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Numerical Analysis of Nonlinear Electron Acoustic Lump Solitons in a Homogeneous, Unmagnetized, Collision less Plasma

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Electron-acoustic waves in a homogeneous, unmagnetized, collision less plasma composed of inertial cold electrons, ϰ-distributed hot electrons, and stationary ions are investigated. Starting from the fluid equations coupled with Poisson's equation, the reductive perturbation method is systematically applied with appropriate stretched coordinates to derive a two-dimensional Kadomtsev–Petviashvili (KP) equation governing the weakly nonlinear evolution of electron-acoustic perturbations, including weak transverse effects. The nonlinear and dispersive coefficients of the KP equation are obtained explicitly in terms of the plasma density ratio and the super thermality index ϰ. Exact lump soliton solutions are then constructed using a rational-function approach, yielding fully localized two-dimensional structures that decay algebraically in space. Parametric analysis shows that ϰ significantly influences the amplitude and localization of the lump solitons; lower ϰ values enhance nonlinearity and produce higher, more localized structures, whereas larger ϰ leads to broader and weaker excitations. These results clarify the role of super thermal electrons in multidimensional nonlinear wave dynamics.

Keywords: Electron Acoustic Waves; KP Equation; Kappa Distribution; Lump Solitons; Numerical Analysis

Introduction:

Electron-acoustic waves (EAWs) are high-frequency electrostatic waves that propagate in a plasma with two different electron species: that provide inertia for the waves and that provide the restoring force, with the ions playing the role of the neutralizing background. The phase velocity of EAWs usually falls within the range of the thermal velocities of the cold and hot electrons, making EAWs applicable to a wide range of space and laboratory plasmas where two-temperature electrons are commonly found. Such waves have been reported in the Earth's magnetosphere, auroral regions, magneto sheath, planetary magnetospheres, and laboratory experiments, and are believed to play an important role in broadband electrostatic noise and solitary structure formation [1][2][3][4][5].

Observations from satellites such as FAST**,** Freja**,** Viking**,** Geotail**,** and Cassini have revealed that electron velocity distributions in space plasmas often deviate significantly from the Maxwellian form. These distributions commonly exhibit enhanced suprasternal tails, which are well described by the ϰ-distribution function. The ϰ-distribution reduces to the Maxwellian distribution in the limit $\varkappa \rightarrow \infty$ and has been widely used to model nonequilibrium features in space and astrophysical plasmas, including the solar wind, magnetospheres of Earth and other planets, and the heliospheric plasma sheet [6][7][8][9][10].

The linear and nonlinear properties of electron-acoustic waves in ϰ-distributed plasmas have been extensively investigated. Previous studies have shown that the spectral index ϰ strongly influences the dispersion, damping, amplitude, and polarity of electron-acoustic solitary waves [11][12][13][14][15]. In particular, ϰ-distributed electrons are ϰnown to modify the nonlinearity and dispersion coefficients of the governing evolution equations, thereby altering the existence conditions and characteristics of nonlinear structures. Most of these investigations, however, have been limited to one-dimensional geometries, where the nonlinear evolution is described by the Korteweg–de Vries (KdV) equation.

In a realistic plasma environment, the propagation of waves is inherently multidimensional. To address the effects of wave transverse perturbations, the Kadomtsev-Petviashvili (KP) equation is the natural generalization of the KdV equation. The KP equation has been successfully used to investigate nonlinear wave propagation in two dimensions in plasmas, fluids, and nonlinear optics [16][17][18]. Unlike the KdV equation, the KP framework has a much richer variety of nonlinear wave solutions, such as line solitons, breathers, rational solutions, and lump solitons.

Lump solitons are localized, non-singular, and two-dimensional, with power-law decay in all directions in the spatial domain. These types of solutions are interesting because they represent isolated energy concentrations, which are often associated with extreme wave phenomena, such as rogue waves, in nonlinear wave mechanics [19][20][21]. Lump soliton solutions to the problem of electron-acoustic waves in ϰ-distributed plasmas have not been adequately addressed, especially within the context of the KP framework.

Motivated by these considerations, the present worϰ investigates the nonlinear propagation of electron-acoustic waves in a collisionless, unmagnetized plasma consisting of cold electrons and hot electrons obeying a ϰ-distribution. By employing the reductive perturbation method, a Kadomtsev–Petviashvili (KP) equation governing the weaϰly nonlinear evolution of electron-acoustic waves is derived. Exact lump soliton solutions are then constructed, and the effects of the superthermal parameter ϰ on the amplitude, width, localization, and stability of the lump structures are examined in detail. The results provide new insights into the role of suprathermal electrons in shaping multidimensional nonlinear structures in space and laboratory plasmas.

Material and Methods:

Now we solve the KP equation and use the fluid model**.** The characteristics of EA solitons with modest amplitude under reductive perturbations in a plasma with impurities and two-temperature electrons following a Vasyliunas distribution are reported. The KP, modified KP, and coupled KP equations are developed using a reductive perturbation approach. In addition, a variety of equations are solved with a focus on single-variable transformations in order to examine the impact of different plasma parameters and higher-order effects on the properties of EA solitons. The parametric range for the presence of positive and negative potential solitons is also found from the nonlinear coefficient of the KP equation. Additionally, the discussion includes the stability analysis of the KP equation's soliton solution. It is noted that the properties of all kinds of tiny amplitude EA solitons are greatly influenced by all distinct physical factors. The study of nonlinear electron-acoustic waves (EAWs) is conducted in a plasma consisting of cold and hot dynamic electrons (non-Maxwellian) and accompanied by background ions.

$$\frac{\partial n}{\partial t} + \left(\frac{\partial n}{\partial x}V_x + \frac{\partial n}{\partial y}V_y\right) = 0 \quad (3)$$

$$\frac{\partial}{\partial t}V_x + \left(\frac{\partial}{\partial x}V_x + \frac{\partial}{\partial y}V_y\right)V_x = \alpha\frac{\partial \varphi}{\partial x} \quad (4)$$

$$\frac{\partial}{\partial t}V_y + \left(\frac{\partial}{\partial x}V_x + V_y\frac{\partial}{\partial y}\right)V_y = \alpha\frac{\partial \varphi}{\partial y} \quad (5)$$

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\varphi = \left(\frac{1}{\alpha}n_i + n_h - \left(1 + \frac{1}{\alpha}\right)\right) \quad (6)$$

Where the Kappa distribution function was a useful choice for explaining the creation of suprathermal tails in distributions [22].

The symbol f represents the Kappa distribution's generic form,

$$f_\kappa(v) = \frac{n_0}{\pi^{\frac{3}{2}}\theta^3}\frac{\Gamma(\kappa+1)}{\kappa^{3/2}\Gamma\left(\kappa-\frac{1}{2}\right)}\left(1 + \frac{1}{\alpha\,\kappa}\left\{\frac{mv^2-2e\varphi}{2KT_e}\right\}\right)^{-\kappa} \quad (6.a)$$

$$\alpha = \frac{(\kappa-3/2)}{\kappa},\ \theta = \sqrt{\frac{(2\kappa-3)}{2\kappa}\frac{2KT_e}{m_e}} \quad (6.b)$$

θ is the modified thermal velocity, and $\varkappa$ is the spectral index representing the strength of the high-energy particles, with the condition $\varkappa > 3/2$.

Integrating the kappa distribution function (6.a) over all velocity spaces, we get the following number density of hot electrons.

$$n_h = n_0\left(1 + A\frac{e\phi}{T_e} + B\frac{e\phi}{T_e} + \cdots\right) \quad (6.c)$$

Where A and B are nonthermal coefficients of the kappa distribution, which are given below

$$A = \frac{\kappa-1/2}{\kappa-3/2},\qquad B = \frac{(\kappa-1/2)(\kappa+1/2)}{2\,(\kappa-3/2)^2} \quad (6.d)$$

Table 1. Physical Meaning of Key Plasma Parameters

Parameter	Description	Physical Meaning	Role in the Model
α	Hot-to-cold electron density ratio	α = n_h0 / n_c0	Controls restoring force contribution and affects nonlinearity
ϰ	Super thermality (spectral) index	Measures deviation from the Maxwellian distribution	Lower ϰ enhances suprathermal effects and modifies dispersion
u	Phase velocity of a nonlinear structure	Propagation speed of soliton/lump	Determines amplitude, width, and stability characteristics

Were,

α denotes the ratio between hot and cold electrons

n_c is the cold electron density

V_x is the cold electron fluid velocity in the x- direction.

V_y is the cold electron fluid velocity in the y-direction.

φ represents electric potential.

x shows the space coordinate.
It tells about the time variable.
The stretched coordinates are;

$$\xi = \epsilon^{\frac{1}{2}} (X - V_0 t)\,; \tau = \epsilon^{\frac{3}{2}}\, t\,; \eta = \epsilon\, y \quad (7)$$

Using the reductive perturbation method, n_c, V_x and φ in perturbed form can be written as

$$\left.\begin{aligned} n_c &= 1 + \epsilon\, n_{c1} + \epsilon^2\, n_{c2} \\ V_x &= \epsilon\, V_{x1} + \epsilon^2\, V_{x2} \\ V_y &= \epsilon^{\frac{3}{2}}\, V_{y1} + \epsilon^{\frac{5}{2}}\, V_{y2} \\ \varphi &= \epsilon\, \varphi_1 + \epsilon^2\, \varphi_2 \end{aligned}\right\} \quad (8)$$

By applying stretched coordinates and expansions to equation (3.1), we get these values for the lower order of ϵ

$$-V_0 n_c 1 = V_{x1} \quad (9)$$

$$-V_0 V_{x1} = \alpha\varphi_1 \quad (10)$$

$$A = \frac{1}{V_0^2} \quad (11)$$

For the next higher order of ϵ, some algebraic manipulations yield

$$\frac{\partial n_c 1}{\partial T} - V_0 \frac{\partial n_{c2}}{\partial \xi} + \frac{\partial V_{x2}}{\partial \xi} + \frac{\partial n_c 1 V_x 1}{\partial \xi} + \frac{\partial V_{y1}}{\partial \eta} = 0 \quad (12)$$

$$\frac{\partial V_{x1}}{\partial T} - V_0 \frac{\partial V_{x2}}{\partial \xi} + V_{x1} \frac{\partial}{\partial \xi} V_{x1} = \alpha \frac{\partial}{\partial \xi} \varphi_2 \quad (13)$$

$$\frac{\partial^2 \varphi_1}{\partial \xi^2} = \frac{1}{\alpha} n_{c2} + A\varphi_2 + B{\varphi_1}^2 \quad (14)$$

The algebraic manipulation of the above equations leads to the following KP equation for the EAWs with the Kappa distribution:

$$\frac{\partial}{\partial \xi}\left[\frac{\partial}{\partial T}\varphi_1 + S\frac{\partial}{\partial \xi}\varphi_1^2 + Q\frac{\partial^3 \varphi_1}{\partial \xi^3}\right] + R\frac{\partial^2 \varphi_1}{\partial \eta^2} = 0 \quad (13)$$

Were,
&

$$S = -\frac{1}{2}\left[\frac{3\alpha}{2V_0} + {V_0}^3 B\right]$$

$$Q = \frac{{V_0}^3}{2}$$

$$R = \frac{V_0}{2}$$

Result and Discussion: Here, we plotted the numerical solution of the electron acoustic KP eq.

$$\phi = \frac{3(u-R)}{S}\,\mathrm{Sech}\left[\frac{\xi}{\Delta}\right]^2 \quad (14)$$

Were

$$\Delta = \sqrt{\frac{4Q}{u-R}}$$

This figure displays the profiles of electron-acoustic dip-type solitons for varying values of the hot-to-cold electron density ratio α (0.1 in red, 0.2 in green, and 0.3 in black), with the super thermality index fixed at ϰ = 2 and the soliton velocity u = 0.3. As α increases, the amplitude of the rarefactive solitons decreases while the width broadens slightly, indicating that a higher proportion of hot electrons weakens the nonlinearity and leads to less localized structures. The dip-shaped nature of the solitons confirms the existence of negative-potential electron-acoustic excitations under these plasma conditions.

The figure illustrates electron-acoustic dip-type solitons for the same range of hot-to-cold electron density ratios α (0.1 in red, 0.2 in green, and 0.3 in black) but with the super thermality index increased to ϰ = 3 and soliton velocity u = 0.3. Compared with Figure 1, the solitons exhibit reduced amplitudes and broader spatial extents as α increases, demonstrating that stronger super thermality (higher ϰ) further suppresses nonlinearity and produces weaker, more extended excitations. The consistent dip polarity highlights the robustness of rarefactive electron-acoustic structures across moderate changes in the spectral index.

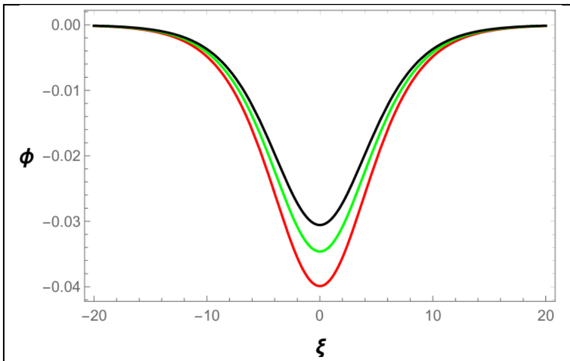

Figure 1. Electron acoustic dip type solitons for different value of α (0.1red,0.2 green and 0.3 black) while ϰ=2 and u=0.3

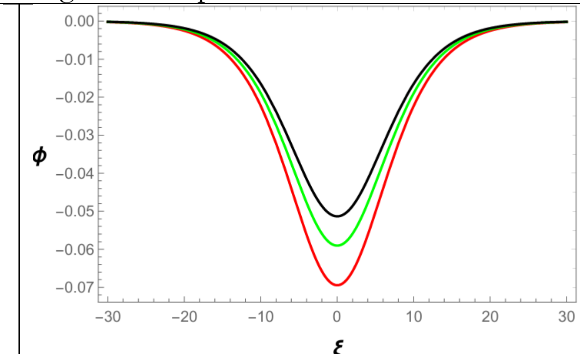

Figure 2. Electron acoustic dip type solitons for different value of α (0.1red,0.2 green and 0.3 black) while ϰ=3 and u=0.3

This figure shows electron-acoustic dip-type solitons for different values of the density ratio α (0.1 in red, 0.2 in green, and 0.3 in black) at a lower super thermality index ϰ = 1.65 and soliton velocity u = 0.3. At this stronger super thermality (lower ϰ), increasing α leads to a noticeable reduction in soliton amplitude and a moderate increase in width. The figure emphasizes that highly non-Maxwellian electron distributions (smaller ϰ) enhance the nonlinear character of the waves, resulting in taller and more localized rarefactive solitons than those observed at higher ϰ values.

The figure presents electron-acoustic dip-type solitons for different values of the super thermality index ϰ (1.55 in red, 1.60 in green, and 1.65 in black), with the density ratio α and soliton velocity u held fixed. As ϰ increases (i.e., the distribution approaches Maxwellian behavior), the soliton amplitude decreases while the width increases, indicating that stronger super thermality produces more pronounced nonlinear effects and tighter localization. This parametric study clearly demonstrates the critical role of the spectral index ϰ in controlling the strength and spatial extent of electron-acoustic solitary structures.

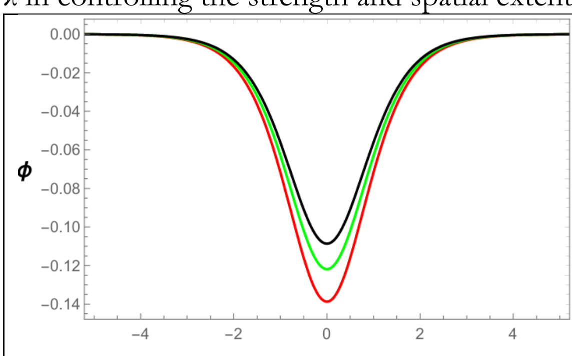

Figure 3. Electron acoustic dip type solitons for different value of α (0.1red,0.2 green and 0.3 black) while ϰ=1.65 and u=0.3

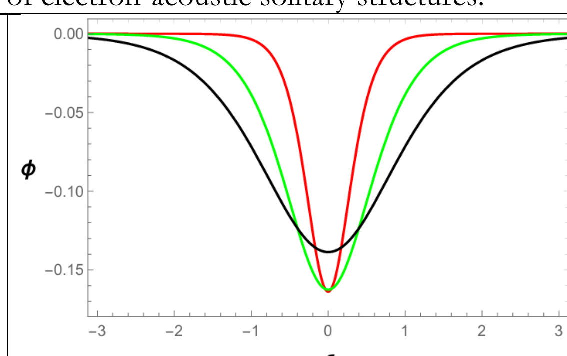

Figure 4. Electron acoustic dip type solitons for different values of k (1.55red,1.60 green, and 1.65 black) while αand u are fixed.

This figure depicts electron-acoustic dip-type solitons for different soliton velocities u (0.25 in red, 0.35 in green, and 0.45 in black) with fixed α = 0.1 and ϰ = 1.65. As the propagation velocity u increases, both the amplitude and the steepness of the rarefactive solitons increase, while the width narrows. The result illustrates that faster-moving electron-acoustic structures become more nonlinear and localized, consistent with the expected behavior of solitons in dispersive media where higher speeds enhance the balance between nonlinearity and dispersion.

The figure shows electron-acoustic dip-type solitons for varying soliton velocities u (0.30 in red, 0.35 in green, and 0.45 in black) at fixed α = 0.1 and ϰ = 2. Similar to Figure 5, increasing u leads to higher amplitudes and narrower soliton profiles. The comparison at this moderate super thermality (ϰ = 2) highlights that the velocity dependence remains strong even as the electron distribution becomes less non-Maxwellian, confirming the robustness of the nonlinear wave steepening effect across different ϰ values.

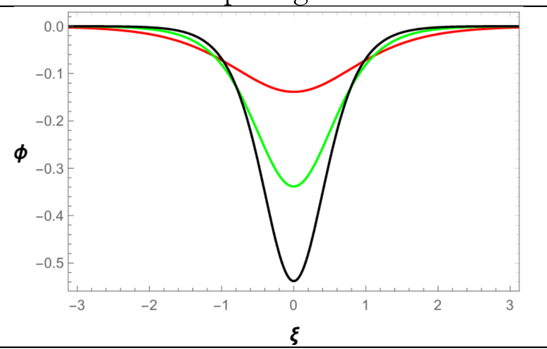

Figure 5. Electron acoustic dip type solitons for different values of u (0.25red,0.35 green, and 0.45 black) while α=.1and ϰ=1.65.

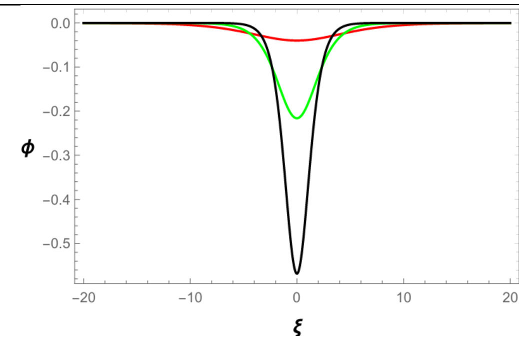

Figure 6. Electron acoustic dip type solitons for different values of u (0.30red,0.35 green, and 0.45 black) while α=.1 and ϰ=2.

This figure illustrates electron-acoustic dip-type solitons for different soliton velocities u (0.40 in red, 0.45 in green, and 0.50 in black) with fixed α = 0.1 and ϰ = 3. As u increases, the soliton amplitude grows while the width decreases, although the overall structures are broader and weaker than those observed at lower ϰ values. The figure demonstrates that even in near-Maxwellian regimes (higher ϰ), faster propagation speeds still enhance nonlinearity, albeit with reduced localization compared to strongly super thermal cases.

The figure displays fully localized two-dimensional lump soliton profiles for different values of the density ratio α while keeping other parameters fixed. The lump structures decay algebraically in both spatial directions, confirming their fully two-dimensional and non-singular nature. As α increases, the amplitude of the lump's decreases, indicating that a higher hot-electron population weakens the nonlinearity and produces less intense, more extended localized excitations in the transverse plane.

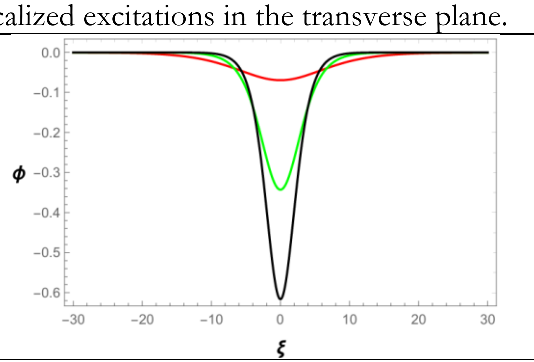

Figure 7. Electron acoustic dip type solitons for different values of u (0.40 red,0.45 green, and 0.5 black) while α=.1 and ϰ=3

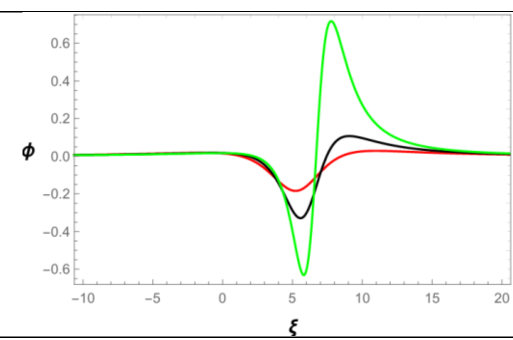

Figure 8. Lump solitons for different values of $t(1 \text{red}, 3 \text{ black and } 4.5 \text{ green})$ while $x = 5, \alpha = 0.2$ and $\kappa = 2$.

Results and Discussion:

Figure 1 is plotted for density ratio α, which is the ratio of hot to cold electrons, it is observed that increasing α leads to the value of α, the width and amplitude of rarefactive solitons decrease at kappa2. Figure 2 is plotted at kappa3 for the density ratio α, which is the ratio of hot to cold electrons, it is noted that increasing α the value of α, the width and amplitude of rarefactive solitons decrease. Figure 3 is plotted at a lower ϰ value (ϰ = 1.65), representing higher super thermality. For the density ratio α, which is the ratio of hot to cold electrons, it is observed that increasing α, the width and amplitude of rarefactive solitons decline. In Figure 4, we noted the increase in high-energy particles; the amplitude of dip-type solitons declined, but the width increased. Figures 5 and 6 are plotted for different values of u. In each figure, we change the value of kappa and note that the amplitude of the solitons is enhanced, but the width remains the same when the velocity of the nonlinear structure increases.

Fully localized two-dimensional lump solitons described by the KP equation may have important implications in space and laboratory plasmas where non-Maxwellian electron populations are commonly observed. In space plasmas such as the Earth's magnetosphere, auroral regions, auroral regions, magneto sheath, solar wind, etc., satellite observations have shown the presence of broadband electrostatic noise and potential structures related to super thermal electron distributions. In these regions, transverse perturbations are naturally present, and hence, multidimensional models are more realistic than one-dimensional models.

Similarly, for laboratory plasmas such as beam-plasma devices, Q-machines, and laser-produced plasmas, two-temperature electron distributions can lead to modes of electron-acoustic type with localized energy concentration. Thus, the soliton solutions for localized lump soliton solutions of the KP equation could model idealized forms of isolated electrostatic structures, moving without appreciable distortion. These findings offer a foundation for understanding nonlinear multidimensional electrostatic structures in plasmas with ϰ-distributed electrons.

Lump Soliton:

In this section, we will derive the lump solutions [23][24] for KP equation.

$$\phi(\xi,\chi,\tau)\phi(\xi,\chi,\tau)$$

$$= 12\left(\frac{6Q^{1\backslash 3}}{S}\right)\frac{\left(1581\tau^2 - \frac{1875\xi^2}{Q^{2\backslash 3}} - 525\frac{\chi^2}{Q^{1\backslash 3}R} + 3000\frac{\xi\chi}{Q^{1\backslash 2}R^{1\backslash 2}} - 1320\frac{\chi\tau}{Q^{1\backslash 6}R^{1\backslash 2}} - 1050\frac{\xi\tau}{Q^{1\backslash 3}} + 15625\right)}{\left(\frac{75\xi^2}{Q^{2\backslash 3}} + 75\frac{\chi^2}{Q^{1\backslash 3}R} + 75\tau^2 - \frac{120\xi\chi}{Q^{1\backslash 2}R^{1\backslash 2}} - \frac{120\xi\chi}{Q^{1\backslash 6}R^{1\backslash 2}} + \frac{42\xi\tau}{Q^{1\backslash 3}} + 625\right)^2}$$

This figure shows lump soliton profiles for different values of the super thermality index ϰ. As ϰ increases, the lump amplitude decreases and the structures become broader, consistent with the transition toward Maxwellian behavior where nonlinearity is reduced. The algebraic decay in both x and y directions is preserved, highlighting the robustness of lump solutions even as the electron distribution approaches thermal equilibrium.

The figure presents lump soliton profiles for varying soliton velocity u. Higher propagation speeds lead to increased lump amplitude and tighter localization in both spatial dimensions. This behavior confirms that faster-moving lumps carry more energy and exhibit stronger nonlinear effects, in agreement with the general properties of multidimensional solitons governed by the KP equation.

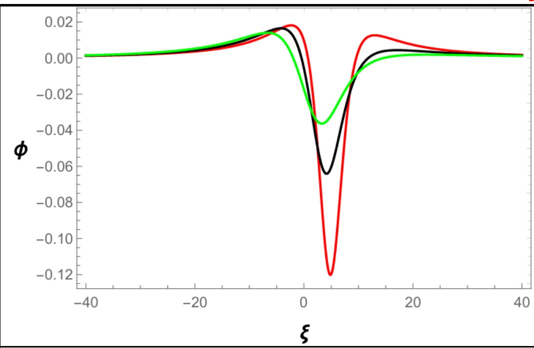

Figure 9. Lump solitons for different values of $t(-1\text{red}, -5 \text{ black and } -10 \text{ green})$ while $x = 5, \alpha = 0.2$ and $\kappa = 2$.

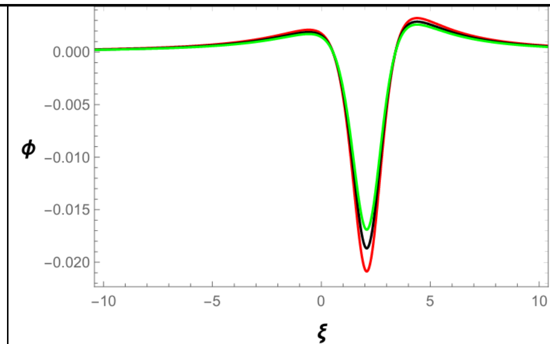

Figure 10. Lump solitons for different values of $\alpha(0.2\text{red}, 0.3 \text{ black and } 0.4 \text{ green})$ while $x = 2, k = 1.55\text{and } t = 1$.

This figure depicts lump soliton profiles for different values of the density ratio α at a fixed higher ϰ value. Increasing α results in reduced lump amplitude and slightly broader spatial extent, demonstrating that the hot-to-cold electron density ratio continues to suppress nonlinearity even in the two-dimensional lump regime.

The figure illustrates lump soliton profiles for different values of the super thermality index ϰ at a fixed density ratio. Lower ϰ (stronger super thermality) produces taller and more localized lumps, whereas higher ϰ yields weaker and more extended structures. The algebraic decay in all directions remains evident, underscoring the important role of non-Maxwellian electron distributions in shaping the strength and localization of multidimensional electron-acoustic lump solitons.

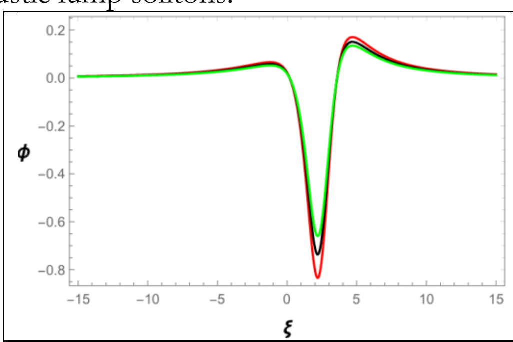

Figure 11. Lump solitons for different values of $\alpha(0.2 \text{ red}, 0.3 \text{ black and } 0.4 \text{ green})$ while $x = 2, k = 2$ and $t = 1$.

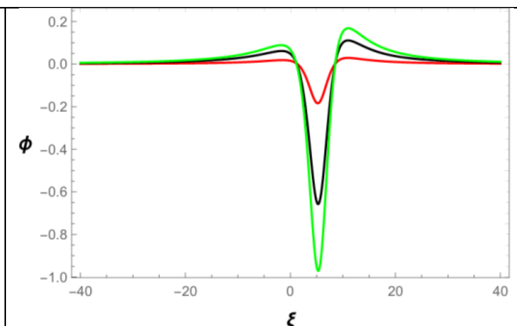

Figure 12. Lump solitons for different values of $k(2 \text{ red}, 3 \text{ black and } 4 \text{ green})$ while $x = 5, \alpha = 0.2$ and $t = 1$

Figure 7 illustrates the temporal evolution of lump solitons at different time values. Figure 8 illustrates the behavior of lump solitons at negative time values. Figure 9 is plotted for density ratio α, which is the ratio of hot to cold electrons, it is observed that increasing α leads to a decrease in the amplitude of rarefactive solitons, while the width of lump solitons remains unchanged at ϰ = 1.55. Figure 10 is also the same plot as in Figure 11, but the value of the spectral indices is changed to 2, and the result is the same. In Figure 12, we noted the increase in high-energy particles; the amplitude of dip-type lump solitons increased, but the width slightly increased.

Novelty and Objectives:

The investigation of the EA waves in the presence of non-Maxwellian distributed electrons has been extensively studied for one-dimensional models, especially by the application of the Korteweg–De Vries equation. However, these models have the limitation of not considering the effect of the transverse perturbations and hence do not account for the multidimensionality of the nonlinear structures as observed in real-world plasmas. Even though the problem has been extended to the Kadomtsev-Petviashvili equation, the investigation of the two-dimensional localized structures, especially lump solitons, for the kappa-distributed electrons is not well addressed.

The originality of this work is in the derivation of a two-dimensional KP equation for EA waves in a plasma containing $\varkappa$-distributed hot electrons, and then the construction of exact lump soliton solutions using a rational function approach. The originality is also in the emphasis placed on multi-dimensional effects, as opposed to most previous works, which dealt mainly with KdV solitons and 1D nonlinear structures.

The main objectives of the present investigation are: (i) to obtain the KP equation through the reductive perturbation method, including the effects of superthermal electrons, (ii) to find the exact lump soliton solution of the derived equation, and (iii) to investigate the effects of the $\varkappa$ parameter and plasma density ratios on the properties of these 2D nonlinear structures.

Conclusion:

In space and laboratory plasmas, it is often observed that the velocity distribution of plasma particles deviates from a Maxwellian distribution due to the presence of super thermal particles. Such a nonthermal effect is modeled using the kappa distribution function, where the effect of super thermal particles is represented through a spectral index $\varkappa$. Using the kappa distribution function, more realistic modeling of space and laboratory plasmas is possible.

To study weakly nonlinear and weakly dispersive wave propagation in a two-dimensional plasma system, the Kadomtsev-Petviashvili (KP) equation is obtained for a plasma with kappa-distributed particles using the reductive perturbation method. The effect of kappa-distributed particles is reflected in the modification of the pressure of the plasma, and it directly affects the nonlinear and dispersive coefficients of the KP equation.

The KP equation allows for the formation of localized nonlinear structures due to the balance between nonlinear and dispersive effects. In a $\varkappa$-distributed plasma, decreasing $\varkappa$ strengthens nonlinear effects, leading to more localized nonlinear structures and higher nonlinear excitations. For large $\varkappa$, the plasma is similar to a Maxwellian distribution, and standard KP equation dynamics are recovered.

Among the exact solutions of the KP equation, lump solitons are rationally localized in space and decay algebraically in both longitudinal and transverse directions. These solutions are fully two-dimensional solitary waves propagating with a constant velocity without requiring exponential localization. The characteristics of lump solitons are determined by the coefficients of the KP equation and are therefore indirectly related to the $\varkappa$ parameter. This framework of $\varkappa$-theory emphasizes the role of super thermal particles in determining multidimensional nonlinear wave structures in plasmas.

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Author's Contribution: The idea for the research, the theoretical model, the analytical derivations, and the initial draft of the paper were prepared by the corresponding author. The co-authors contributed to the discussion and critical revision of the paper and the final approval for publication.

Conflict of Interest: The authors state that there is no conflict of interest in the publication of this manuscript in IJIST.

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