Exploring the Dynamic Interplay between Kinetic Alfvén Waves and Magnetic null points in the Magnetosphere

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Abstract

The nonlinear interaction between kinetic Alfvén waves (KAWs) and null points in the magnetosphere can result in the transfer of energy and the release of stored magnetic energy in the form of particle acceleration and the generation of heat. KAWs are a type of plasma wave that can propagate in the magnetosphere and are generated by the motion of charged particles in a magnetic field [1]. Null points, on the other hand, are locations in the field where the magnetic field strength vanishes. Magnetic reconnection, which can cause a change in the magnetic field configuration, plays a cradle role for this interaction to take place. In this work, we looked at the nonlinear interactions and how the structures they created changed over time. At first, these structures were clear and symmetrical, but we later saw that they were chaotic and shaky. As these turbulent structures grow, these waves can cause changes in the magnetic field strength, direction and play a pivotal role in the dynamics of the magnetosphere. This process can have big effects on how the magnetosphere moves and how much radiation there is in the area.

To examine these structures developed in the magnetosphere by the nonlinear interaction of propagating KAW and null points, we proposed a 3D Kinetic Alfvén wave model. We have used the finite difference method for temporal domain and the pseudospectral approach with the predictor-corrector method for the spatial domain to solve and simulate this model equation. The numerical simulation demonstrates that without nonlinearity, the field structure changes slowly, but keeping the pondermotive nonlinearity on, it changes rapidly and approaches quasi-steady state with a fully chaotic structure, indicating turbulent filamentation with further temporal evolution. Further, we have also done a semi-analytical analysis and studied the current sheet structures.

Introduction

Turbulence is a disorderly and chaotic plasma motion that can result from a large-scale plasma flow with varying velocity and pressure. This can result in the production of eddies and vortices that transport and mix plasma and magnetic fields. Turbulence is significant in numerous astrophysical situations, including the interstellar medium, the solar wind, and the intergalactic medium, where it contributes to the mixing and movement of energy, momentum, and magnetic fields. On the other hand, magnetic reconnection is a physical process that takes place in plasmas when magnetic field lines break, reconnect in a different way, and then release the energy that has been trapped in the magnetic fields. The plasma may heat up, particles may accelerate, and electromagnetic radiation may be released explosively as a result of this. According to Chaston, KAWs is a specific kind of plasma wave that can travel across the magnetosphere and are caused by the passage of charged particles in a magnetic field [1]. The magnetic field lines cross at null sites, on the other hand, where the magnetic field strength is zero. This interaction is made possible by magnetic reconnection, which can change how the magnetic field is configured.

By helping to move energy and momentum between various areas of the plasma and magnetic field, kinetic Alfvén waves play a significant part in the magnetosphere. Moreover, they can affect how charged particles behave and support the emergence of instability and turbulence. The dynamics of the Earth's magnetic field and the behavior of particles trapped in the magnetosphere can be impacted by the presence of kinetic Alfvén waves in the magnetosphere[2].

We have done the study of the nonlinear interaction of KAW and null points in the solar corona region. Now we are extending the study to different regions and different magnetic structures. In this course of action, here we have modified the parameters for the magnetosphere region. The numerical simulation is performed using the finite difference method and pseudo-spectral method.

The simulation results have revealed the presence of chaotic structures, which are postulated to play a role in the conversion of stored magnetic energy into thermal and kinetic energy forms. Moreover, this phenomenon potentially leads to particle acceleration and the generation of heat through the nonlinear interaction between KAWs and null sites in the magnetosphere.

Model Equation of dynamics

In this study, the two-fluid model has been effectively used to create a three-dimensional (3D) model of KAW. In this study, we have made assumption that a KAW with a wave vector represented as $\vec{k}0=\vec{k}0x+\vec{k}0y+\vec{k}0z$ is propagating within a medium characterized by an equilibrium magnetic field $\vec{B_0}=B_{0x}\left(\frac{x}{L}\right)\hat{x}-B_{0y}\left(\frac{y}{L}\right)\hat{y}+B_{0z}\hat{z}$. The dynamical equation for the KAW can be derived using the equations of motion for electrons and ions, the continuity equation, and the equations of Maxwell

$$\frac{\partial \vec{v_j}}{\partial t}=\frac{q_j}{m_j}\vec{E}+\frac{q_j}{cm_j}(\vec{v_j}\times\vec{B_0})-\frac{k_B T_j}{m_j}\vec{\nabla}\frac{n_j}{n_0}, \tag{1}$$

$$\frac{\partial \vec{n_j}}{\partial t}+\vec{\nabla}\cdot(n_j v_j)=0, \tag{2}$$

$$(\vec{\nabla}\times\vec{E}) = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}, \tag{3}$$

$$\nabla^2\times\vec{E}-\vec{\nabla}(\vec{\nabla}\cdot\vec{E}) = \frac{4\pi}{c^2}\frac{\partial\vec{J}}{\partial t}+\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}. \tag{4}$$

By considering density perturbation and a modified background magnetic field of KAW, we derive the dynamical equation governing the behavior of the KAW, which turns out to be:

$$(1-\lambda_e^2\nabla_\perp^2)\frac{\partial^2 A_z}{\partial t^2}-{v_A}^2\left(1-\frac{\delta n}{n_0}\right)(1-\rho_s^2\nabla_\perp^2)\left(\frac{\partial^2 A_z}{\partial z^2}+\left(\frac{B_{0x}}{B_{0z}}\right)^2\frac{\partial^2 A_z}{\partial x^2}+\left(\frac{B_{0y}}{B_{0z}}\right)^2\frac{\partial^2 A_z}{\partial y^2}\right)=0. \tag{5}$$

Considering the envelope solution as $A_z = A_0(x,y,z,t)e^{\imath(k_x\hat{x}+k_y\hat{y}+k_z\hat{z}-\omega t)}$ and using the null point profile along with x and y direction with neglection higher order terms, the author can get the normalized form of the dynamical equation of KAW

$$\begin{aligned}-2\imath\frac{\partial A_0}{\partial t}-2\imath\frac{\partial A_0}{\partial z}+2\imath\frac{\partial A_0}{\partial x}+2\imath\frac{\partial A_0}{\partial y}+C_1\frac{\partial^2 A_0}{\partial x^2}+C_2\frac{\partial^2 A_0}{\partial y^2}\\ +\left(\left(\frac{x}{L}\right)^2+\left(\frac{y}{L}\right)^2+\frac{\delta n}{n_0}\right)A_0=0.\end{aligned} \tag{6}$$

The solution to the model equation for parameters in the magnetosphere region is obtained numerically through the finite difference and pseudospectral method. The numerical simulation uses grid resolution of $(128)^3$ and a periodic domain of $(10\pi)^3$. The typical parameters applicable for the magnetosphere are , $B_0 = 31\times10^{-5}G, \quad n_0 = 21cm^{-3}, \quad T_e = 37eV, \quad T_i = 235eV$ [3].

Results and Discussion

The simulation results show that the evolution of the KAW's coherent structures and the generation of localized magnetic field structures play a significant role in turbulence generation and magnetic field amplification. With magnetic field amplification observed to reach up to three to four times the initial magnetic field strength in figure 1, this highlights the importance of further research into the KAW-null point interaction in the magnetosphere.

The time-averaged magnetic turbulence generation observed in the simulation results, as shown in figure 2, In inertial range, it shows $-5/3$ power law and further, it becomes steeper with the power law of -3. This steepening shows the enhancement in energy dissipation after the $k_\perp\rho > 1$. This suggests that magnetic reconnection plays an important role in the KAW-null point interaction and its impact on turbulence and energy dissipation in the magnetosphere.

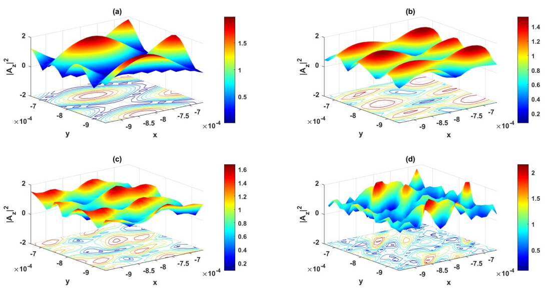

Figure 1: Magnetic flux surface contour plot in the x–y plane at various times $(a)t = 0, (b)t = 3, (c)t = 7$ and $(d)t = 10$

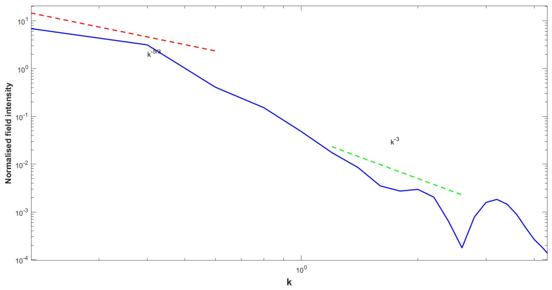

Figure 2: The averagedmagnetic field power spectrum

Conclusion

The outcomes of the simulation show how 3D-KAW behaves as they interact with Null points and give rise to formation of chaotic structures. These measurements provide clear evidence that the system is producing turbulence. Localized structure of Alfven waves are formed due to the density perturbation in the background medium. These structures are a source of energy cascade from a larger scale to a smaller scale which are responsible for turbulence. KAW breaks up into localized structures and the turbulent nature became more obvious with temporal evolution. In inertial range it shows $-5/3$ power law and further, it becomes steeper with power law of -3.

Further research into the KAW-null point interaction in the magnetosphere can provide valuable insights into the fundamental processes driving turbulence and energy dissipation in plasma systems. This has potential applications in various fields, such as space weather forecasting and the development of advanced technologies for space exploration.

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References

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