Abstract

Magnetic fields and waves in the solar environment set the stage for a range of physical phenomena, whose implications are studied here. The conditions of solar plasma generate different kinds of wave modes. These wave modes carry energy while travelling and redistribute it in different regions of the Sun. In the solar corona region, a rise in the temperature is observed, which needs an explanation, as the usual trends suggest a decline in the temperature as we move outwards from the solar surface. The pervasive magnetic field reshuffles, and in the juggling, it connects and breaks. This reconnection paves the way for the transformation of magnetic energy into thermal and kinetic energy. It also launches different wave modes and contributes to the plasma wave modes in the already rich environment of the solar atmosphere.

Different magnetic topologies have been observed in the solar atmosphere, and further investigation also suggests their role in energy exchange processes. In the myriad of wave modes present in the solar corona, kinetic Alfvén waves (KAWs) have been observed to interact strongly with charged particles, heat them, and drive the kind of fine-scale structures observed in the corona and solar wind. When these waves interact with magnetic structures like null points and islands, they can trigger or feed into turbulence, i.e., the chaotic motion of plasma across many scales. This interaction in nonlinear form further enhances the energy transfer rate and contributes to the energy dynamics of the solar corona and the solar winds.

This thesis investigates how KAW with nonlinearity and magnetic field perturbations like magnetic islands and null points affect their dynamics and how these processes contribute to the formation and evolution of current sheets near reconnection regions in both the solar corona and solar wind regions. KAWs are known to be a potential source of electron acceleration and electron temperature anisotropy in reconnection regions, and this work aims to clarify these roles. Here, the focus is on what happens when KAWs meet and interact with magnetic topologies that we know exist from observations, in particular, null points and magnetic islands. When these structures are present, and when the waves are supported by ponderomotive forces, turbulence and fine filamentary patterns tend to grow. The study employs a fully three-dimensional computational KAW model that accounts for ponderomotive nonlinearities and the inhomogeneous magnetic fields of the chosen topologies, allowing for an examination of energy transport processes. The simulation results in wave structure interaction, which facilitates the evolution of turbulence, which further changes the way energy moves and is lost in the system, and it does so across a range of scales, from large-scale size down to kinetic scales in both the low-beta corona and the high-beta solar wind.

Chapter 1 introduces concise yet comprehensive basic concepts of plasma physics that are relevant to this work of wave motion in plasmas, how turbulence develops, and the different ways we can model a plasma, from simple fluid approaches to fully kinetic descriptions. The chapter also summarizes what we know from observations of the solar atmosphere, especially about magnetic reconnection and wave activity, and why KAWs are considered important carriers of energy. It outlines the motivation behind the work, the broader scientific questions addressed, and the specific objectives of the thesis.

Chapter 2 presents the nonlinear interaction between a $3D$ KAW and a magnetic null point in the solar corona. The model is used to simulate how KAWs evolve in the presence of coronal conditions and to provide practical applications of turbulence theory in a controlled setting. Numerical simulations reveal the formation of filamentary current sheets and localized structures, followed by chaotic transitions indicating turbulence onset. A semi-analytical model in the paraxial limit provides additional insights into the current sheet scale lengths. A Fokker-Planck diffusive formalism was applied to show the thermal tail stretching due to these interactions.

Chapter 3 investigates KAW interaction with magnetic islands in the solar corona region. The results show that the island geometry significantly modifies turbulence spectra and structure localization. Simulation outcomes are compared with semi-analytical solutions to better understand scale-dependent energy transfer. The simulations show that the presence of both the null points and the magnetic islands can drive the system toward chaotic and turbulent states, with null points producing more rapid structural evolution than islands, though both cases show spectral steepening in the kinetic regime.

Chapter 4 further explores X-type and O-type null point configurations in solar corona, like magnetized plasmas, exploring how each influences turbulence and current sheet formation by nonlinear interaction with KAWs near magnetic null points. Different null point configurations (X-type and O-type) show their distinct effects on the evolution of turbulent structures. The simulations also compare scenarios where ponderomotive nonlinearity is removed, but the null point remains, and vice versa. Results show that when both nonlinearity and null point topology are present, the rate of structure evolution is significantly higher.

Chapter 5 extends the study to relatively high beta solar wind plasmas, examining localized structures and turbulent spectra resulting from KAW and null point interactions. Differences in spectral indices and structure evolution between solar wind and coronal conditions are quantified. It showed that the evolution is relatively slow compared to the coronal case.

Chapter 6 replaces the null point topology with magnetic islands, analyzing the spatiotemporal evolution of current sheets and their interaction with KAW modes. Simulations suggest that KAWs fragment current sheets into smaller structures, while semi-analytical results indicate that current sheet dimensions may depend on wave mode and thermal effects. The results highlight the combined influence of nonlinearity and island geometry on inertial-range spectra, steepening at sub-ion scales, and reconnection-driven turbulence.

Chapter 7 shows the exploration of different instabilities, like parametric and modulation types associated with Alfvén waves in the corona and their nonlinear saturation. Up to Chapter 6, the thesis has focused on cascade-type turbulence. Chapter 7 expands the scope by exploring different turbulence regimes: cascade turbulence dominated by the parametric decay instability (PDI), mixed turbulence where multiple modes contribute comparably, and cavity turbulence dominated by the oscillating two-stream instability (OTSI). While such studies have been common in Earth's ionospheric context, here they are applied to the solar corona using Alfvén waves as the driver.

Chapter 8 concludes with a synthesis of the main findings and a discussion of future research directions. It summarizes the findings, emphasizing how magnetic topology governs KAW evolution, turbulence self-organization, and multiscale energy dissipation. The proposed extensions, incorporating more realistic and dynamic magnetic geometries, additional plasma physics, and direct comparisons with upcoming spacecraft observations, promise to deepen our understanding of these processes. Such studies could also help bridge the gap between astrophysical plasma theory and laboratory experiments, offering new opportunities to test and refine models of KAW-driven turbulence in reconnection environments.

Overall, the thesis integrates numerical simulations and semi-analytical models to connect wave–structure interaction physics with observable turbulent signatures. The results attempt to contribute to a more comprehensive understanding of turbulence evolution, which has implications in plasma heating and acceleration processes in the solar atmosphere.