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ELECTROMAGNETIC MODELING OF KINETIC ALFVÉN SOLITARY WAVES IN LOW-β MAGNETIZED PLASMA MATERIALS FOR ELECTRICAL ENGINEERING APPLICATIONS

ELEKTROMAGNETNO MODELIRANJE KINETIČNIH ALFVÉNOVIH SOLITARNIH VALOV V ELEKTROTEHNIŠKIH MATERIALIH, MAGNETIZIRANIH S PLAZMO Z NIZKIM PARAMETROM β

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This study analyzes low-amplitude kinetic Alfvén waves (KAWs) in a theoretical magnetized plasma in which ions and electrons are modeled using a regularized kappa distribution (RKD). The RKD was adopted to address limitations of the classical kappa model. A Korteweg–de Vries model, derived via a multiple-scale perturbation method, was then applied to investigate weakly nonlinear kinetic Alfvén waves. The results show that increasing the spectral index κ reduces soliton amplitude and width, indicating weaker nonlinearity in more Maxwellian-like plasmas. Conversely, larger values of α (the regularization parameter) increase soliton amplitude and spatial extent by extending the supra-thermal tail. Higher plasma β broadens the soliton without affecting amplitude, while variations in wave propagation angle l_z demonstrate that waves propagating nearly parallel to the magnetic field are more localized and intense. The parallel electric field shows a corresponding sensitivity to these parameters, highlighting the competition between nonlinear steepening and dispersive spreading. Overall, the study establishes predictive criteria for compressive KASWs in RKD plasmas, demonstrating how the parameters of the regularized kappa distribution, which govern microscopic electron dynamics, directly influence macroscopic wave characteristics and Alfvénic energy transport in realistic plasma environments.

Keywords: conductive fluids, propagation, electromagnetic field, electron distribution, low-β magnetized plasma

Avtorji v članku opisujejo študijo analize obnašanja nizkoamplitudnih kinetičnih Alfvénovih valov (KAWs) v teoretično magnetizirani plazmi. Pri tem so modelirali ione in elektrone z regulirano kappa porazdelitvijo (RKD). Ta je bila uporabljena za premagovanje omejitev klasičnega kappa modela. Za raziskovanje šibko nelinearnih kinetičnih Alfvénovih valov so avtorji nato uporabili Korteweg de Vriesov model, izpeljan z metodo večstopenjskih motenj. Rezultati analize so pokazali, da povečanje spektralnega indeksa κ zmanjša amplitudo in širino solitona, kar kaže na oslabljeno nelinearnost v bolj Maxwellovi podobnih plazmah. Nasprotno pa večji α (povezano z reguliranim parametrom) poveča intenzivnost in prostorski obseg solitona z razširitvijo supratermalnega repa. Višji plazemski β razširi soliton, ne da bi to vplivalo na amplitudo, medtem ko spremembe kota širjenja valov l_z kažejo, da so valovi, ki se širijo skoraj vzporedno z magnetnim poljem, bolj lokalizirani in intenzivni. Vzporedno električno polje kaže ustrezno občutljivost na te parametre, kar poudarja tekmovanje med nelinearnim strmim vzpenjajočim se in disperzivnim širjenjem. Študija na splošno vzpostavlja napovedne kriterije za tlačne KASWs v RKD plazmi in prikazuje, kako parametri regulirane kappa porazdelitve, ki določajo mikroskopsko dinamiko elektronov, neposredno vplivajo na makroskopske valovne značilnosti in Alfvénov transport energije v realnih plazemskih okoljih.

Ključne besede: prevodne tekočine, širjenje, elektromagnetno polje, porazdelitev elektronov, plazma z nizko β magnetizacijo

1 INTRODUCTION

Waves are observed in the ionosphere, planetary magnetospheres, and the solar wind, among other space environments.[1–3] In laboratory settings, they can also be produced from electrically conducting suspensions. In both natural and laboratory plasmas, these waves are important for understanding energy transport within plasma systems.[4–6]

Alfvén waves, discovered by Hannes Alfvén in 1942 from the equations governing charged fluids,[7,8–10] have since been recognized as important for energy transfer and particle dynamics. Since their discovery, they have been central to studies of solitary wave propagation and nonlinear dynamics in plasma systems.[11–13]

In magnetically confined nuclear fusion, Alfvén waves are important for controlling plasma stability and confinement because collective charged-particle motion must be controlled to achieve effective energy confinement.[13–15] The dispersive effects associated with suprathermal particles are captured by kinetic Alfvén waves,[1,16] which exhibit more complex dynamics and occur on scales comparable to the proton skin depth. The

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behavior of these waves can be studied using nonlinear differential equations, such as the nonlinear Schrödinger equation and the Korteweg–de Vries equation (KdV). These equations therefore enable systematic study of solitary-wave formation and of variations in amplitude and stability under different plasma conditions.[1,17–19]

While Alfvén waves are crucial in fusion, understanding their behavior in diverse environments, particularly those with high-energy particles (as found in laboratory and space plasmas), requires appropriate kinetic models.[20–23] Because these environments contain substantial populations of energetic particles, their velocity distributions often deviate from a Maxwellian form. The resulting distributions exhibit enhanced high-energy tails. The kappa (κ) distribution is commonly used to describe wave dynamics in the presence of energetic particles.[24,25] It is well suited to such nonthermal conditions. Particle trapping is a fundamental plasma phenomenon in which groups of particles, primarily electrons, are confined to certain regions of phase space. This process generates localized phase-space vortices known as "electron holes." Laboratory and space observations, together with numerical simulations, show that this wave-trapping process significantly affects wave stability and energy transport.[26,27]

Modified kappa distributions, including the RKD, are often required because Maxwellian distributions do not adequately represent suprathermal particle populations. RKD captures the finite spatial and temporal ranges over which acceleration occurs by imposing an exponential limit at high speeds. This provides a more realistic description of particle dynamics in laboratory and space plasmas.[23,28] RKD also enables quantitative analysis of how high-energy particles interact with Alfvén waves and how these interactions affect the nonlinear evolution of plasma disturbances.[29]

This study specifically examines the regularized kappa-distribution-based nonlinear dynamics of kinetic Alfvén waves in a low-β plasma composed of inertial ions and inertialess electrons. Using the reductive perturbation method (RPM) together with a two-fluid plasma model, we derive the Korteweg–de Vries (KdV) equation that governs the propagation of the kinetic Alfvén solitary wave. The analytical solution is used to examine the influence of the underlying plasma parameters on the amplitude, width, and stability of solitary structures.

2 MATHEMATICAL FORMULATION AND KdV DERIVATION

In this section, we introduce the governing equations for the evolution of KAWs in a low-β magnetized plasma. The plasma is composed of inertial ions and inertial electrons that obey a regularized kappa distribution (RKD). Using a quasi-neutral, small-amplitude perturbation approach, the system of fluid and Poisson equations for ions, electrons, and their corresponding electrostatic potentials is normalized to facilitate analytical treatment.

2.1 Fundamental Equations

We consider a plasma immersed in a uniform magnetic field $B_0 = B_0$?. The dynamics are confined to the x-z plane, with perturbations propagating obliquely to B_0. In the low-β limit, the electric field components are expressed in terms of scalar potentials:[30]

$$\begin{cases} E_z = -\dfrac{\partial \psi}{\partial z} \\ E_x = -\dfrac{\partial \varphi}{\partial x} \end{cases} \tag{1}$$

Where ψ and φ denote the parallel and perpendicular electrostatic potentials, respectively

2.2 Ion Fluid Dynamics

The continuity equation, expressing conservation of ion number density, takes the form:[31]

$$\frac{\partial n}{\partial t} + \frac{\partial (n v_x)}{\partial x} + \frac{\partial (n v_z)}{\partial z} = 0 \tag{2}$$

The ion motion in the perpendicular (x-direction), including magnetic coupling, is written as:[31,32]

$$v_x + \left(\frac{\beta}{2}\right) \cdot \frac{\partial^2 \varphi}{\partial x \partial t} = 0 \tag{3}$$

The ion motion parallel (z-direction) to the magnetic field is given by:[33]

$$\frac{\partial v_z}{\partial t} + \left(v_x \frac{\partial}{\partial x} + v_z \frac{\partial}{\partial z} \right) v_z = \left(\frac{\beta}{2}\right) \cdot \frac{\partial^2 \psi}{\partial z} \tag{4}$$

2.3 Electrostatic Coupling and Electron Density

The Poisson equation, which relates potential variations to charge density, is written as:[34,35]

$$\frac{\partial^2 \partial^2}{\partial x^2 \partial z^2} (\varphi - \psi) = \left(\frac{2}{\beta}\right) \left[\frac{\partial^2 n}{\partial t^2} + \frac{\partial}{\partial t} \frac{\partial}{\partial z} (n v_z) \right] \tag{5}$$

For RKD electrons, the normalized density is given by:[35,36]

$$n_e = e^{\alpha^2 \psi} \left(1 - \frac{\psi}{\kappa}\right)^{-\kappa + \frac{1}{2}} \cdot \frac{U\left[\frac{3}{2}, \frac{3}{2} - \kappa, \alpha^2 \kappa \left(1 - \frac{\psi}{\kappa}\right)\right]}{U\left[\frac{3}{2}, \frac{3}{2} - \kappa, \alpha^2 \kappa\right]} \tag{6}$$

where U is the Kummer confluent hypergeometric function, α is the cutoff parameter, and κ represents the superthermal index. For $\alpha \to 0$, the RKD reduces smoothly to the standard κ distribution.

Expanding for small ψ/κ, we obtain:

$$n_e = 1 + c_1 \psi + \ldots \tag{7}$$

with:

$$c_1 = \left(k - \frac{1}{2}\right) + \kappa\alpha^2 - \frac{3\kappa\alpha^2 U\left[\frac{5}{2}, \frac{5}{2} - \kappa, \alpha^2\kappa\right]}{2U\left[\frac{3}{2}, \frac{3}{2} - \kappa, \alpha^2\kappa\right]} \quad (8)$$

2.4 Perturbation Expansion and Reduction to KdV Equation

Applying the reductive perturbation method (RPM), we introduce the stretched variables:

$$\xi = \varepsilon^{1/2}(l_x x + l_z z - St),\ \tau = \varepsilon^{1/2} t \quad (9)$$

where $\varepsilon << 1$ is the perturbation amplitude, l_x and l_z are the direction cosines of the wave vector, and S is the phase velocity.

The dependent variables are expanded as follows:

$$\begin{cases} n = 1 + \varepsilon n_1 + \varepsilon^2 n_2 + \varepsilon^3 n_3 + \ldots \\ v_{x,z} = \varepsilon v_{x1,z1} + \varepsilon^2 v_{x2,z2} + \varepsilon^3 v_{x3,z3} + \ldots \\ \psi = \varepsilon\psi_1 + \varepsilon^2\psi_2 + \varepsilon^3\psi_3 + \ldots \\ \varphi = \varphi_1 + \varepsilon\varphi_2 + \varepsilon^2\varphi_3 + \ldots \end{cases} \quad (10)$$

Substituting these expansions into the governing equations and collecting terms of equal powers of ε, the first-order equations yield the linear dispersion relation. At second order, nonlinear and dispersive terms emerge and combine to form the KdV-type evolution equation:

$$\frac{\partial\varphi}{\partial t} + A_1\psi\frac{\partial\psi}{\partial\xi} + A_2\frac{\partial^3\psi}{\partial\xi^3} = 0 \quad (11)$$

where:

$$A_1 = -c_1 l_z, \quad A_2 = -\frac{\beta l_x^2 l_z}{4c_1 - 2\beta}$$

Here, A_1 characterizes the nonlinearity arising from the non-Maxwellian nature of the RKD electrons, while A_2 represents the dispersion due to the magnetic field and plasma β.

2.5 Solitary Wave Solution

Using the travelling-wave transformation $\psi = \psi(\xi - u\tau)$, Eq. (11) reduces to:

$$-u\psi' + A_1\psi\psi' + A_2\psi'' = 0 \quad (12)$$

Integrating twice and applying the boundary conditions $(\psi,\psi',\psi'') \to 0$ as $|x| \to \infty$, the solitary wave solution is obtained as follows:

$$\psi(x) = \psi_0 \sec h^2\left(\frac{x}{\omega}\right) \quad (13)$$

Where $\psi_0 = 3u/A_1$ and $\omega = \sqrt{4A_2/u}$ represent the amplitude and width of the kinetic Alfvén solitary wave (KASW), respectively.

The parallel electric field E_ξ, is obtained from the potential as:[37]

$$E_\xi = -\frac{d\psi}{dx} \quad (14)$$

which yields, using

$$\frac{d}{dx}\operatorname{sech}^2\left(\frac{x}{\omega}\right) = -\frac{2}{\omega}\operatorname{sech}^2\left(\frac{x}{\omega}\right)\tanh\left(\frac{x}{\omega}\right),$$

$$E_\xi = -\frac{d\psi}{dx} = \frac{2\psi_0}{\omega}\tanh\left(\frac{x}{\omega}\right)\operatorname{sech}^2\left(\frac{x}{\omega}\right) \quad (15)$$

3 RESULTS AND DISCUSSION

This section presents numerical results on the influence of various plasma parameters on the characteristics of Kinetic Alfvén Solitary Waves (KASWs), with emphasis on the electrostatic potential, electric field, and governing nonlinearity and dispersion coefficients. As shown in **Figure 1A**, the influence of the super-thermal index κ on the KASW electrostatic potential indicates that both the soliton amplitude and spatial width decrease with increasing κ. A larger κ indicates that the electron population approaches a Maxwellian distribution, which reduces the contribution of supra-thermal particles to nonlinear effects. As a result, the solitary wave profile becomes flatter and narrower, reflecting diminished energy localization and weaker nonlinear steepening. In contrast, for smaller κ values corresponding to strongly non-Maxwellian plasmas, the larger population of energetic electrons enhances the electric potential, producing solitons with larger amplitudes and broader spatial extents.

Figure 1B demonstrates the role of the cutoff parameter α in shaping the KASW potential profile. Increasing α increases both the soliton amplitude and width. This behavior indicates that larger values of the cutoff parameter effectively extend the supra-thermal tail of the electron distribution, allowing more energetic electrons to participate in wave dynamics. Consequently, the enhanced electron pressure strengthens the restoring force opposing ion inertia, thereby generating wider and more pronounced compressive solitary structures. In the limit $\alpha \to 0$, the plasma approaches the standard κ distribution and nonthermal effects gradually diminish.

We next consider the combined effects of plasma beta and propagation geometry. **Figure 2A** shows the influence of the plasma-beta parameter β, which represents the ratio of thermal to magnetic pressure and primarily affects the medium's dispersive characteristics. Since β enters explicitly through the dispersive coefficient A_2, changes in β mainly alter the soliton width with little change in amplitude. As β increases, magnetic confinement weakens, and the solitary wave extends over a larger spatial region. Consequently, higher β values lead to broader and less confined structures, while the ampli-

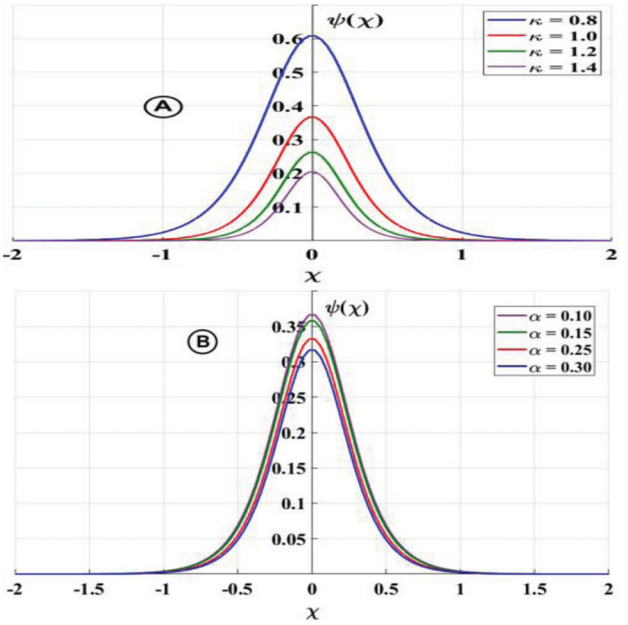


Figure 1: Variation of the KASW potential profile with (A) nonthermal parameter κ and (B) dispersion parameter α

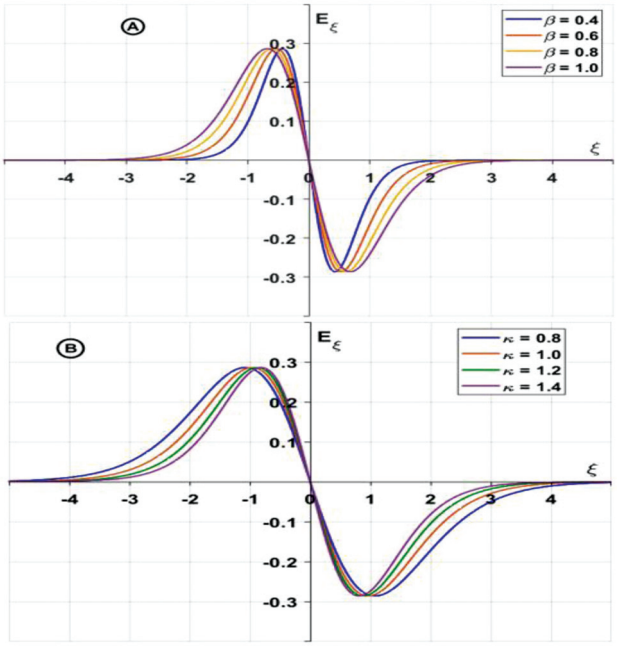


Figure 3: Electric field of kinetic Alfvén solitary waves for varying (A) trapping parameter β and (B) superthermality index κ

tude remains nearly constant due to the weak dependence of the nonlinear coefficient A1 on β.

Figure 2B illustrates the effect of the obliqueness parameter l_z, where l_z equals cos θ and defines the propagation direction relative to the ambient magnetic field. Increasing the propagation angle, corresponding to smaller l_z values, reduces both the soliton amplitude and width.

When propagation occurs nearly parallel to the magnetic field, the solitary structure becomes more intense and more localized. As the angle increases, the wave energy is distributed over a wider region. This trend is consistent with the analytical dependence of the coefficients A_1 and A_2 on the propagation geometry, since A_1 approaches zero and A_2 decreases as the angle approaches 90°. Therefore, KASWs support stronger, narrower solitary structures when propagation is closely aligned with the external magnetic field.

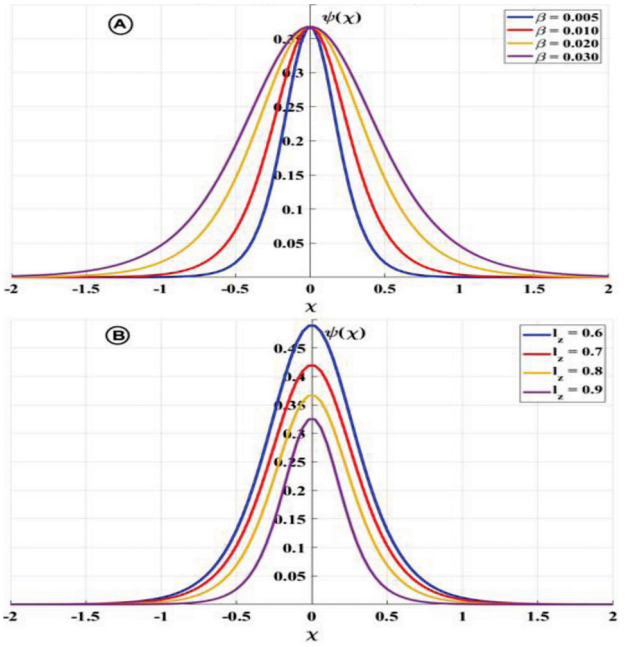


Figure 2: Variation of the KASW potential with (A) the plasma beta parameter β and (B) the obliquity factor l_z

To further characterize the waves, **Figure 3** shows the corresponding electric field E_ξ associated with KASWs under variations of the trapping parameter β and the superthermality index κ. In **Figure 3A**, increasing β from 0.4 to 1 produces higher peak electric-field amplitudes and sharper localization near the wave center. This result indicates that stronger trapping intensifies the wave and enhances its steepness.

In **Figure 3B**, increasing κ from 0.8 to 1.4 reduces the peak electric-field amplitude while increasing the spatial width. This behavior reflects the moderating influence of superthermal electrons, which reduce field gradients and weaken nonlinear steepening. Overall, these results demonstrate that β and κ regulate both the strength and spatial extent of the electric field associated with KASWs, highlighting the competition between nonlinear enhancement and dispersive spreading.

Finally, **Figure 4** summarizes the dependence of the dispersion and nonlinearity coefficients on key plasma parameters. **Figures 4A** and **4B** show the variations of the dispersive (A_2) and nonlinear (A_1) factors of Eq. (11) as functions of the cut-off parameter α for different values of the superthermal index κ. Both coefficients (A_1, A_2) remain negative for all plasma parameters. Therefore,

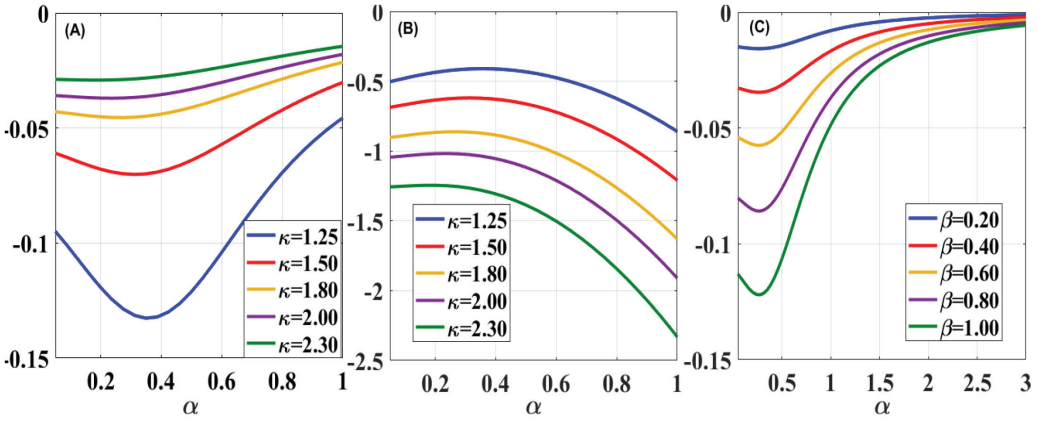


Figure 4: Variations in the dispersion (A_1) and nonlinearity (A_2) coefficients: (A) A_1 versus (α,κ); (B) A_1 versus (α,κ); and (C) A_2 versus (α, β)

the soliton width becomes imaginary when $u_0 > 0$. To ensure the existence of a real soliton solution, the soliton velocity must satisfy $u_0 < 0$. For $u_0 < 0$, the potential amplitude and width of the solitary wave become positive, which corresponds to compressive solitons. Under this condition, the nonlinearity parameter A_1 turns positive, indicating that the system supports only positive (compressive) solitary structures.

The results indicate that departures from a Maxwellian electron distribution, represented by the regularized kappa distribution, act as a fundamental source of nonlinearity and strongly influence the morphology of solitary wave structures. These results are interpreted within the broader context of Alfvén wave dynamics, with particular emphasis on their relevance to laboratory and space plasma settings. A key finding is that the RKD provides a more realistic representation of plasmas containing energetic particles than a Maxwellian or a simple kappa model. The solitary wave amplitude and width vary systematically with κ and α, thereby connecting macroscopic wave features directly to the underlying particle statistics. As illustrated in **Figure 1A**, the soliton amplitude decreases as κ increases, indicating that nonlinearity weakens when the electron distribution approaches a thermal Maxwellian and the supra-thermal tail becomes less important.

Conversely, the increase in soliton amplitude and width with increasing α (**Figure 1B**) highlights the role of the RKD's exponential cutoff in regulating the contribution of the highest-energy electrons. A larger α extends the effective supra-thermal tail, increasing the electron pressure and thereby strengthening the restoring force that opposes ion inertia, leading to more intense, spatially extended solitary wave structures. These morphological trends are complemented by the kinetic characteristics of the waves. Specifically, as illustrated in **Figure 3**, the electric field E_ξ associated with the KASW potential shows the capacity of kinetic Alfvén waves to do work on particles. Kinetic Alfvén waves differ from ideal, dispersionless magnetohydrodynamic Alfvén waves because they possess a parallel electric-field component that enables direct energy transfer between fields and particles. The sensitivity of E_ξ to β and κ highlights how plasma conditions control the efficiency of that energy exchange, consistent with recent in situ observations of Alfvénic energy transport. Furthermore, the requirement for a negative soliton velocity ($u_0 < 0$) to obtain physically meaningful (positive) compressive solitons, stemming from the consistently negative nonlinear (A_1) and dispersive (A_2) coefficients (**Figure 4**), is a crucial result. It defines the precise parametric regime where such solitary structures can exist. This analytical condition provides a predictive criterion for the formation of compressive KASWs in low-β, non-Maxwellian plasmas, which can be tested against in situ measurements and simulations.

Overall, the parametric dependencies identified in this study have broad implications for energy dynamics in space plasmas, where non-Maxwellian distributions are common. The analytical and graphical results together provide practical criteria for when compressive KASWs should appear and how their properties vary under realistic variations in κ, α, β, and l_z. These conclusions point to targeted observational tests and numerical experiments to further refine our understanding of Alfvénic energy transport in both natural and laboratory settings.

4 CONCLUSIONS

This study investigated the characteristic properties of KASWs in a low-β magnetized plasma featuring supra-thermal electrons, a common condition in space environments. The aim was to determine how an RKD, which more realistically represents energetic particles than standard distributions, governs the nonlinear dynamics and morphology of these compressive wave structures. The analysis used a reductive perturbation technique, which yielded a KdV equation whose nonlinear and dispersive coefficients capture the effects of key plasma parameters: the superthermal index κ, the cutoff parameter α, the plasma beta β, and the obliqueness fac-

tor l_z. This approach enabled systematic analysis of solitary wave solutions and their associated electric fields. The results show that these parameters control the balance between nonlinear steepening and dispersive spreading. Specifically, a decrease in κ (stronger non-Maxwellian character) or an increase in α (extended supra-thermal tail) enhances soliton amplitude and width, while increased β primarily broadens the structures. Furthermore, propagation more closely aligned with the magnetic field (larger l_z) yields more intense and localized solitary waves. The derived coefficients remain negative across the parameter space, imposing the condition that the soliton velocity must be negative ($u_0 < 0$) to yield physically meaningful, compressive solitary structures with positive potential amplitude. Overall, the study confirms that the statistics of the electron population, as described by the RKD, are a fundamental source of nonlinearity shaping KASWs. The identified parametric dependencies and the explicit condition for soliton existence provide a predictive framework for interpreting and modelling the formation of these waves in laboratory and space plasmas, such as the Earth's magnetosphere and solar wind, where supra-thermal particles are prevalent, and Alfvénic energy transport is crucial.

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