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Compressive solitons in a moving e-p plasma under the effect of dust grains and an external magnetic field

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Abstract

A theoretical investigation concerning the propagation of compressive solitons in a plasma comprising electrons, positrons, and dust grains is presented by considering the dust grains of either positive charge or negative charge. Using reductive perturbation technique, a relevant Korteweg-deVries (KdV) equation is derived and then solved to obtain the expressions of amplitude and width of the solitons. The magnetic field is found to alter the dispersive property of the plasma, and hence, only the width of the solitons is reduced in the presence of higher magnetic field. Soliton amplitude is found to decrease/increase and the width to increase/decrease for the higher densities of negatively/positively charged dust grains. Moreover, the amplitude of such a soliton remains larger in the case of positively charged dust grains in comparison with the negatively charged dust grains. The effect of electron/positron drift velocities of the charged species is not pronounced on the properties of the compressive solitons. Under the limiting cases, our calculations reduce to the calculations by other investigators. This substantiates the generality of the present analysis.

Keywords: Electron-positron plasma; Dust grains; Drift velocity; Magnetic field

Introduction

The study of wave propagation and solitary structures in electron-positron (e-p) plasmas [1-7] has received a worldwide attention in the realm of plasmas. A large number of analytical and numerical work has been published, exploring the unique physics of these plasmas, including basic wave physics [4], reconnection [8-10], and nonlinear phenomena such as solitons [11,12]. The e-p plasmas are composed of fully ionized particles with the same mass and opposite charges. These pair plasmas have been widely investigated theoretically, owing to their relevance in pulsars, active galactic nuclei, early universe, and inertial confinement fusion (ICF) scheme using ultra-intense lasers [13-16]. Electron-positron pair production and subsequent plasma formation is also possible when the electrons are accelerated to relativistic velocities either by intense laser beams or by a large-amplitude wake field [17-23] generated by intense short laser pulses [24]. The semiconductor plasma, where holes behave like positive charges with a mass equal to that of the electrons, is another example of an e-p-like plasma [25]. The development of high-efficiency techniques for accumulating pure positron plasmas in Penning traps [26,27] now makes laboratory experiments possible to create e-p plasmas. Helander and Ward [28] have shown that positrons can be produced within tokamaks due to collisions of runaway electrons with plasma ions or thermal electrons. It is shown that e-p pair production is expected to occur in post-disruption plasmas in large tokamaks, including JET and JT-60U where up to about 10^{14} positrons may be created in collisions between multi-MeV runaway electrons and thermal particles.

The physics of an e-p pair plasma is quite different from electron-ion plasmas due to the large ion-to-electron mass ratio [29,30]. The pair plasmas at the surface of fast rotating neutron stars and magnetars are held in strong magnetic fields, while superstrong magnetic fields can be created in intense laser-plasma interaction experiments. Therefore, the understanding of collective phenomena in magnetized pair plasmas has been a topic of significant interest [4,5,31-34]. Iwamoto

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[5] has discussed a kinetic description of numerous linear collective modes in a nonrelativistic pair magnetoplasma. Zank and Greaves [4] have presented the linear properties of various electrostatic and electromagnetic modes in an unmagnetized and magnetized pair plasmas, and also considered two-stream instability in an unmagnetized e-p plasma and nonenvelope solitary wave solutions. Lontano et al. [35] have investigated the interaction between arbitrary amplitude electromagnetic (EM) fields and hot e-p plasma. It is found that a nonzero temperature makes the possibility of the existence of nondrifting soliton-like solutions, which do not occur in strictly cold plasma. Stewart and Laing [36] have presented a study of normal modes using a multifluid description. On the other hand, the ion acoustic waves and solitary structures have been studied in different conditions of plasma [37-42].

Astrophysical pair plasmas are often strongly magnetized. Therefore, it would be of particular interest to study soliton evolution in a magnetized pair plasma having dust particulates, which are present in realistic situation and acquire positive or negative charge. To the best of our knowledge, no investigation has been made on the nonlinear propagation of electrostatic waves in such a magnetized e-p plasma in the presence of dust grains. Hence, in the present article, we attempt for the same and show that only the compressive solitons are supported by this plasma.

Basic fluid equations

We consider a magnetized e-p pair plasma, which comprises negatively or positively charged dust grains in addition to the electrons and positrons. The equilibrium charge neutrality condition is given by $n_{p0} = n_{e0} + \alpha Z_d n_{d0}$, where α is + ve for negatively charged dust and –ve for positively charged dust, and n_{p0} (n_{e0}) is the density of positrons (electrons). A static magnetic field $\underset{0}{\vec{B}}(= B_0\hat{z})$ is applied in the z-direction, and the wave is taken to propagate in the (x, z) plane at an angle θ with it.

In order to study the wave and its evolution as a soliton in the present model of magnetized plasma, we use the fluid approach by considering the positron fluid and electron fluid with high frequency wave nature, where the dust grains simply create a background for them. In view of the finite Lorentz force, the basic fluid equations for the magnetized case will be different from the unmagnetized e-p plasma [43], given by

$$\frac{\partial n_j}{\partial t} + \frac{\partial(n_j v_{jx})}{\partial x} + \frac{\partial(n_j v_{jz})}{\partial z} = 0, \tag{1}$$

$$\frac{\partial v_{jx}}{\partial t} + v_{jx}\frac{\partial v_{jx}}{\partial x} + v_{jz}\frac{\partial v_{jx}}{\partial z} \pm S_j\frac{\partial \phi}{\partial x} \mp S_j A v_{jy} + \sigma_j\frac{\partial n_j}{\partial x} = 0, \tag{2}$$

$$\frac{\partial v_{jy}}{\partial t} + v_{jx}\frac{\partial v_{jy}}{\partial x} + v_{jz}\frac{\partial v_{jy}}{\partial z} \pm S_j A v_{jx} = 0, \tag{3}$$

$$\frac{\partial v_{jz}}{\partial t} + v_{jx}\frac{\partial v_{jz}}{\partial x} + v_{jz}\frac{\partial v_{jz}}{\partial z} \pm S_j\frac{\partial \phi}{\partial z} + \sigma_j\frac{\partial n_j}{\partial z} = 0, \tag{4}$$

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} - n_e + n_p + \alpha n_{d0} Z_d = 0, \tag{5}$$

where $j = p$ (e) for the positrons (electrons), $\sigma_j = \sigma\left(\equiv \frac{T_p}{T_e}\right)$ for the case of positron fluid, and 1 for the electron fluid. Furthermore, n_p, n_e, and n_{d0} are the positrons, electrons, and dust densities, respectively; v_{jx}, v_{jy}, and v_{jz} are the x-, y-, and z-components of the positron and electron fluid velocities; and ϕ is the electric potential. All these quantities are normalized as per our earlier work [43] together with $A = B_0(\varepsilon_0/n_{p0}m_p)^{1/2}$ as the ratio of positron cyclotron frequency to positron plasma frequency.

Stretched coordinates, expansion of physical quantities, and Korteweg-deVries solitons

In view of the oblique propagation of the wave, the unit vector $\hat{k}$ in the (x, z) plane requires $\hat{k}\cdot\vec{r} = x\sin\theta + z\cos\theta$. Therefore, the space coordinate x, generally used in the case of unmagnetized plasma [43], should be replaced with $x \sin\theta + z \cos\theta$ in order to retain information of the obliqueness of the wave vector to the magnetic field. Therefore, we introduce the following stretched coordinates:

$$\xi = \varepsilon^{1/2}\left(\hat{k}\cdot\vec{r} - \lambda_0 t\right) = \varepsilon^{1/2}(x\sin\theta + z\cos\theta - \lambda_0 t), \tag{6}$$

$$\eta = \varepsilon^{3/2} t \tag{7}$$

Here, λ_0 is the phase velocity of the wave. In the said reductive perturbation method (RPM), the expansion of densities, velocities, and potential has to be done about their equilibrium position in the form of a small parameter ε, the smallness of which determines the strength of the perturbation. This expansion has to be made in view of the powers of ε in the stretched coordinates such that the effects of nonlinearity and dispersion are balanced, i.e., the stretching (transformation of coordinates to the wave frame of reference) and expansion of dependent quantities (type of oscillations/perturbation) lead to this balance. The higher powers of ε mean that the physical quantity varies more slowly in comparison with the one which carries lower powers of ε. Since the Lorentz force acts in the perpendicular direction of the magnetic field, the variation/perturbation along the transverse directions (x- and y-axes) should be different from the one along the direction of the magnetic field (z-axis). In view of this lengthy description, we expand the densities, fluid velocities, and electric potential in terms of ε by taking into account the oblique incidence of the wave with respect to the magnetic field as follows:

$$n_j = n_{j0} + \varepsilon n_{j1} + \varepsilon^2 n_{j2} + \dots\dots\dots, \tag{8a}$$

$$v_{jx} = v_{jx0} + \varepsilon^{3/2} v_{jx1} + \varepsilon^2 v_{jx2} + \dots\dots\dots, \tag{8b}$$

$$v_{jy} = v_{jy0} + \varepsilon^{3/2} v_{jy1} + \varepsilon^2 v_{jy2} + \dots\dots\dots, \tag{8c}$$

$$v_{jz} = v_{jz0} + \varepsilon v_{jz1} + \varepsilon^2 v_{jz2} + \dots\dots\dots, \tag{8d}$$

$$\phi = \varepsilon \phi_1 + \varepsilon^2 \phi_2 + \dots\dots\dots \tag{8e}$$

Now, the RPM yields the following relations between various first-order quantities

$$v_{pz1} = \frac{\left(\lambda_0 - v_{p\theta}\right)\cos\theta}{\left\{\left(\lambda_0 - v_{p\theta}\right)^2 - \sigma\cos^2\theta\right\}}\phi_1, \tag{9a}$$

$$v_{ez1} = \frac{-\left(\lambda_0 - v_{e\theta}\right)\cos\theta}{\left\{\left(\lambda_0 - v_{e\theta}\right)^2 - \cos^2\theta\right\}}\phi_1, \tag{9b}$$

$$n_{p1} = \frac{\cos^2\theta}{\left\{\left(\lambda_0 - v_{p\theta}\right)^2 - \sigma\cos^2\theta\right\}}\phi_1, \tag{9c}$$

$$n_{e1} = \frac{-n_{e0}\cos^2\theta}{\left\{\left(\lambda_0 - v_{e\theta}\right)^2 - \cos^2\theta\right\}}\phi_1, \tag{9d}$$

$$n_{p1} = n_{e1}, \tag{9e}$$

together with $v_{p\theta} = v_{px0}\sin\theta + v_{pz0}\cos\theta$ and $v_{e\theta} = v_{ex0}\sin\theta + v_{ez0}\cos\theta$. From the above equations, we obtain the following expression for the phase velocity λ_0:

$$\lambda_0 = \frac{v_{e\theta} + n_{e0}v_{p\theta} \pm \left[\left(v_{e\theta} + n_{e0}v_{p\theta}\right)^2 - \left\{v_{e\theta}^2 + n_{e0}v_{p\theta}^2 - (1 + n_{e0}\sigma)\right\}\cos^2\theta\right]^{1/2}}{(1 + n_{e0})}. \tag{10}$$

Just like the previous cases [43], in the said magnetized plasma also, two types of the modes corresponding to plus and minus signs in Equation (10) can be possible.

In the present investigation, we focus only on the right-going wave and derive relevant KdV equation in order to realize the evolution of this wave into soliton. In this regard, the following second-order equations are obtained:

$$\left(-\lambda_0 + v_{j\theta}\right)\frac{\partial n_{p2}}{\partial \xi} + \frac{\partial n_{p2}}{\partial \eta} + \sin\theta\frac{\partial v_{px2}}{\partial \xi} + \cos\theta\frac{\partial v_{pz2}}{\partial \xi} + \cos\theta\frac{\partial}{\partial \xi}\left(n_{p1}v_{pz1}\right) = 0, \tag{11a}$$

$$(-\lambda_0 + v_{e\theta})\frac{\partial n_{e2}}{\partial \xi} + \frac{\partial n_{e2}}{\partial \eta} + n_{e0}\sin\theta\frac{\partial v_{ex2}}{\partial \xi} + n_{e0}\cos\theta\frac{\partial v_{ez2}}{\partial \xi} + \cos\theta\frac{\partial}{\partial \xi}(n_{e1}v_{ez1}) = 0, \tag{11b}$$

$$\left(-\lambda_0 + v_{p\theta}\right)\frac{\partial v_{px2}}{\partial \xi} + \sin\theta\frac{\partial \phi_2}{\partial \xi} + n_{p1}\sin\theta\frac{\partial \phi_1}{\partial \xi} - S_j A n_{p1} v_{py1} + \sigma\sin\theta\frac{\partial n_{p2}}{\partial \xi} = 0, \tag{11c}$$

$$n_{e0}\left(-\lambda_0 + v_{p\theta}\right)\frac{\partial v_{ex2}}{\partial \xi} - n_{e0}\sin\theta\frac{\partial \phi_2}{\partial \xi} - n_{e1}\sin\theta\frac{\partial \phi_1}{\partial \xi} + A n_{e1} v_{ey1} + \sin\theta\frac{\partial n_{e2}}{\partial \xi} = 0, \tag{11d}$$

$$\left(-\lambda_0 + v_{p\theta}\right)\frac{\partial v_{py2}}{\partial \xi} + A n_{p1} v_{px1} = 0, \tag{11e}$$

$$n_{e0}(-\lambda_0 + v_{e\theta})\frac{\partial v_{ey2}}{\partial \xi} - A n_{e1} v_{ex1} = 0, \tag{11f}$$

$$\left(-\lambda_0 + v_{p\theta}\right)\frac{\partial v_{pz2}}{\partial \xi} + \frac{\partial v_{pz1}}{\partial \eta} + v_{pz1}\cos\theta\frac{\partial v_{pz1}}{\partial \xi} + \left(-\lambda_0 + v_{p\theta}\right) \times n_{p1}\frac{\partial v_{pz1}}{\partial \xi}, + \frac{\partial \phi_2}{\partial \xi} + n_{p1}\cos\theta\frac{\partial \phi_1}{\partial \xi} + \sigma\cos\theta\frac{\partial n_{p2}}{\partial \xi} = 0 \tag{11g}$$

$$n_{e0}(-\lambda_0 + v_{e\theta})\frac{\partial v_{ez2}}{\partial \xi} + n_{e0}\frac{\partial v_{pz1}}{\partial \eta} + n_{e0}v_{ez1}\cos\theta\frac{\partial v_{ez1}}{\partial \xi} + (-\lambda_0 + v_{e\theta})n_{e1}\frac{\partial v_{ez1}}{\partial \xi}, - n_{e0}\frac{\partial \phi_2}{\partial \xi} - n_{e1}\cos\theta\frac{\partial \phi_1}{\partial \xi} + \cos\theta\frac{\partial n_{e2}}{\partial \xi} = 0 \tag{11h}$$

$$\left(-\lambda_0 + v_{p\theta}\right)\frac{\partial v_{px1}}{\partial \xi} - A v_{py2} = 0, \tag{11i}$$

$$(-\lambda_0 + v_{e\theta})\frac{\partial v_{ex1}}{\partial \xi} + A v_{ey2} = 0, \tag{11j}$$

$$\left(-\lambda_0 + v_{p\theta}\right)\frac{\partial v_{py1}}{\partial \xi} + A v_{px2} = 0, \tag{11k}$$

$$(-\lambda_0 + v_{e\theta})\frac{\partial v_{ey1}}{\partial \xi} - A v_{ex2} = 0. \tag{11l}$$

Now, all the second-order quantities n_{p2}, n_{e2}, v_{px2}, v_{pz2}, v_{py2}, v_{ex2}, v_{ez2}, v_{ey2}, and ϕ_2 appearing in Equations (11a) (11l) are eliminated using the phase velocity relation (10). Finally, one obtains the following KdV equation in the firs-order perturbed density n_{p1}, where the coefficients of nonlinearity and dispersion are taken as $\alpha_N = \frac{\left\{\left(\lambda_0 - v_{p\theta}\right)^2 - \sigma\cos^2\theta\right\}L}{K\cos^2\theta}$ and $\beta_D = M/K$, together with

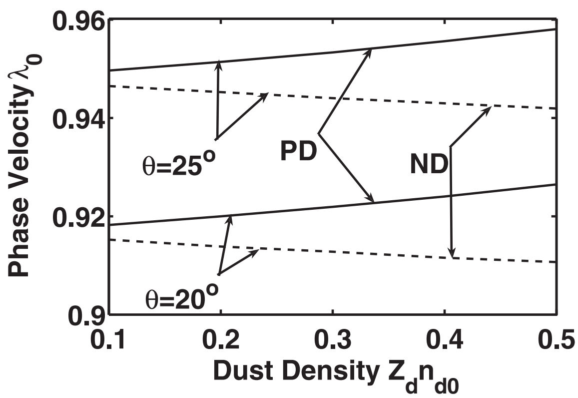

Figure 1 Variation of the phase velocity with dust density $Z_d n_{d0}$ at $\theta = 20°$ and $\theta = 25°$. Dashed lines show the presence of negative dust, and solid lines show the presence of positive dust. Other parameters are $\sigma = 0.9$, $v_{px0} = v_{py0} = v_{pz0} = 0.02$, $v_{ex0} = v_{ey0} = v_{ez0} = 0.03$ and $B_0 = 0.05$.

$$K = 2\cos^2\theta\left[\frac{(\lambda_0 - v_{p\theta})}{\left\{(\lambda_0 - v_{p\theta})^2 - \sigma\cos^2\theta\right\}^2} + \frac{(\lambda_0 - v_{e\theta})n_{e0}}{\left\{(\lambda_0 - v_{e\theta})^2 - \cos^2\theta\right\}^2}\right],$$

$$L = \cos^4\theta\left[\frac{\left\{3(\lambda_0 - v_{p\theta})^2 - \sigma\cos^2\theta\right\}}{\left\{(\lambda_0 - v_{p\theta})^2 - \sigma\cos^2\theta\right\}^3} - \frac{\left\{3(\lambda_0 - v_{e\theta})^2 - \sigma_e\cos^2\theta\right\}n_{e0}}{\left\{(\lambda_0 - v_{e\theta})^2 - \cos^2\theta\right\}^3}\right], \text{ and}$$

$$M = 1 + \frac{\sin^2\theta}{A^2}\left[\frac{(\lambda_0 - v_{p\theta})^4}{\left\{(\lambda_0 - v_{p\theta})^2 - \sigma\cos^2\theta\right\}^3} + \frac{n_{e0}(\lambda_0 - v_{e\theta})^4}{\left\{(\lambda_0 - v_{e\theta})^2 - \cos^2\theta\right\}^3}\right].$$

$$\frac{\partial n_{p1}}{\partial \eta} + \alpha_N n_{p1}\frac{\partial n_{p1}}{\partial \xi} + \beta_D\frac{\partial^3 n_{p1}}{\partial \xi^3} = 0. \qquad (12)$$

If we transform the coordinates to $X = \xi - U\eta$ (where U is the constant velocity shift) and integrate the KdV equation considering that n_{p1} and its derivatives vanish at large distances ($|X| \to \infty$), we find the following soliton solution:

$$n_{p1} = n_{pm}\,\mathrm{sech}^2\left(\frac{X}{W}\right), \qquad (13)$$

where the peak soliton amplitude is $n_{pm} = \frac{3U}{\alpha_N}$, and the soliton width is $W = \sqrt{\frac{4\beta_D}{U}}$.

Results on phase velocity and compressive solitons

Figure 1 shows the variation of the phase velocity with the density of the positive dust (PD) and negative dust (ND) grains. The effect of propagation angle θ on the phase velocity is also shown in this figure. It is noticed that the phase velocity decreases with the increase in the density of negatively charged dust grains but oppositely this increases with the increasing density of positively charged dust grains. It is further found that the presence of magnetic field also affects the wave properties and the phase velocity increases with the enhancement in the wave propagation angle. The enhancement in the phase velocity in the presence of magnetic field is attributed to the additional frequency of oscillations, i.e., the cyclotron frequency.

In order to analyze the nature of the solitons, we perform numerical calculations and find that the solitons evolve in the form of density hill, i.e., only compressive solitons exist in this plasma. This is true for both the cases of positively and negatively charged dust grains. This is a new result, as in the plasmas having electrons, positive ions, and negative ions, rarefactive solitons are also possible. The suppression of rarefactive solitons in the present e-p uniform magnetized plasma is due to the stationary dust grains. In order to further explore this investigation, we have prepared Table 1. The table shows that the nonlinearity coefficient α_N never vanishes for the different values of dust grains, drift velocities, and temperatures of the present plasma support only compressive solitons. In the present case, the KdV approach fails only when $\sigma = 1$ and $v_{p0} = v_{e0}$ because in this case,

Table 1 Effect of different plasma parameters on the nonlinearity coefficient α_N

	$\alpha_N(\sigma < 1)$				$\alpha_N(\sigma = 1)$		$\alpha_N(\sigma > 1)$	
					$v_{p0} = 0.28$		$v_{p0} = 0.28$	
	ND		PD		ND	PD	ND	PD
$z_d n_{d0}$	$v_{p0} = 0.14$	$v_{p0} = 0.28$	$v_{p0} = 0.14$	$v_{p0} = 0.28$				
0	0.7483	0.7564	0.7483	0.7564	0.7756	0.7756	0.8125	0.8125
0.1	0.8002	0.8204	0.7092	0.7073	0.8406	0.7256	0.8798	0.7609
0.2	0.8704	0.9049	0.6793	0.6689	0.9267	0.9267	0.9688	0.7208
0.3	0.9675	1.0194	0.6562	0.6388	1.0432	0.656	1.0893	0.6894
0.4	1.1062	1.1792	0.6382	0.6148	1.2057	0.6318	1.257	0.6646
0.5	1.3133	1.412	0.6302	0.5957	1.4421	0.6125	1.5004	0.645

the coefficient α_N does become indeterminate, similar to the case of uniform plasma [43]. This is further noticed that the nonlinearity coefficient does not vary significantly with the higher values of drift velocities of electrons and positrons. Therefore, peak soliton amplitude does not significantly change with the drift velocities.

In Figure 2, we have plotted the soliton profile against the positively charged dust grains density, where the soliton amplitude is found to increase with the increase in the dust density. As per basic characteristics of the soliton, the soliton width shows its opposite trend with the density. On the other hand, in Figure 3, we study the soliton profile against the negatively charged dust grains. It is noticed that the soliton amplitude decreases, but the width increases with the increase of concentration of negative dust. So, the soliton amplitude and width show their opposite trend with the positively and negatively charged dust density. This opposite trend is also observed in the variation of the phase velocity (shown in Figure 1) with the negative and positive dust grains. This shows a general picture of the behavior of solitons, phase velocity, amplitude and width. Similar to our result, Choi et al. [44] have noticed the reduced soliton amplitude and enhanced width with the increasing concentration of negatively charged dust grains in a magnetized dusty plasma. However, in the case of Tiwari and Mishra [45], the amplitude and width of the soliton were found to increase with the increasing concentration of negatively charged dust grains n_{d0} and charge number Z_d in a collisionless unmagnetized plasma consisting of hot isothermal electrons and cold ions. The reduction in the soliton amplitude with negative dust concentration is also opposite to the behavior of the solitons in a plasma having trapped electrons and dust grains [46], and to the result obtained in an experiment on the dusty plasma without trapped electrons [47].

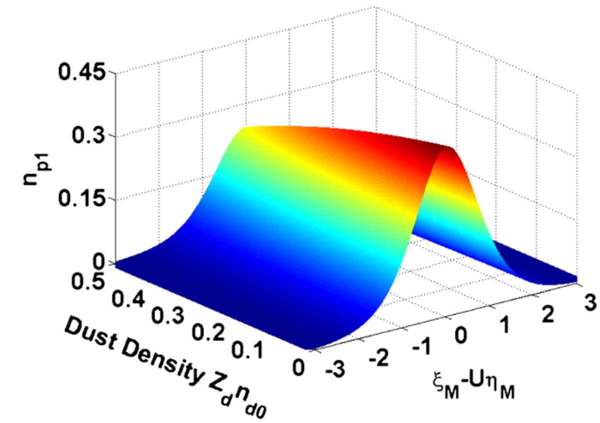

Figure 3 Solitary structure showing the effect of density of negatively charged dust grains $Z_d n_{d0}$. For the parameters $\sigma = 0.9$, $U = 0.1$, $v_{px0} = v_{py0} = v_{pz0} = 0.02$, $v_{ex0} = v_{ey0} = v_{ez0} = 0.03$, $B_0 = 0.05$ and $\theta = 40°$.

In Figure 4, we have plotted the solitary structure with the positron-to-electron temperature ratio. Here, the soliton amplitude decreases, but the soliton width is enhanced with the increasing temperature ratio. If we discuss the limiting cases of zero drift and zero magnetic field, as discussed by Esfandyari-Kalejahi et al. [48], we observe the similar effect of temperature ratio. However, in the present case of moving plasma in the presence of magnetic field, the reduction in the amplitude with σ or positron temperature is contrary to the observation

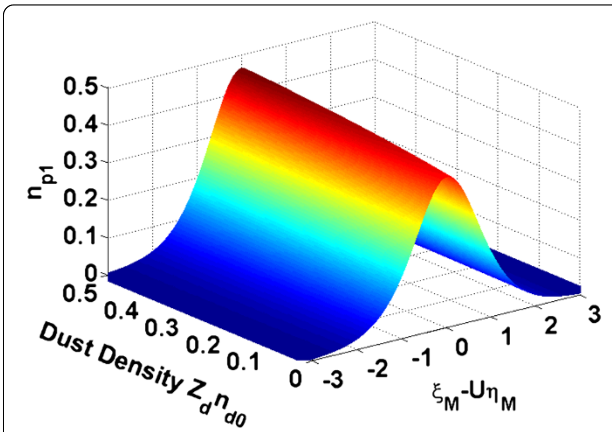

Figure 2 Solitary structure showing the effect of density of positively charged dust grains $Z_d n_{d0}$. For the parameters $\sigma = 0.9$, $U = 0.1$, $v_{px0} = v_{py0} = v_{pz0} = 0.02$, $v_{ex0} = v_{ey0} = v_{ez0} = 0.03$, $B_0 = 0.05$ and $\theta = 40°$.

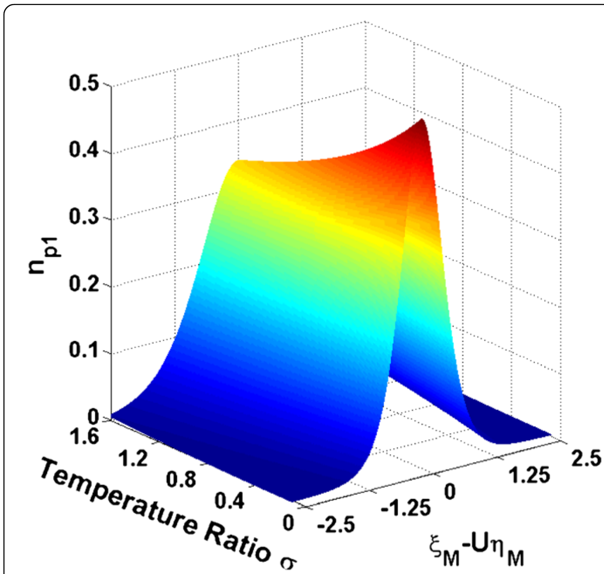

Figure 4 Solitary structure showing the effect of temperature ratio σ in the presence of negative dust. For the parameters $U = 0.1$, $v_{px0} = v_{py0} = v_{pz0} = 0.02$, $v_{ex0} = v_{ey0} = v_{ez0} = 0.03$, $B_0 = 0.05$, $\theta = 40°$ and $Z_d n_{d0} = 0.02$.

made by Moslem [49] in an e-p plasma and by Mahmood and Ur-Rehman [50] in an unmagnetized hot electron-positron-ion (e-p-i) plasma, but the enhancement in the width is the similar result as obtained by them [49,50]. Tiwari et al. [51] have noticed that for the higher temperature ratio σ, the amplitude as well as width of the KdV and dressed solitons decreases in collisionless, unmagnetized plasma consisting of hot electrons, positrons, and singly charged cold positive ions.

The effect of magnetic field B_0 on the soliton propagation is seen through the term $A = B_0(\varepsilon_0/n_{p0}m_p)^{1/2}$. In Figure 5, we have plotted the soliton width variation with the magnetic field. The width is found to reduce continuously with the increase of the magnetic field, which means the soliton gets narrower in the presence of stronger magnetic field. Moreover, the reduction in the soliton width is at a faster rate under the effect of weaker magnetic field, and the width does not alter much in the presence of higher magnetic field. This result is similar to other investigations made in homogeneous and inhomogeneous magnetized plasmas [52,53]. Hence, it is understood that the dispersive property of the e-p plasma shows the similar behavior as in e-i plasmas. However, the soliton amplitude does not vary with the magnetic field, which has also been observed by El-Labany and El-Shamy [54] for solitary waves in a hot magnetized dusty plasma and by Mishra et al. [52] in a negative ion containing uniform plasma. On the other hand, the amplitude of the soliton increases with the larger value of wave propagation angle (shown in Figure 6). Moreover, it is also noticed that the amplitude of such solitons remain larger in the case of positively charged dust grains in comparison with negatively charged dust grains.

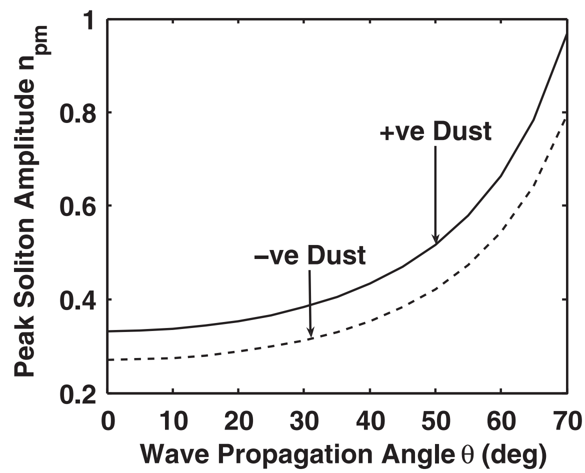

Figure 6 Variation in the peak soliton amplitude with wave propagation angle θ. In the presence of negative dust (dashed line) and positive dust (solid line) when $\sigma = 0.9$, $U = 0.1$, $v_{px0} = v_{py0} = v_{pz0} = 0.02$, $v_{ex0} = v_{ey0} = v_{ez0} = 0.03$ and $Z_d n_{d0} = 0.02$.

Figure 7 shows the variation of solitary structure with the electron drift velocity, where both the soliton amplitude and width are found to decrease very slowly with the enhanced electron drift velocity. Similar effect of the positron drift velocity is seen on the solitary structures (figure is not shown). So, we can say that the drift velocities of both the species have very insignificant effect on the solitary structures. This is attributed to the weak dependence of nonlinear properties of plasma on the drift velocities (Table 1). However, in the case of an unmagnetized e-p plasma [43], the drift velocities had drastically modified the solitary structures by reducing the soliton width. It means that the contribution of initial drift to the soliton evolution stays a little in the presence of magnetic field.

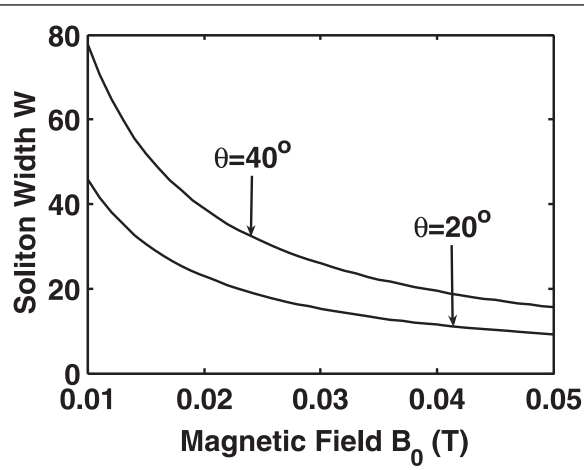

Figure 5 Variation in the soliton width with magnetic field B_0 in the presence of negative dust. For the different values of θ and when $\sigma = 0.9$, $U = 0.1$, $v_{px0} = v_{py0} = v_{pz0} = 0.02$, $v_{ex0} = v_{ey0} = v_{ez0} = 0.03$ and $Z_d n_{d0} = 0.02$.

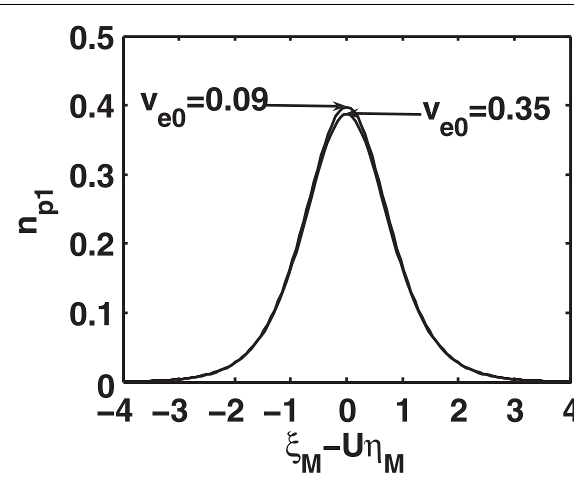

Figure 7 Solitary structure showing the weak effect of electron drift $v_{e0} = \sqrt{v_{ex0}^2 + v_{ez0}^2}$ in the presence of negative dust. For the parameters $U = 0.1$, $v_{px0} = v_{py0} = v_{pz0} = 0.03$, $B_0 = 0.05$, $\theta = 40°$ and $Z_d n_{d0} = 0.02$.

With regard to the generalization of our calculations, we say that the phase velocity relation and the KdV equation exactly match with the equations obtained by Malik et al. [43] in the absence of the magnetic field, i.e., under the limiting case of $\theta = 0$. Further, if the initial drift velocity and magnetic field are neglected, the phase velocity relation and the KdV equation take the form of respective equations of Esfandyari-Kalejahi et al. [48].

Summary of new results and the physics behind them

In the present article, we have studied the evolution of solitons in a homogeneous and magnetized e-p plasma that has dust grains. Our main focus has been on the contribution of dust grains to the soliton propagation characteristics. The distinct features of our work can be summarized as follows:

(1) We have studied the soliton evolution and its propagation in a homogeneous plasma and discussed the effect of magnetic field. However, Malik et al. [43] had focused on the effect of dust grains and did not consider magnetic field.
(2) In the present work, we have solved the problem with oblique propagation of the wave; it means that our calculations are more general.
(3) We have studied in detail the behavior of phase velocity variation with the dust grains (both positively and negatively charged). However, Malik et al. [43] had investigated only the case of negatively charged dust grains.
(4) In the present model, only the compressive solitons are possible in the plasma. However, in [43], rarefactive solitons were also observed for higher-order nonlinearity.
(5) The negatively and positively charged dust grains in the plasma are found to indulge opposite effects on the soliton propagation characteristics. The variation of the soliton amplitude with positive and negative dust grains is in accordance with the phase velocity variation with the dust grains.
(6) The magnetic field does not affect the soliton amplitude, and it only alters the soliton width.
(7) The effect of positron-to-electron temperature ratio was found to reduce the amplitude but enhance the width of the solitary structures.
(8) The effect of drift velocities of the electrons and positrons on the soliton structure in the present case is insignificant, whereas the drifts had drastically modified the soliton structure in [43] in the absence of magnetic field.

The enhancement in the phase velocity with the higher density of positive dust grains is attributed to the reduced density of positrons and increased density of electrons in view of the charge neutrality condition. Then, the larger force of attraction between the dust grains and electrons leads the oscillating species to make smaller excursions about their equilibrium position. This causes the enhanced frequency of oscillations and hence the larger phase velocity. Consequently, the solitons evolve with their higher amplitudes for the constant velocity shift U. On the other hand, the Lorentz force in the situation of larger wave propagation angle becomes stronger that adds to the restoring force and leads to higher frequency of oscillations. So, larger phase velocity and hence the enhanced soliton amplitude is realized under the effect of larger wave propagation angle. The effect of positron-to-electron temperature ratio is to reduce the soliton amplitude due to the reduced frequency of oscillations and the phase velocity under the effect of their higher thermal motions. The effect of positively and negatively charged dust grains is opposite on the soliton propagation due to the opposite variation of coefficient of nonlinearity (Table 1) with the dust density. Hence, in one case, the nonlinearity of the plasma is stronger, and in the other case, it is weaker.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

RM carried out all the mathematical calculations and wrote the manuscript in suggestion of HKM. The manuscript was finalized by HKM. Both authors read and approved the final manuscript.

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RM was born in Muzaffarnagar, India, on May 10, 1983. After receiving her M. Sc. degree in Physics in 2005, she received the M. Phil degree in Physics from CCS University, Meerut, India in 2007. She received her Ph.D. degree in Plasma Physics from the Indian Institute of Technology Delhi, India in 2013. She is currently a research associate in the CSIR Project at IIT Delhi, India. HKM received his doctoral degree in Plasma Physics from the Indian Institute of Technology (IIT) Delhi, India in the year 1995 at the age of 24 and half. He has been working as an Associate Professor in the Department of Physics of IIT Delhi. His fields of research are nonlinear solitary waves, instabilities, Hall thrusters, terahertz radiation generation, microwave and plasma interaction, particle acceleration, and plasma-material interaction. So far, he has guided 11 doctoral theses along with more than 40 UG and PG theses. He has published more than 100 articles in international journals of repute and is on the Editorial Board of The Open Plasma Physics Journal (Bentham Open, USA), Journal of Physics, Astrophysics, and Physical Cosmology (SJI, USA), and the Journal of Theoretical and Applied Physics (Springer). He has written a book entitled "Engineering Physics" for the UG students, which was published from McGraw Hill and has been received very well all over the world. His chapter entitled "Electromagnetic Waves and Their Application to Charged Particle Acceleration" published in Wave Propagation (Book 2), INTECH Open Science, Croatia is also one of the works which has been appreciated much.

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