \tag{24}$$

The spin pressure depends on angle between the magnetic field vector and spin vector $\emptyset$. When $\emptyset = 0$ the spin is aligned along the magnetic field i. e. parallel and when $\emptyset = \pi$ the spin is aligned against the magnetic field i. e. antiparallel. Consider the magnetic field in z direction so $\mathbf{B}=B_0\hat{\mathbf{z}}$, and let $\mathbf{S}=\frac{\hbar}{2}\,\eta(\alpha)\cos\emptyset\,\hat{\mathbf{z}}$, where (α) = tan $\left(\frac{\mu B_0}{k_B T_e}\right)$ is Brillion function due to magnetization of spin distribution.

Differentiating Eq. (23) with respect to time then simplifying we get

$-\omega^2\boldsymbol{u_{e1}} + (C_s^2 + V_A^2)\,(\mathbf{k}.\boldsymbol{u_{1e}})\mathrm{k} + (\mathbf{k}.\boldsymbol{V_A})\,[-(\boldsymbol{V_A}.\boldsymbol{u_{1e}})\,\mathrm{k} + (\boldsymbol{V_A}.\mathbf{k})\boldsymbol{u_{1e}} - (\mathbf{k}.\boldsymbol{u_{1e}})V_A]$

$$+\frac{\hbar^2 k^3 \boldsymbol{k}.\boldsymbol{u_{1e}}}{4m_e m_i} - \frac{\mu_q B_0}{\rho_{m0}}\,\omega\,\mathrm{k}\,(\alpha)cos\emptyset = 0. \qquad (25)$$

In the perpendicular propagation i.e. $\mathbf{k}.\mathbf{V_A}=0$ we get the wave propagation equation with phase velocity

$$\left(\frac{\omega}{k}\right)^2 = C_s^2 + V_A^2 + \frac{\hbar^2 k^2}{4m_{e\,m_i}} - \frac{\mu_q B_0}{\rho_{m0}}\eta(\alpha)cos\emptyset. \qquad (26)$$

In the case of parallel propagation when $\mathbf{k}.\mathbf{V_A} = \mathrm{k}V_A$ we get longitudinal wave propagation with phase velocity-

$$\left(\frac{\omega}{k}\right)^2 = C_s^2 + \frac{\hbar^2 k^2}{4m_{e\,m_i}} - \frac{\mu_q B_0}{\rho_{m0}}\eta(\alpha)cos\emptyset. \qquad (27)$$

From these two dispersion relations it is clear that the Alfven velocity has not any role in the longitudinal mode of propagation. If we remove the spin effect then we get general MHD wave propagation for quantum plasma as obtained in Eqs. (18) and (21) respectively.

4.4 Quantum MHD oblique wave propagation

Now we consider QMHD wave propagate in an arbitrary direction with respect to the magnetic induction **B.** We consider the coordinate such that y axis is normal to the plane of propagation **k** and the magnetic field **B.** We take **B** along $\hat{\boldsymbol{z}}$ and the angle between **k** and **B** is θ then $\mathbf{k} = \mathrm{k}\,(\hat{\boldsymbol{x}}\sin\theta + \hat{\boldsymbol{z}}\cos\theta)$, $\mathbf{V_A} = \mathrm{V_A}\,\hat{\boldsymbol{z}}$, and $\boldsymbol{u_1} = u_{1x}\hat{\boldsymbol{x}} + u_{1y}\hat{\boldsymbol{y}} + u_{1z}\hat{\boldsymbol{z}}$.
Substituting these value in Eq. (17) and resolve the x, y and z components respectively

$$u_{1x}\,(-\omega^2 + k^2V_A^2 + k^2C_s^2\,sin^2\theta + \frac{\hbar^2 k^4}{4m_e m_i}\sin\theta) + u_{1z}(k^2c_s^2\sin\theta\,\cos\theta) = 0, \qquad (28)$$

$$u_{1y}\,(-\omega^2 + k^2V_A^2\cos\theta) = 0, \qquad (29)$$

$$u_{1x}(k^2c_s^2\mathrm{Sin}\theta\cos\theta) + u_{1z}\,(-\omega^2 + k^2C_s^2\,cos^2\,\theta + \frac{\hbar^2k^4}{4m_e m_i}\cos\theta) = 0. \qquad (30)$$

With the help of these equations we construct a matrix whose determinant setting equal to zero gives the general dispersion relation for oblique QMHD wave propagation.

$$\begin{pmatrix} \left(-\omega^2 + k^2V_A^2 + k^2C_s^2\,sin^2\theta + \frac{\hbar^2k^4}{4m_e m_i}\sin\theta\right) & (k^2c_s^2\sin\theta\cos\theta) \\ (k^2c_s^2\sin\theta\cos\theta) & \left(-\omega^2 + k^2C_s^2\,cos\theta^2 + \frac{\hbar^2k^4}{4m_e m_i}\cos\theta\right) \end{pmatrix} = 0. \qquad (31)$$

After solving this matrix we get the following dispersion relation

$$\left(\frac{\omega}{k}\right)^2 = \frac{1}{2}\left[V_A^2 + C_s^2 + \frac{\hbar^2k^2}{4m_e m_i}\,(\sin\theta + \cos\theta)\right]$$

$$\pm\frac{1}{2}\left[\left\{V_A^2 + C_s^2 + \frac{\hbar^2k^2}{4m_e m_i}\,(\sin\theta + \cos\theta)\right\}^2 - 4C_s^2V_A^2cos^2\theta - \frac{\hbar^2}{m_e m_i}\left\{k^2C_s^2sin\theta\,cos\theta\,(sin\theta + cos\theta) + k^2V_A^2cos\theta + \right.\right.$$

$\hbar 2k44memi\sin\theta\cos\theta 12.$

(32)

The solutions of Eq. (32) corresponding to plus sign yields the dispersion relation of fast QMHD wave and when we take minus sign we obtain the dispersion relation of slow QMHD wave mode. It is obvious that square root of $\left(\frac{\omega}{k}\right)^2$ provides two wave modes with opposite direction of propagation to each other. Obviously, we can say that when a magnetosonic waves propagates obliquely to the background magnetic field, the wave phase velocity becomes quite different from the purely parallel or perpendicular cases.

5 Conclusion

In present paper the QMHD wave propagation in dense Fermi degenerate quantum fluid plasma is investigated. The possible collision processes in classical and quantum plasmas are discussed. We have derived analytically the linear dispersion relation using QMHD equations in quantum plasma including Bohm potential. For perpendicular and parallel propagations we have obtained the modified dispersion relations which are reduced with previous published results. The quantum effects do not have influence in the parallel propagation of QMHD waves. From graph we find that when we increase Alfven velocity and quantum acoustic speed for particular wavenumber, the phase velocity also increases in both parallel and perpendicular modes of propagations. The modified dispersion relation due to the presence of electron spin is also obtained using the quantum fluid model for electron fluid. We find the spin contribution of electron affects the Alfven mode. The dispersion relation is also obtained for oblique propagation which is more complicated than parallel and perpendicular propagations in QMHD waves. The results of the present work may be useful to understand the wave propagation in dense Fermi degenerate quantum plasma system like dwarf and neutron stars.

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