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Theory and Simulation of Kinetic Alfvén Waves in Space Plasmas

Jay R. Johnson[1], Yu Lin[2], Lei Cheng[3], Peter Delamere[4], Peter Damiano[4], and C. Z. Cheng[1,5]
[1] Andrews University, [2] Auburn University, [3]Florida Institute of Technology, [4]University of Alaska, [5]Princeton Plasma Physics Laboratory
e-mail (speaker): jrj@andrews.edu

Kinetic Alfvén waves play a fundamental role in plasma transport, heating, and acceleration in space plasmas because there is efficient transfer of energy between the waves and particles at kinetic scales. These waves are thought to be important for heating in the corona, solar wind, and magnetosphere where nonlinear wave-particle interactions can lead to stochastic heating. Kinetic Alfvén waves are closely associated with solar wind-magnetosphere coupling processes including reconnection, Kelvin-Helmholtz instability, and solar wind compressions and can be responsible for the observed heating and plasma entry and the increase in plasma entropy across the magnetopause. To illustrate some of these processes, we present hybrid simulations of kinetic Alfvén waves, which include the full dynamics of ions and fluid electrons.

Kinetic Alfvén waves are frequently observed at the magnetopause interface between the magnetosheath and magnetosphere. Compressions in the solar wind and magnetosheath can drive kinetic Alfvén waves through mode conversion [1]. We show hybrid simulations that demonstrate how compressional waves mode convert into kinetic Alfvén waves as the result of linear mode conversion followed by nonlinear wave-wave coupling that transforms the spectrum from dominantly radial to azimuthal, which facilitates plasma transport.

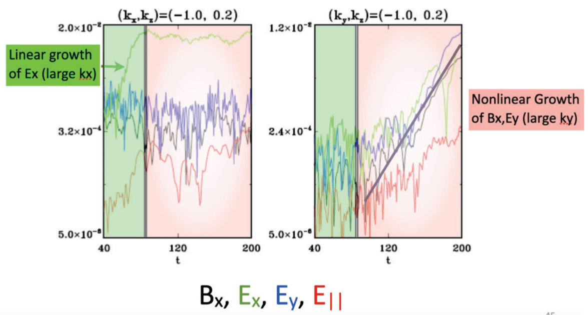

Figure 1. Hybrid simulation of mode conversion of compressional waves to kinetic Alfvén waves shows linear mode conversion to radial (k_x) KAWs followed by nonlinear growth of azimuthal (k_y) KAWs [2].

Kinetic Alfvén waves are also closely associated with Kelvin-Helmholtz structures that are driven by shear in the velocity profile at the magnetopause. We show simulations of Kelvin-Helmholtz instability including the development of a turbulent spectrum of kinetic Alfvén waves. The theoretical heating rate based on the wave spectrum is consistent with the observed particle heating in the simulations [3]. We use information theory to identify cross-scale coupling in the simulation that drives an inverse cascade.

Dynamical processes in the magnetotail provide a general picture of turbulent flows excited by sporadic reconnection. Global hybrid simulations [4] show that kinetic Alfvén waves are generated in magnetic reconnection and located around the fast flows. Moreover, the kinetic energy in these flows is also converted into Poynting flux of kinetic Alfvén waves as the flows brake in the inner magnetosphere, leading to electron acceleration and ion heating that facilitates magnetosphere-ionosphere coupling.

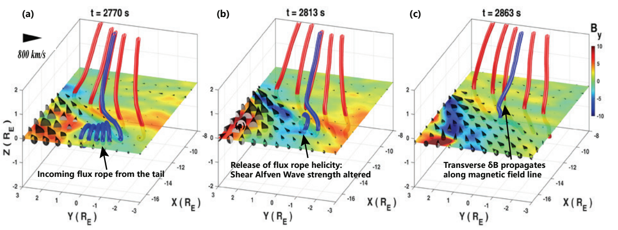

Figure 2. As magnetic ropes are carried Earthward by tail flows, kinetic Alfvén waves are generated as magnetic helicity is released [4].

To understand whether the Poynting fluxes carried by the shear Alfvén waves/KAWs in the plasma sheet can be carried directly along field lines to the ionosphere, we track the wave propagation from the plasma sheet to the ionosphere. We show that in front of the flow-braking region, the structure and strength of the shear Alfvén waves are significantly altered due to interaction with the dipole-like field, mainly by the flow shear associated with the azimuthal convection. Also, in front of the dipole-like field region, ion kinetic effects (Hall effects) lead to the generation of additional pairs of kinetic Alfvén waves. The global simulations are analyzed using information theory to compare the ionospheric Poynting flux with causal drivers, showing that tail flows in the region 10-12 R_E in the tail are primarily responsible for the ionospheric Poynting flux.

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