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Magnetosonic Shocks in Ultra-Relativistic Dissipative Degenerate Plasmas

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Magnetosonic shock structures in dissipative magnetized degenerate electron ion plasma are studied. The two fluid quantum magnetohydrodynamic equations for non-degenerate ions and ultra-relativistic degenerate electron fluids with the Maxwell equations are presented. Using the reductive perturbation technique the Korteweg de Vries Burgers (KdVB) equation is derived and its solution is presented with the tanh *method. Astrophysical plasma parameters are used to study the effects of variation of plasma density, magnetic field intensity and kinematic viscosity on the propagation characteristics of nonlinear shock structures in such plasma systems.*

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In the last decade many plasma wave researchers have paid considerable attention to analyses of electromagnetic waves in ultra-relativisitic plasmas due to their important role in a variety of astrophysical phenomena. For example, in the interior of astrophysical objects like neutron stars, the thermal energy is smaller than their Fermi energy due to the pressure of degenerate electron gas. This pressure may be either non-relativistic, somewhat relativistic, or ultra-relativistic. The speed of electrons approaches the speed of light for ultra-relativistic cases and in this situation the mass of the astrophysical object approaches a constant. This is known as the Chandrasekhar limit. The equation of state for degenerate ultra-relativistic electrons is defined as $p_{\rm Fe} \sim n_{\rm e}^{4/3}$, where $n_{\rm e}$ is the density of electrons, and $p_{\rm Fe}$ is the Fermi pressure.[1,2]

Many researchers have studied electrostatic and electromagnetic non-linear structures in ultra-relativistic degenerate plasmas. Zeba *et al.*[3] studied the electrostatic solitary wave excitations in a plasma system having degenerate ultra-relativistic electrons and positrons. Their numerical investigations reveal the fact that subsonic or supersonic solitary wave structures may exist in white dwarfs whereas only subsonic solitary wave structure excites for magnet corona. Mahmood *et al.*[4] investigated the excitations of electrostatic ion acoustic solitary wave structures in magnetized dense plasmas with ultra relativistic degenerate electrons and noticed that phase speed of the ion acoustic wave enhances and the width of the solitary wave structure decreases with the increase of the magnetic field intensity. Roy *et al.*[5] studied the solitary waves and double layers in ultra relativistic degenerate electron positron ion dusty plasma and explored the coexistence of negative and positive solitary pulses in such a plasma system. Recently, Hussain *et al.*[6] studied the propagation of magnetosonic solitary wave structures in a low beta plasma system comprised of ions and ultra-relativistic degenerate electrons. We have analyzed the astrophysical data and concluded that the formation of the solitary structures are influenced by the presence of ultra-relativistic degenerate electrons.

The study of shock structure plays an important role in many astrophysical scenarios such as cosmic ray generation, during supernova explosions, strong field generation in the bow-shock region, nonlinear dynamics of solar wind, and in laser plasma experiments.[7–9] Sultana *et al.*[10] studied the electrostatic shock dynamics in superthermal plasmas and showed that dynamics of low amplitude shocks is modeled by a hybrid KdVB equation in which the nonlinear and dispersion coefficients are functions of the spectral index. Sahu *et al.*[11] investigated the formation of shock structures in degenerate quantum plasmas with the inclusion of Bohm potential and spin force for electrons and pointed out that magnetic diffusivity is responsible for dissipation in such a plasma system.

We consider a two-fluid non-relativistic degenerate dissipative magnetoplasma. The external magnetic field is along the $\hat{z}$ direction, i.e., $\boldsymbol{B} = B_0\hat{z}$. The continuity and momentum equations for the ions can be written as

$$\frac{\partial N}{\partial t} + \nabla \cdot (N\boldsymbol{V}) = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{V}}{\partial t} + (\boldsymbol{V}\cdot\nabla)\boldsymbol{V} = \frac{e}{m_{\rm i}}\Big[\boldsymbol{E} + \frac{1}{c}\Big(\boldsymbol{V} \times \boldsymbol{B}\Big)\Big] + \frac{\mu}{m_{\rm i}n_{\rm i}}\nabla^2\boldsymbol{V}. \tag{2}$$

The continuity equation for inertial degenerate electrons are given by

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{v}) = 0. \tag{3}$$

The Fermi pressure for the electron quantum fluid in the ultra-relativistic regime is defined as $p_{\rm ur} = \frac{\hbar c}{4}(3\pi^2)^{1/3}n_{\rm e}^{4/3}$. The electron Fermi temperature and density in a degenerate electron gas with ultra-relativistic energies (i.e., $v_{\rm Fe} \simeq c$) are related by $T_{\rm Fe} = \frac{c}{8\pi k_{\rm B}}(3\hbar^3 N_0)^{1/3}$.[12] Under these assumptions the electron momentum equation can be written as

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\frac{e}{m_{\rm e}}\Big[\boldsymbol{E} + \frac{1}{c}\Big(\boldsymbol{v}\times\boldsymbol{B}\Big)\Big] - \frac{1}{nm_{\rm e}}\nabla p_{\rm ur}. \tag{4}$$

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Faraday's laws are written as

$$\nabla \times \boldsymbol{E} = -\frac{1}{c}\frac{\partial \boldsymbol{B}}{\partial t}. \tag{5}$$

Ampere's laws are written as

$$\nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{j}. \tag{6}$$

The term corresponding to the displacement current in Eq. (6) is ignored under the assumption of low frequency waves. The current density $\boldsymbol{j}$ is defined as

$$\boldsymbol{j} = e(N\boldsymbol{V} - n\boldsymbol{v}), \tag{7}$$

where N, V and n, v are the number density and the velocity of ions and electron species, respectively. The electric and magnetic field intensities are denoted by $\boldsymbol{E}$ and B, while $m_{\rm i}$ is the mass of ions, and c is the speed of light in vacuum.

We are studying the wave propagation across the ambient magnetic field (directed along the z-axis) in the $\hat{x}$-direction, i.e., $\nabla = (\partial_x, 0, 0)$ and the electric field is taken in the plane perpendicular to the magnetic field, i.e., $\boldsymbol{E} = E_x\hat{\imath} + E_y\hat{\jmath}$. Under these assumptions, the above set of dynamic Eqs. (1)–(7) can be written in the component form. The ion continuity equation is given by

$$\frac{\partial N}{\partial t} + \frac{\partial}{\partial x}(NV_{\rm ix}) = 0. \tag{8}$$

The x and y components of the ion momentum equation are written as

$$\begin{aligned}&\frac{\partial V_{\rm ix}}{\partial t} + V_{\rm ix}\frac{\partial}{\partial x}V_{\rm ix} = \frac{e}{m_{\rm i}}\Big(E_x + \frac{1}{c}V_{\rm iy}B_z\Big)\\ &+\eta\Big(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\Big)V_{\rm ix},\end{aligned} \tag{9}$$

$$\begin{aligned}&\frac{\partial V_{\rm iy}}{\partial t} + V_{\rm ix}\frac{\partial}{\partial x}V_{\rm iy} = \frac{e}{m_{\rm i}}\Big(E_y - \frac{1}{c}V_{\rm ix}B_z\Big)\\ &+\eta\Big(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\Big)V_{\rm iy}.\end{aligned} \tag{10}$$

The electron continuity equation is given by

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x}(nv_{\rm ey}) = 0. \tag{11}$$

The x and y components of the momentum equation for the degenerate electrons are written as

$$\begin{aligned}&\frac{\partial v_{\rm ey}}{\partial t} + v_{\rm ey}\frac{\partial}{\partial x}v_{\rm ey} = -\frac{eE_x}{m_{\rm e}}\\ &-\frac{e}{m_{\rm e}c}v_{\rm ey}B_z - \frac{2k_{\rm B}T_{\rm Fe}}{6m_{\rm e}n_{\rm e}N_0^{\frac{1}{3}}}\nabla n_{\rm e}^{\frac{4}{3}},\end{aligned} \tag{12}$$

$$\frac{\partial v_{\rm ey}}{\partial t} + v_{\rm ey}\frac{\partial}{\partial x}v_{\rm ey} = \frac{-eE_y}{m_{\rm e}} + \frac{e}{m_{\rm e}c}v_{\rm ey}B_z. \tag{13}$$

The z component of Faraday's law yields

$$\frac{\partial E_y}{\partial x} = -\frac{1}{c}\frac{\partial B_z}{\partial t}. \tag{14}$$

The x and y components of Ampere's law yield

$$\frac{\partial B_z}{\partial x} = \frac{4\pi e}{c}(nv_{\rm ey} - NV_{\rm iy}), \tag{15}$$

$$0 = 4\pi e(NV_{\rm ix} - nv_{\rm ey}). \tag{16}$$

The stretching of the space and time coordinates defined in a standard way[15] read

$$\xi = \epsilon^{1/2}(x - \lambda t), \quad \tau = \epsilon^{3/2}t,$$

where ϵ is a small expansion parameter which characterizes the strength of nonlinearity, and λ is the phase velocity of the wave. We expand the perturbed quantities N, n, V_{ix}, v_{ey}, B_z in terms of the smallness parameter ϵ as follows:

$$\begin{bmatrix} N \\ V_{\rm ix} \\ n \\ v_{ey} \\ B_z \end{bmatrix} = \begin{bmatrix} N_0 \\ 0 \\ N_0 \\ 0 \\ B_0 \end{bmatrix} + \epsilon \begin{bmatrix} N^{(1)} \\ V^{(1)} \\ n^{(1)} \\ v^{(1)} \\ B^{(1)} \end{bmatrix} + \epsilon^2 \begin{bmatrix} N^{(2)} \\ V^{(2)} \\ n^{(2)} \\ v^{(2)} \\ B^{(2)} \end{bmatrix} + \ldots, \tag{17}$$

while for $V_{\rm iy}$, v_{ey}, E_x, we have

$$\begin{pmatrix} V_{\rm iy} \\ v_{ey} \\ E_x \end{pmatrix} = \epsilon^{3/2}\begin{pmatrix} U^{(1)} \\ u^{(1)} \\ E^{(1)} \end{pmatrix} + \epsilon^{5/2}\begin{pmatrix} U^{(2)} \\ u^{(2)} \\ E^{(2)} \end{pmatrix} + \ldots,$$

$$\eta = \epsilon^{1/2}\eta_0.$$

Using the above perturbation scheme in the dynamics Eqs. (8)–(16) and collecting the lowest order terms of the ion continuity and the x-component of the ion momentum equations, the following set of equations obtained are given as

$$-\lambda\frac{\partial N^{(1)}}{\partial \xi} + N_0\frac{\partial V^{(1)}}{\partial \xi} = 0, \tag{18}$$

$$\lambda\frac{\partial V^{(1)}}{\partial \xi} + \frac{e}{m_{\rm i}}E_x^{(1)} + \frac{e}{m_{\rm i}}\frac{1}{c}(B_0U^{(1)}) = 0. \tag{19}$$

Similarly, the lowest order ($\epsilon^{3/2}$) terms from the electron continuity and the x and y components of the electron momentum equations are given as follows:

$$-\lambda\frac{\partial n^{(1)}}{\partial \xi} + N_0\frac{\partial v^{(1)}}{\partial \xi} = 0, \tag{20}$$

$$\begin{aligned}&-\lambda\frac{\partial v^{(1)}}{\partial \xi} = -\frac{e}{m_{\rm e}}E_x^{(1)}\\ &-\frac{e}{m_{\rm e}c}B_0u^{(1)} - \frac{2}{6}\frac{k_{\rm B}T_{\rm Fe}}{m_{\rm e}}\frac{\partial n^{(1)}}{\partial \xi}.\end{aligned} \tag{21}$$

The lowest order ($\epsilon^{3/2}$) terms from Faraday's law give

$$B_0\frac{\partial v^{(1)}}{\partial \xi} - \lambda\frac{\partial B^{(1)}}{\partial \xi} = 0. \tag{22}$$

The lowest order terms from the x and y components of Ampere's law yields

$$N_0(V^{(1)} - v^{(1)}) = 0, \tag{23}$$

$$\frac{\partial B^{(1)}}{\partial \xi} + \frac{4\pi eN_0}{c}(U^{(1)} - u^{(1)}) = 0. \tag{24}$$

The phase velocity of the wave is obtained from Eqs. (18)–(24),

$$\lambda = \sqrt{\frac{1}{6}c_{\rm s}^2 + v_{\rm a}^2}, \tag{25}$$

where $v_{\rm a} = \sqrt{B_0^2/4\pi m_{\rm i} N_0}$ is the Alfvén speed and $c_{\rm s} = \sqrt{2k_{\rm B}T_{\rm Fe}/m_{\rm i}}$ is the ion acoustic speed. From the above set of Eqs. (18)–(24), the variables $v^{(1)}$, $N^{(1)}$, $B^{(1)}$, $E^{(1)}$ and $U^{(1)}$ can be written in terms of $V^{(1)}$ as follows:

$$v^{(1)} = V^{(1)},\ N^{(1)} = n^{(1)} = \frac{N_0}{\lambda}V^{(1)},$$

$$B^{(1)} = \frac{B_0}{\lambda}V^{(1)}, \tag{26}$$

$$E_x^{(1)} = \Big(-\lambda\frac{m_{\rm i}}{e} - \frac{m_{\rm e}}{3e\lambda}c_{\rm s}^2\Big)\frac{\partial V^{(1)}}{\partial \xi}, \tag{27}$$

$$U^{(1)} = \frac{cm_{\rm e}}{3e\lambda B_0}c_{\rm s}^2\frac{\partial V^{(1)}}{\partial \xi}, \tag{28}$$

$$u^{(1)} = \Big(\lambda\frac{cm_{\rm i}}{eB_0} - \frac{cm_{\rm i}}{3e\lambda B_0}c_{\rm s}^2\Big)\frac{\partial V^{(1)}}{\partial \xi}. \tag{29}$$

To derive the KdVB equation for magnetosonic waves, the next higher order terms ($\epsilon^{5/2}$) of the ion continuity and x, y components of the ion momentum equation give

$$\frac{\partial N^{(1)}}{\partial \tau} - \lambda\frac{\partial N^{(2)}}{\partial \xi} + \frac{\partial}{\partial \xi}N^{(1)}V^{(1)} + N_0\frac{\partial V^{(2)}}{\partial \xi} = 0, \tag{30}$$

$$\frac{\partial V^{(1)}}{\partial \tau} + V^{(1)}\frac{\partial V^{(1)}}{\partial \xi} - \lambda\frac{\partial V^{(2)}}{\partial \xi} - \frac{e}{m_{\rm i}}\Big(E_x^{(2)} + \frac{1}{c}B_0U^{(2)}\Big) - \frac{e}{m_{\rm i}c}B^{(1)}U^{(1)} - \eta_0\frac{\partial^2 V^{(1)}}{\partial \xi^2} = 0, \tag{31}$$

$$-\lambda\frac{\partial U^{(1)}}{\partial \xi} + \frac{e}{m_{\rm i}c}B^{(1)}U^{(1)} = \frac{e}{m_{\rm i}}\Big(E_y^{(2)} - \frac{1}{c}B_0U^{(2)}\Big). \tag{32}$$

The next higher order terms ($\epsilon^{5/2}$) of the electron continuity and the x, y components of the electron momentum equation give

$$\frac{\partial n^{(1)}}{\partial \tau} - \lambda\frac{\partial n^{(2)}}{\partial \xi} + \frac{\partial n^{(1)}v^{(1)}}{\partial \xi} + N_0\frac{\partial v^{(2)}}{\partial \xi} = 0, \tag{33}$$

$$\frac{\partial v^{(1)}}{\partial \tau} + v^{(1)}\frac{\partial v^{(1)}}{\partial \xi} + \frac{e}{m_{\rm e}c}B^{(1)}u^{(1)} - \frac{2}{9m_{\rm e}N_0^2}k_{\rm B}T_{\rm Fe}n^{(1)}\frac{\partial n^{(1)}}{\partial \xi} = \lambda\frac{\partial v^{(2)}}{\partial \xi} - \frac{e}{m_{\rm e}}\Big(E_x^{(2)} + \frac{1}{c}B_0u^{(2)}\Big) - \frac{2}{3m_{\rm e}N_0}k_{\rm B}T_{\rm Fe}\frac{\partial n^{(2)}}{\partial \xi}, \tag{34}$$

$$-\lambda\frac{\partial u^{(1)}}{\partial \xi} + \frac{e}{m_{\rm i}c}B^{(1)}u^{(1)} = \frac{e}{m_{\rm i}}\Big(E_y^{(2)} - \frac{1}{c}B_0u^{(2)}\Big). \tag{35}$$

The next higher order terms ($\epsilon^{5/2}$) of Faraday's law yield

$$\frac{1}{c}\frac{\partial B^{(1)}}{\partial \tau} - \frac{\lambda}{c}\frac{\partial B^{(2)}}{\partial \xi} + \frac{\partial E_y^{(2)}}{\partial \xi} = 0. \tag{36}$$

The next higher order terms (ϵ^2) of the x component of Ampere's law give

$$\frac{4\pi eN_0}{c}(V^{(2)} - v^{(2)}) = 0. \tag{37}$$

The next higher order terms ($\epsilon^{5/2}$) of the y component of Ampere's laws yield

$$\frac{\partial B^{(2)}}{\partial \xi} + \frac{4\pi e}{c}(N_0U^{(2)} + N^{(1)}U^{(1)} - N_0u^{(2)} - n^{(1)}u^{(1)}) = 0. \tag{38}$$

Finally, eliminating $N^{(2)}$, $V^{(2)}$, $U^{(2)}$ and $E^{(2)}$, $B^{(2)}$, $n^{(2)}$, $v^{(2)}$, $u^{(2)}$ from Eqs. (30)–(37) and using the relation given in Eq. (25), we obtain the KdVB equation for the magnetosonic wave in dense magnetized plasmas with ultra-relativistic degenerate electrons as follows:

$$\frac{\partial V^{(1)}}{\partial \tau} + A_{\rm ur}V^{(1)}\frac{\partial V^{(1)}}{\partial \xi} + B_{\rm ur}\frac{\partial^3 V^{(1)}}{\partial \xi^3} - C_{\rm ur}\frac{\partial^2 V^{(1)}}{\partial \xi^2} = 0, \tag{39}$$

where the nonlinear, dispersive and dissipative coefficients $A_{\rm ur}$, $B_{\rm ur}$, $C_{\rm ur}$ are defined as

$$A_{\rm ur} = \frac{1}{2\lambda_{\rm ur}^2}\Big(\frac{8c}{9m_{\rm i}}(3\hbar^3N_0)^{1/3} + \frac{11}{3}v_{\rm a}^2\Big),$$

$$B_{\rm ur} = \frac{\lambda_{\rm e}^2v_{\rm a}^2}{2\lambda_{\rm ur}},\quad C_{\rm ur} = \frac{\eta_0}{2},$$

with $\lambda_{\rm e} = c/\omega_{\rm pe}$ being the electron inertial length or skin depth, and $\omega_{\rm pe} = \sqrt{4\pi e^2N_0/m_{\rm e}}$ being the electron plasma frequency. We have defined the transformed coordinate χ such that $\chi = \xi - U\tau$ of the co-moving frame with speed U and used the boundary conditions i.e., $V^{(1)} \to 0$ and $\partial_\chi V^{(1)}$, $\partial_\chi^2 V^{(1)}$, $\partial_\chi^3 V^{(1)} \to 0$ as $\chi \to \infty$ for a localized solution.

The analytical solution to KdVB Eq. (39) is derived by using the tanh method,[16–18] which is given by

$$V^{(1)}(\zeta) = A_{\rm ur}U + \frac{3C_{\rm ur}^2}{25B_{\rm ur}}{\rm Sech}^2\Big[\frac{C_{\rm ur}}{10B_{\rm ur}}(\xi - U\tau)\Big] - \frac{3C_{\rm ur}^2}{25B_{\rm ur}}\Big\{1 - \tanh\Big[\frac{C_{\rm ur}}{10B_{\rm ur}}(\xi - U\tau)\Big]\Big\}. \tag{40}$$

The speed of the co-moving frame is related to the weak dispersive and diffraction coefficients such as $U = \frac{(100B_{\rm ur}^2k^2 - C_{\rm ur}^2 + 60kB_{\rm ur}C_{\rm ur})}{25AB_{\rm ur}}$, where $k = \frac{C_{\rm ur}}{10B_{\rm ur}}$ is the inverse of shock spatial width, which has been obtained by using the boundary conditions, i.e., as $\chi \to \infty$, then $V^{(1)}(\chi) \to 0$ and $\tanh^2(\chi) \to 1$. The amplitude of the nonlinear shock structure in this case is defined as $\frac{12C_{\rm ur}^2}{25AB_{\rm ur}}$.

We investigate the formation of magnetosonic shock in dense ultra-relativistic plasma using the astrophysical plasma parameters $N_0 = 10^{32}$–$10^{34}\,{\rm cm}^{-3}$, $B_0 = 10^5 - 10^7$ Gauss and $T = 10^9$ K.[6,13,14] For

numerical analysis of KdVB Eq. (40) we use the plasma density $N_0 = 10^{32}\,\mathrm{cm}^{-3}$. The Fermi temperature and the plasma density are related by $T_{\mathrm{Fe}} = (ch/k_{\mathrm{B}})(3N_0/8\pi)^{1/3}$, where c is the speed of light, h is the Plank constant. The value of the Fermi temperature comes out to be $2.43 \times 10^9\,\mathrm{K}$, which is greater than the system temperature. The value of Fermi Debye length, i.e., $\lambda_{\mathrm{Fe}} = (k_{\mathrm{B}}T_{\mathrm{Fe}}/2\pi N_0 e^2)^{1/2}$ comes out as $1.5 \times 10^{-10}\,\mathrm{cm}$, which is larger than the interparticle distance to be $2.9 \times 10^{-11}\,\mathrm{cm}$ in this case as $(d_{\mathrm{e}} = 3/4\pi N_0)^{1/3}$. Under the validation of these conditions, the applicability of fluid theory for a quantum plasma system holds for the case of ultra-relativistic degenerate electron pressure.

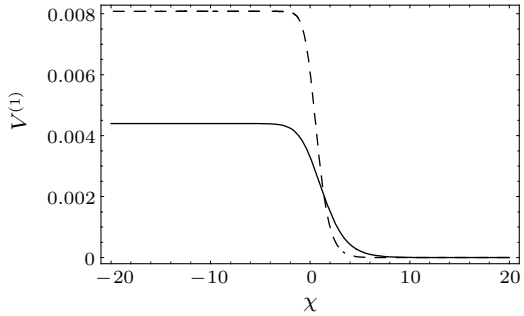

Fig. 1. The variations in the strength of the magnetosonic shock structure at plasma densities $N_0 = 0.1 \times 10^{32}\,\mathrm{cm}^{-3}$ (bold curve) and $N_0 = 0.15 \times 10^{32}\,\mathrm{cm}^{-3}$ (dashed curve) with the magnetic field intensity $B_0 = 7 \times 10^7$ Gauss and $\eta_0 = 0.005$.

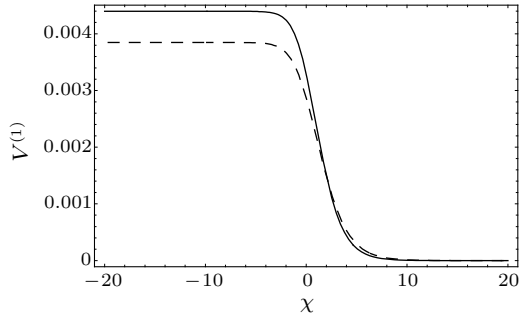

Fig. 2. The decrease in the strength of the magnetosonic shock structure at magnetic field intensities $B_0 = 7\times10^7$ Gauss (bold curve) and $B_0 = 8\times10^7$ Gauss (dashed curve) with plasma density $N_0 = 0.1 \times 10^{32}\,\mathrm{cm}^{-3}$ and $\eta_0 = 0.005$.

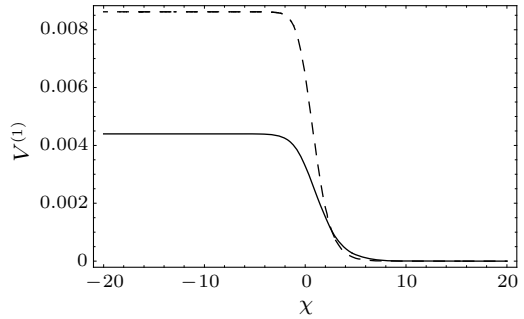

Fig. 3. The increase in the strength of the magnetosonic shock structure at different values of kinematic viscosities at $\eta_0 = 0.005$ (bold curve) and $\eta_0 = 0.05$ (dashed curve) with $B_0 = 7 \times 10^7$ Gauss and plasma density $N_0 = 0.1 \times 10^{32}\,\mathrm{cm}^{-3}$.

It can be seen that nonlinear, dispersive, and dissipative coefficients of the KdVB equation depends on density of ultra-relativistic electrons. Consequently the amplitude and the width of the structure are sensitive to density of these nondegenerate electrons. It is seen that by increasing the density of plasma species the amplitude of the shock enhances and the spatial width of the structure decreases as shown in Fig. 1. It is worth mentioning here that by increasing the density of the plasma species the quantum effects appear more dominantly due to the fact that the Fermi temperature increases with the density of the plasma species. It is seen that, with increasing the magnetic field intensity, the Alfvén speed of the magnetosonic shock structure increases, on the other hand the amplitude of the shock structure diminishes as shown in Fig. 2. It is also noticed that, with increasing the value of the kinematic viscosity, the strength of the shock increases as shown in Fig. 3. This is due to the fact that the dissipation coefficient is directly proportional to the kinematic viscosity of the plasma system. Nonlinear shock structure is a source of energy transport in astrophysical objects. Our findings have relevance in dense astrophysical objects like white dwarfs where ultra-relativistic degenerate electrons exist.

In summary, we have studied the propagation of magnetosonic waves in dense quantum magnetoplasmas in which electrons are ultra-relativistic. The KdVB equation is derived and it is found that plasma density, magnetic field intensity and kinematic viscosity of ion species have significant impact on the dynamics of magnetosonic waves in such plasma systems.

References

[1] Chandrasekhar S 1935 *Mon. Not. R. Astron. Soc.* **95** 207
[2] Misra A P and Shukla P K 2012 *Phys. Rev.* E **85** 026409
[3] Zeba I, Moslem W M and Shukla P K 2012 *Astrophys. J.* **750** 72
[4] Mahmood S, Sadiq S and Haque Q 2013 *Phys. Plasmas* **20** 122305
[5] Roy N, Tasnim S and Mamun A A 2012 *Phys. Plasmas* **19** 033705
[6] Hussain S, Mahmood S and Rehman A 2014 *Phys. Plasmas* **21** 112901
[7] Kulsrud R M, Ostriker J P and Gunn J E 1972 *Phys. Rev. Lett.* **28** 636
[8] Lee E, Parks G K, Wilbr M and Lin N 2009 *Phys. Rev. Lett.* **103** 031101
[9] Zakharov Y P 2003 *IEEE Trans. Plasma Sci.* **31** 1243
[10] Sultana S, Sarri G and Kourakis I 2012 *Phys. Plasmas* **19** 012310
[11] Sahu B, Sinha A, Roychoudhury R and Khan M 2013 *Phys. Plasmas* **20** 112303
[12] Meyer-Vernet N 2007 *Basics of Solar Wind* (Cambridge: Cambridge Press) p 56
[13] Sabry R, Moslem W M and Shukla P K 2012 *Phys. Plasmas* **19** 122903
[14] Rasheed A, Tsintsadze N L and Murtaza G 2011 *Phys. Plasmas* **18** 112701
[15] Washimi H and Tanuiti T 1966 *Phys. Rev. Lett.* **17** 996
[16] Malfliet W 1992 *Am. J. Phys.* **60** 650
[17] Hussain S, Rehman A, Hasnain H and Mustafa N 2015 *Astrophys. Space Sci.* **359** 29
[18] Hussain S, Akhtar N and Hasnain H 2015 *Astrophys. Space Sci.* **360** 25