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CONDENSED MATTER

Cylindrical and Spherical Positron-Acoustic Shock Waves in Nonthermal Electron-Positron-Ion Plasmas

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Abstract The nonlinear propagation of cylindrical and spherical positron-acoustic shock waves (PASWs) in an unmagnetized four-component plasma (containing nonthermal distributed hot positrons and electrons, cold mobile viscous positron fluid, and immobile positive ions) is investigated theoretically. The modified Burgers equation is derived by employing the reductive perturbation method. Analytically, the effects of cylindrical and spherical geometries, nonthermality of electrons and hot positrons, relative number density and temperature ratios, and cold mobile positron kinematic viscosity on the basic features (viz. polarity, amplitude, width, phase speed, etc.) of PASWs are briefly addressed. It is examined that the PASWs in nonplanar (cylindrical and spherical) geometry significantly differ from those in planar geometry. The relevance of our results may be useful in understanding the basic characteristics of PASWs in astrophysical and laboratory plasmas.

Keywords Positron-acoustic shock waves · Electron-positron-ion plasmas · Modified Burgers equation · Nonthermality

1 Introduction

The propagation characteristics of linear and nonlinear waves behave differently in electron-positron-ion (e-p-i) plasmas rather than the usual electron-ion plasmas. In various astrophysical plasmas, there exist a significant number of ions along with electrons and positrons. Thus, it is important to study the behavior of linear and nonlinear waves in e-p-i plasmas. During the past few decades, the research works on linear as well as nonlinear wave propagation in e-p-i plasmas have attracted a considerable interest from many authors [1–17], because they have great importance to understand the behavior of astrophysical plasmas viz. cluster explosions, pulsar environments, supernovas, and active galactic nuclei [10, 18, 19].

Positron-acoustic (PA) waves are acoustic type of waves, where the inertia comes from the cold positron mass, and the restoring force is provided by the thermal pressure of hot positrons and electrons. Recently, the nonlinear phenomena such as solitons, shocks, double layers, etc. associated with the PA waves have been studied by a number of authors [4, 10, 20–25]. Tribeche et al. [10] investigated the PA solitary waves in e-p-i plasmas containing immobile positive ions, mobile cold positrons, and Maxwellian distributed electrons and positrons. Biswajit Sahu [21] analyzed the planar and nonplanar PASWs in an unmagnetized e-p-i plasma system consisting of stationary positive ions, inertial cold positrons, and Maxwellian distributed electrons and hot positrons. Most of these works related with the PA waves are concentrated on the Maxwellian electrons and positrons [10, 20–22].

It is well established that the shock waves appear in a plasma medium with significant dissipative properties. These waves are formed due to the balance between the nonlinearity and the dissipation. The dissipation arises due to Landau damping, kinematic viscosity among the plasma species, wave particle interaction etc., which is responsible to form the shock structures in a plasma system [26]. The

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shock structures were found by Andersen et al. [27] in laboratory experiments such as Q machine experiments. Many authors [26, 28–34] have investigated shock waves both theoretically and experimentally. Masood et al. [35] studied the planar and nonplanar ion-acoustic shock waves (IASWs) in e-p-i plasma system. They found that the shock structures are modified by the ratio of ion to electron temperature and positron concentration. Recently, Pakzad and Tribeche [36] investigated the IASWs in dissipative e-p-i plasmas consisting of relativistic ions, Maxwellian distributed positrons, and superthermal electrons. The relativistic and dissipative effects significantly reshaped the arrangement of these IASWs. At the same year, Masud et al. [37] analyzed the dust-ion-acoustic shock waves in e-p-i dusty plasmas composed of kappa distributed electrons with two distinct temperatures [38, 39], positrons following Maxwellian distribution, inertial ions, and negatively charged immobile dust grains.

Astrophysical plasmas are often described by a particle distribution function with high energy tail and they may deviate from the Maxwellian [34, 40–44]. The plasma systems containing nonthermal distributed ions or electrons [45–50] may exist in the heliospheric environments. These energetic particles following nonthermal distribution have received an impressive interest from many researchers searching to understand the nature of nonlinear electrostatic perturbations in different astrophysical plasmas, viz. upper Martian ionosphere [51], auroral acceleration region [52], in/around the Earth's bow shock [53], etc. Nonthermal distributed electrons and positrons are predicted to exist in the expansion phenomenon of laser induced plasmas [54]. Chatterjee et al. [55] investigated the planar and nonplanar IASWs in e-p-i plasma system consisting of nonthermal distributed electrons and positrons, and singly charged adiabatically hot positive ions. Cairns et al. [56] used nonthermal distributed electrons to study the ion-acoustic solitary waves. Pakzad and Javidan [57] considered dissipative e-p-i plasmas comprising of nonthermal electrons, Maxwellian positrons, and relativistic ions to investigate the IASWs.

However, all of these works [3, 4, 6, 10, 22, 36, 57] are limited to one dimensional (1D) planar geometry associated with ion-acoustic solitons, or PA waves, or IASWs, which may not be a realistic situation in space plasmas and laboratory devices, since in many situations the wave structures observed in space plasmas or laboratory devices are certainly not infinite (unbounded) in one dimension [58]. Thus, nonplanar geometries are important to understand star formation, supernova explosions, capsule implosion (spherical geometry), shock tube (cylindrical geometry), etc. The author of ref. [21] used both planar and nonplanar geometry to study the PASWs in an unmagnetized e-p-i plasma system comprising of stationary positive ions, inertial cold positrons, and Maxwellian distributed electrons and hot positrons. Sahu [59] considered an adiabatic dusty plasma comprising of adiabatic ion fluid, static negatively charged dust fluid, and Boltzmann distributed electrons, and studied the nonplanar (cylindrical and spherical) dust-ion acoustic (DIA) shock waves (where the inertia comes from the ion mass and the restoring force is provided by the thermal pressure of electrons). On the other hand, we, in our present work, consider an unmagnetized e-p-i plasma (containing nonthermal distributed hot positrons and electrons, cold mobile viscous positron fluid, and immobile positive ions) and investigate the basic features of PASWs (where the inertia comes from the cold positron mass and the restoring force is provided by the thermal pressure of hot positrons and electrons) in nonplanar geometry. The time scale of PA waves is significantly different from that of DIA waves. Besides, in our present investigation, we consider nonthermal (Cairns) distribution for hot positrons and electrons, whereas Sahu [59] considered Maxwell-Boltzmann distributed electrons. It is noted here that the Maxwell-Boltzmann distribution is inadequate to model the energetic space plasma particles. To model such nonthermal particles, Cairns distribution [56] is suitable rather than a Maxwell-Boltzmann distribution. But up to now, to the best of our knowledge, no theoretical investigation has been made on the cylindrical and spherical PASWs in e-p-i plasmas with nonthermal (Cairns distributed) electrons and hot positrons. Therefore, we consider an unmagnetized four-component plasma system consisting of nonthermal (Cairns distributed) electrons and hot positrons, mobile cold positrons, and immobile positive ions to investigate the structures and the basic features of cylindrical and spherical PASWs.

The manuscript is arranged as follows: The basic governing equations are presented in Section 2. The modified Burgers equation is derived and the basic features of the shock waves are numerically analyzed in Section 3. Finally, a brief discussion is provided in Section 4.

2 Governing Equations

We consider a nonplanar (cylindrical or spherical) geometry, and nonlinear propagation of the PA waves in an unmagnetized four-component plasma system consisting of nonthermal distributed electrons and hot positrons, mobile cold positrons, and immobile positive ions. Hence, at equilibrium, $n_{e0} = n_{pc0} + n_{ph0} + n_{i0}$, where n_{i0}, n_{e0} are the unperturbed ion number density and electron number density, respectively. n_{pc0} (n_{ph0}) is the number density of unperturbed cold (hot) positron. The electrons and hot positrons are assumed to obey nonthermal distribution on the PA wave time scale and are given by the following expressions [56]:

$$n_e = n_{e0}\left(1-\beta\phi+\beta\phi^2\right)e^{\left(\frac{e\phi}{T_e}\right)},$$

$$n_{ph} = n_{ph0}\left(1+\beta\phi+\beta\phi^2\right)e^{\left(\frac{-e\phi}{T_{ph}}\right)},$$

where β is the nonthermal parameter, n_e and n_{ph} are the number densities of perturbed electron and hot positron, while T_e and T_{ph} are the temperatures of electron and hot positron (in the energy units), respectively.

The normalized basic equations governing the dynamics of the PA waves in a nonplanar geometry are given in dimensionless variables as follows:

$$\frac{\partial n_{pc}}{\partial t}+\frac{1}{r^\nu}\frac{\partial}{\partial r}\left(r^\nu n_{pc}u_{pc}\right)=0, \tag{1}$$

$$\frac{\partial u_{pc}}{\partial t}+u_{pc}\frac{\partial u_{pc}}{\partial r}=-\frac{\partial\phi}{\partial r}+\eta\frac{1}{r^\nu}\frac{\partial}{\partial r}\left(r^\nu\frac{\partial u_{pc}}{\partial r}\right), \tag{2}$$

$$\frac{1}{r^\nu}\frac{\partial}{\partial r}\left(r^\nu\frac{\partial\phi}{\partial r}\right)=-n_{pc}-\mu_1\left(1+\beta\sigma\phi+\beta\sigma^2\phi^2\right)e^{(-\sigma\phi)} +\mu_2\left(1-\beta\phi+\beta\phi^2\right)e^{(\phi)}-\mu_3. \tag{3}$$

It is to be noted that $\nu = 0$ for $1D$ planar geometry, and $\nu = 1$ (2) for a nonplanar cylindrical (spherical) geometry. Here, n_{pc} is the cold positron number density normalized by its equilibrium value n_{pc0}; u_{pc} is the cold positron fluid speed normalized by $C_{pc} = (k_BT_e/m_p)^{1/2}$; ϕ is the electrostatic wave potential normalized by k_BT_e/e; k_B is the Boltzmann constant; m_p is the positron mass, $\sigma = T_e/T_{ph}$, $\mu_1 = n_{ph0}/n_{pc0}$, $\mu_2 = n_{e0}/n_{pc0}$, $\mu_3 = n_{i0}/n_{pc0}$; and η is the cold positron kinematic viscosity normalized by $\omega_{pc}\lambda_D^2$. The time variable t is normalized by $\omega_{pc}^{-1} = (m_p/4\pi n_{pc0}e^2)^{1/2}$, and the space variable x is normalized by the Debye length $\lambda_D = (k_BT_e/4\pi n_{pc0}e^2)^{1/2}$.

3 Derivation of Modified Burgers Equation

To study the finite amplitude PASWs, we derive the modified Burgers (MB) equation by introducing the following stretched coordinates:

$$\zeta = \epsilon\left(r-V_pt\right), \tag{4}$$

$$\tau = \epsilon^2 t, \tag{5}$$

where V_p is the phase speed of the PASWs and ϵ is a smallness parameter measuring the weakness of the dispersion ($0 < \epsilon < 1$). To obtain a dynamical equation, we also expand the perturbed quantities n_{pc}, u_{pc}, and ϕ, in power series of ϵ. Let S be any of the system variables n_{pc}, u_{pc}, and ϕ, describing the systems's state at a given position and instant. We consider small deviations from the equilibrium state $S^{(0)}$, which explicitly is $n_{pc}^{(0)} = 1$, $u_{pc}^{(0)} = 0$, and $\phi^{(0)} = 0$, by taking

$$S = S^{(0)}+\sum_{n=1}^{\infty}\epsilon^n S^{(n)}. \tag{6}$$

To the lowest order in ϵ, (1)–(6) give

$$u_{pc}^{(1)} = \frac{1}{V_p}\psi, \tag{7}$$

$$n_{pc}^{(1)} = \frac{1}{V_p^2}\psi, \tag{8}$$

$$V_p = \frac{1}{\sqrt{(1-\beta)(\mu_1\sigma+\mu_2)}}, \tag{9}$$

where $\psi = \phi^{(1)}$. Equation (9) represents the phase speed of the PASWs. To the next higher order in ϵ, we obtain a set of equations, which, after using (7)–(9), can be simplified as

$$\frac{\partial n_{pc}^{(1)}}{\partial\tau} - V_p\frac{\partial n_{pc}^{(2)}}{\partial\zeta}+\frac{\partial u_{pc}^{(2)}}{\partial\zeta}+\frac{\partial}{\partial\zeta}\left[n_{pc}^{(1)}u_{pc}^{(1)}\right] +\frac{u_{pc}^{(1)}\nu}{V_p\tau}=0, \tag{10}$$

$$\frac{\partial u_{pc}^{(1)}}{\partial\tau} - V_p\frac{\partial u_{pc}^{(2)}}{\partial\zeta}+u_{pc}^{(1)}\frac{\partial u_{pc}^{(1)}}{\partial\zeta}+\frac{\partial\phi^{(2)}}{\partial\zeta} -\eta\frac{\partial^2u_{pc}^{(1)}}{\partial\zeta^2}=0, \tag{11}$$

$$\frac{\partial n_{pc}^{(2)}}{\partial\zeta} - (1-\beta)(\mu_1\sigma+\mu_2)\frac{\partial\phi^{(2)}}{\partial\zeta} +(\mu_1\sigma^2-\mu_2)\psi\frac{\partial\psi}{\partial\zeta}=0. \tag{12}$$

We note here that the choice of our stretching coordinates allows us to drop out the left hand side of (3). The omission of left hand side of (3) means that the stretched coordinates are valid for quasineutrality condition. Now, combining (10)–(12), we obtain a new equation of the form:

$$\frac{\partial\psi}{\partial\tau}+A\psi\frac{\partial\psi}{\partial\zeta}+\frac{\nu}{2\tau}\psi-C\frac{\partial^2\psi}{\partial\zeta^2}=0, \tag{13}$$

where

$$A = \frac{V_p^3}{2}\left[\frac{3}{V_p^4}+\mu_1\sigma^2-\mu_2\right], \tag{14}$$

$$C = \frac{\eta}{2}. \tag{15}$$

Equation (13) is known as the MB equation modified by the extra term $(\nu/2\tau)\psi$ which arises due to the effect of the nonplanar cylindrical ($\nu = 1$) or spherical ($\nu = 2$) geometry. The third and fourth terms on the left hand side of (13) represent the geometry effects and dissipation, respectively. It is obvious from (13) that the nonplanar geometrical effect is important when $\tau \to 0$ and weaker for larger value of $|\tau|$.

At first, we consider 1D planar geometry ($\nu = 0$) and examine the basic features of the shock wave solutions of (13). The stationary shock wave solution of (13) in a planar geometry ($\nu = 0$) is

$$\psi(\nu = 0) = \psi_m \left[1 - \tanh\left(\frac{\zeta}{\Delta}\right)\right], \qquad (16)$$

where $\Delta = 2C/U_0$ is the width and $\psi_m = U_0/A$ is the amplitude of the shock wave. It is found that for $A >$ ($<$)0, the plasma system supports compressive (rarefactive) PASWs which are associated with a positive (negative) potential, and no shock waves exist at $A = 0$ and $A \sim 0$. It is obvious that A is a function of μ_1, μ_2, and σ. Therefore, $A(\mu_1 = \mu_c) = 0$ and μ_1 can be expressed as

$$\mu_1 = \mu_c = -\frac{1}{6P^2} + \frac{\sqrt{\sigma^2 + 12\mu_2 P^2(1+\sigma)}}{6\sigma P^2} - \frac{\mu_2}{\sigma}, \qquad (17)$$

where $P = (-1 + \beta)$. Equation (17) represents the critical value of μ_1 below (above) which the shock waves with a negative (positive) potential exists. We can find $A = 0$ for a certain (critical) value of μ_1, i.e., $A = 0$ for $\mu_1 = \mu_c \simeq 0.154$ [obtained from $A(\mu_1 = \mu_c) = 0$ for a set of plasma parameters viz. $\mu_2 = 1.5$, $\sigma = 2$, and $\beta = 0.7$]. It is clear that $\psi_m = \infty$ at $\mu_1 = \mu_c$ and the MB equation that we have derived is no longer valid at this condition, so the shock waves are found for $\mu_1 \neq \mu_c$.

Since an exact analytical solution of (13) is not possible, we have numerically solved (13) and studied the effects of cylindrical ($\nu = 1$) and spherical ($\nu = 2$) geometries on the time-dependent PA shock structures. We start with a large (absolute) value of τ ($\tau = -20$), as for a large value of τ, the term $(\nu/2\tau)\psi$ is negligible. This large value of τ we choose in (16) [which is the stationary solution of (13) without the term $(\nu/2\tau)\psi$] as our initial aim. The variation of the amplitude of positive and negative shock structures with nonthermal parameter β is shown in Fig. 1. Figure 2 also shows the variation of the amplitude of positive and negative shock structures with ratio of the electron temperature to the hot positron temperature σ and ratio of the electron number density to the cold positron number density μ_2, respectively. In Figs. 3, 4, 5, and 6, the effect of cold mobile positron kinematic viscosity η in both cylindrical and spherical geometries is investigated, respectively, for different values of τ. Figure 7 shows the variation of width Δ of the shock waves with cold positron fluid speed U_0 and η. The effect of β on the phase speed V_p of PASWs is shown in Fig. 8 for different values of μ_2.

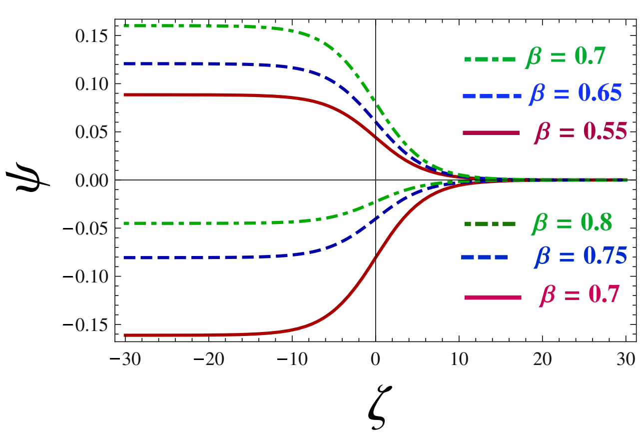

Fig. 1 Variation of the amplitude of one dimensional ($\nu = 0$) positive and negative shock structures with β at $\mu_1 = 0.25$ and $\mu_1 = 0.08$, respectively. Here, $\mu_2 = 1.5$, $\sigma = 2$, and $U_0 = 0.05$

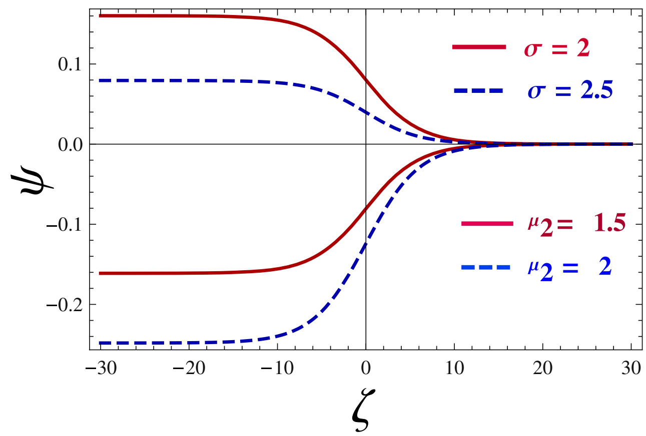

Fig. 2 Variation of the amplitude of one dimensional ($\nu = 0$) positive and negative shock structures with σ and μ_2, respectively. Here, the values of μ_1 and U_0 are same as given in Fig. 1, and $\beta = 0.7$

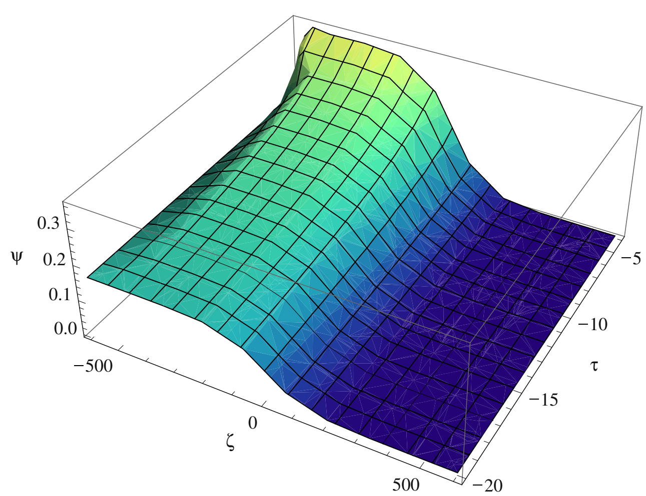

Fig. 3 The effect of cylindrical ($\nu = 1$) geometry on PA shock structure for above the critical value $\mu_1 = 0.25$ for $\mu_2 = 1.5$, $\sigma = 2$, $\eta = 0.3$, $\beta = 0.7$, and $U_0 = 0.05$

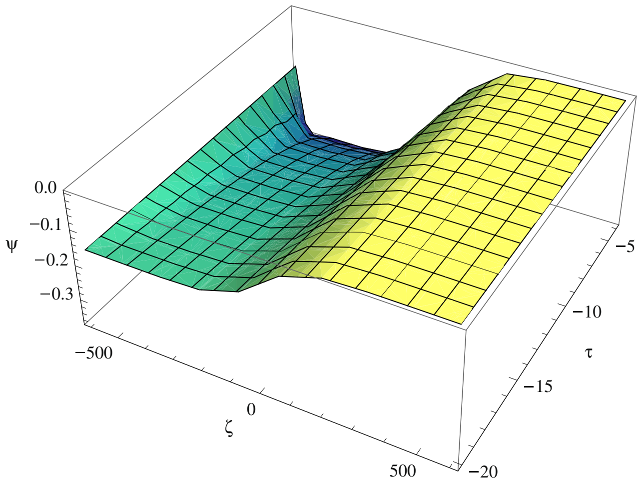

Fig. 4 The effect of cylindrical ($\nu = 1$) geometry on PA shock structure for below the critical value $\mu_1 = 0.08$ for $\mu_2 = 1.5$, $\sigma = 2$, $\eta = 0.3$, $\beta = 0.7$, and $U_0 = 0.05$

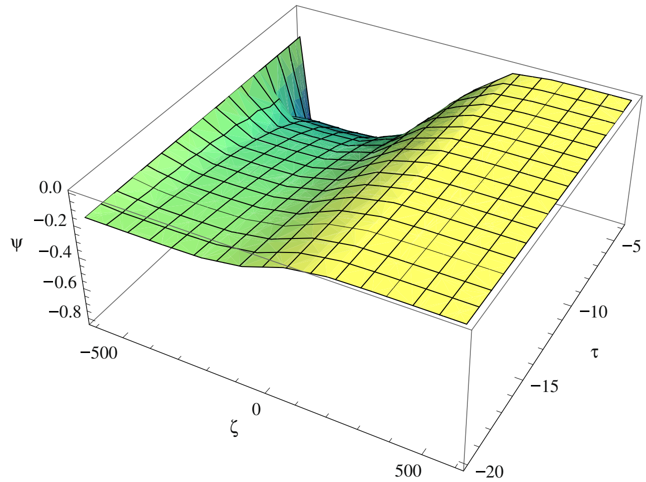

Fig. 6 The effect of spherical ($\nu = 2$) geometry on PA shock structure for below the critical value $\mu_1 = 0.08$ for $\mu_2 = 1.5$, $\sigma = 2$, $\eta = 0.3$, $\beta = 0.7$, and $U_0 = 0.05$

4 Discussions

We have considered an unmagnetized four-component plasma system consisting of nonthermal distributed electrons and hot positrons, mobile cold positrons, and immobile positive ions, and investigated the cylindrical and spherical PASWs. By using the reductive perturbation method, we have derived the modified Burgers equation and numerically analyzed that modified Burgers equation. The plasma system under consideration supports small but finite amplitude shock structures, whose basic features (viz. polarity, amplitude, width, phase speed, etc.) strongly depend on the plasma parameters viz. μ_1, μ_2, σ, β, and η.

The results that have been found from our present investigation can be pinpointed as follows:

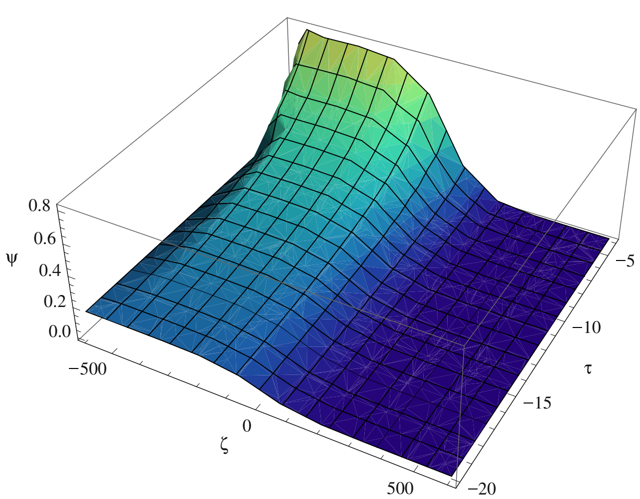

Fig. 5 The effect of spherical ($\nu = 2$) geometry on PA shock structure for above the critical value $\mu_1 = 0.25$ for $\mu_2 = 1.5$, $\sigma = 2$, $\eta = 0.3$, $\beta = 0.7$, and $U_0 = 0.05$

1. The shock waves are formed for μ_1 far above and below the critical value (i.e., when $\mu_1 > \mu_c$ and $\mu_1 < \mu_c$) but do not form for $\mu_1 \simeq \mu_c$.
2. It is observed that for $\mu_1 > 0.154$, compressive (positive) shock waves exist, whereas for $\mu_1 < 0.154$, rarefactive (negative) shock waves exist (displayed in Figs. 1–6).
3. It is found that the amplitude of the 1D positive (negative) potential shock structures increases (decreases) gradually with the increase of nonthermal parameter β (shown in Fig. 1). On the other hand, the amplitude of the 1D positive and negative potential shock structures increases steeply with the increase of the temperature ratio σ and relative number density ratio μ_2, respectively, (displayed in Fig. 2).
4. With the comparison of Figs. 1, 2, 3–6, it is observed that the time evolution of the cylindrical and spherical

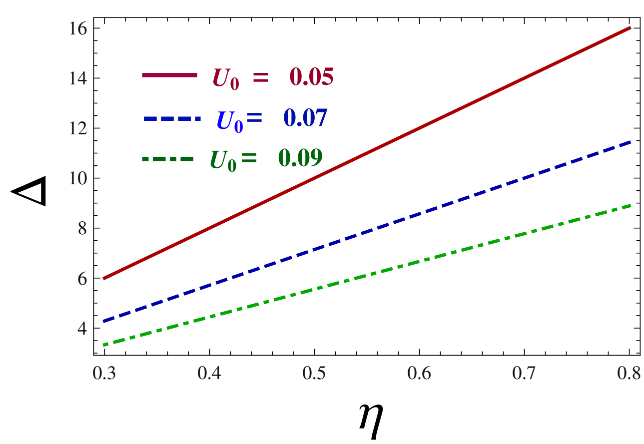

Fig. 7 Variation of the width of shock waves with η for different values of U_0. Here, $\mu_1 = 0.25$, $\mu_2 = 1.5$, $\sigma = 2$, and $\beta = 0.7$

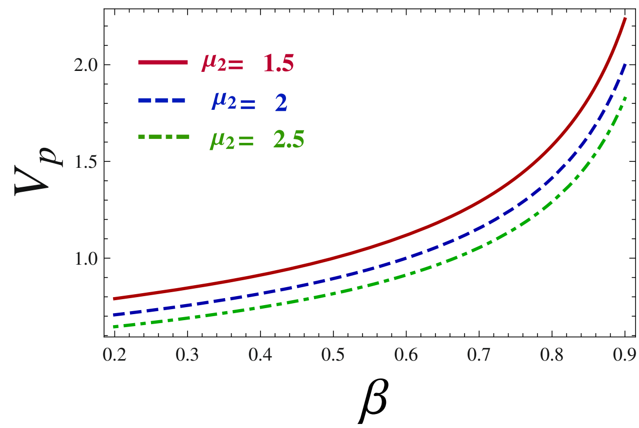

Fig. 8 Variation of the phase speed V_p of PASWs with β for different values of μ_2. Here, $\mu_1 = 0.25$ and $\sigma = 2$

PASWs significantly differs from the 1D planar PASWs. It is found that as time (τ) decreases, the amplitude of the cylindrical and spherical PASWs increases (shown in Figs. 3–6).

5. The height and steepness of the cylindrical shock wave are larger than that of the 1D shock wave but smaller than that of the spherical shock wave. In other words, the amplitude of the cylindrical PASWs is larger than that of the 1D planar PASWs, but smaller than that of the spherical PASWs (see Figs. 3–6).
6. The width of the shock waves decreases gradually with the increase of cold positron fluid speed U_0. On the other hand, the width of the shock waves increases linearly with the increase of cold positron kinematic viscosity η (depicted in Fig. 7). It can also be said that the shock waves become smoother and weaker when the dissipation is increased.
7. The phase speed of the PASWs increases almost exponentially with the increase of nonthermal parameter β but decreases with the increase of the relative number density ratio μ_2 (shown in Fig. 8).

The results of our present investigation reveal that the basic properties (viz. polarity, amplitude, width, phase speed, etc.) of the shock structures are significantly modified by the effects of nonplanar geometry ν, nonthermal parameter β, relative number density ratios μ_1 and μ_2, relative temperature ratio σ, and cold positron kinematic viscosity η. The nonthermality has a positive (negative) effect on the amplitude of positive (negative) potential shock structures because with the increase of β, there is an increase (decrease) in the amplitude of positive (negative) potential shock structures (see Fig. 1). Thus, it is predicted that the strength and steepness of the positive potential shock increases by increasing the value of β. The temperature ratio σ and number density ratio μ_2 have negative and positive effect on the amplitude of positive and negative potential shock waves, respectively (displayed in Fig. 2). When the time τ increases the amplitude of the cylindrical and spherical PASWs decreases (see Figs. 3–6). There is an increase in width of the PASWs with increasing dissipation (see Fig. 7). β has also a positive effect on the phase speed V_p for different values of μ_2. V_p is found to be increased almost exponentially with the increase of β (displayed in Fig. 8). In conclusion, we stress that the current study on the basic features of cylindrical and spherical PASWs may be useful in understanding the behaviors of the various dissipative space plasma environments (viz. star formation, auroral acceleration regions [60, 61], supernovae explosion, cluster explosions, active galactic nuclei, etc.) as well as laboratory plasmas [62–64], where nonthermal distributed electrons and hot positrons, cold mobile viscous positron fluid, and immobile positive ions can be the major plasma species.

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