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Multi-channel evolution of Alfvén wave parametric decay in 3-D space plasma

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Large-amplitude, parallel-propagating Alfvén waves are known to interact with density perturbations of the ambient plasma, leading various wave-wave couplings. The wave nonlinearity plays an important role in space plasmas such as solar wind's evolution into turbulence. The decay instability is one of the wave-wave interaction types, and is considered the dominant process in low-beta plasmas, as established by the early theoretical studies in 1970's and also by numerical studies in 1980's. The earlier simulation studies focused on the decay process in one-dimensional spatial configuration, which limits the daughter waves to develop only along the mean field. But in fact, two-dimensional theoretical analyses as well as magnetohydrodynamic simulations assure the importance of parallel-type decay dominating over the growth rate for the oblique-type decays (with density perturbations propagating obliquely to the mean field). In a more general situation with the 3-D spatial configuration, the decay of Alfvén wave can develop not only along the mean field but also obliquely or perpendicular to the field. The parametric instabilities are also sensitive to the polarization sense of the pump wave. Recent 3-D hybrid simulations for circularly polarized pump Alfvén waves show that the wave-wave couplings occur in a multi-channel fashion with a competition between the decay instability (generating daughter waves parallel to the mean field) and the filamentation and magnetoacoustic instabilities (generating daughter waves in the perpendicular direction).

Moreover, the magnetic filaments and magnetosonic waves excited by the oblique-type instabilities develop nearly gyrotropically around the mean field. The 3-D hybrid simulations show the evidence that the perpendicular scattering and heating of protons by the obliquely-propagating daughter waves is efficient. Thermal core particle population is effectively heated in three dimensions as well in the longitudinal (to the wavevector) and parallel (to the mean magnetic field) directions. The oblique-type parametric instabilities are likely operating in the inner heliosphere, and are a possible heating mechanism of solar wind. The 3-D hybrid simulations provide more realistic predictions for the wave-heating problem in nonlinear space plasma dynamics. The on-going measurements by Parker Solar Probe and Solar Orbiter may as well find the filaments and the magnetosonic waves in the inner heliosphere.

References

[1] H. Comisel *et al*, Earth Planets Space **72**, 32 (2020)

[2] H. Comisel *et al*, Ann. Geophys. **39**, 1 (2021)

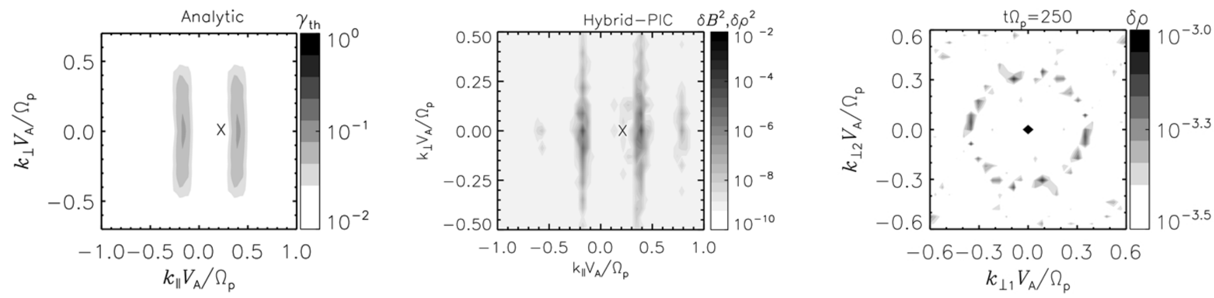

Figure 1. Multi-channel evolution of Alfvén wave parametric decay in 3-D space plasma. Two-dimensional theoretical analysis of growth rates (left panel, Ref. 2) and density wave spectra from a three-dimensional hybrid simulation in the $k_\parallel$-$k_\perp$ plane (middle, Ref. 2) and $k_{\perp 1}$-$k_{\perp 2}$ plane (right, Ref. 1). The large-amplitude Alfvén mother wave (represented by cross symbol in panels left, middle) is propagating parallel to the ambient magnetic field direction in a low-beta plasma.