Growth rate evaluation for the decay instability in space plasmas

Horia Comişel[1,2], Yasuhito Narita[3], and Uwe Motschmann[1,4]

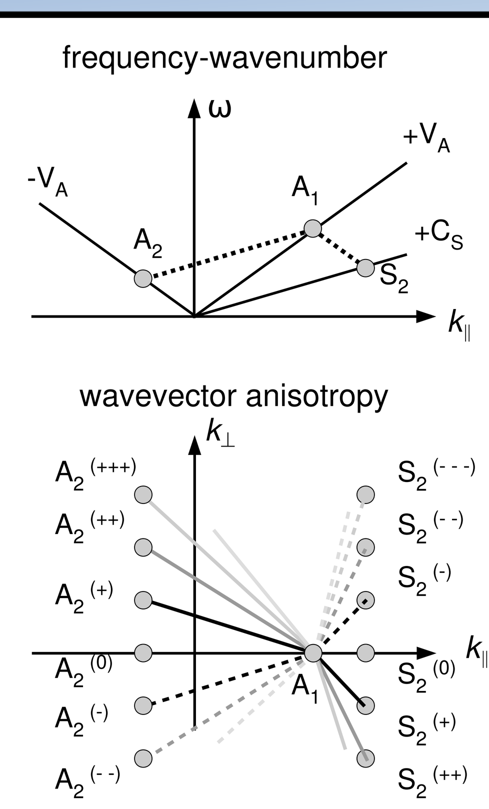
[1]Institut für Theoretische Physik, Technische Universität Braunschweig, Germany, [2]Institute for Space Sciences, Bucharest, Romania,
[3]Space Research Institute, Graz, Austria, [4]Deutches Zentrum für Luft- und Raumfahrt, Institut für Planetenforschung, Berlin, Germany

Abstract

Here we visualize for the first time the growth rate of the decay instability in the 2-D wavevector domain spanning the parallel and perpendicular directions to the mean magnetic field. The growth rate is computed for the density perturbations based on the Hall MHD wave-wave coupling theory, which serves as a proxy for the energy spectrum of the compressive magnetic field fluctuations. The growth rate is then also determined for the daughter waves by considering the conservation of the frequencies and the wavevectors for the wave transmission (additive wave-wave coupling) and the wave reflection (subtractive wave-wave coupling). The visualized growth rate is helpful in evaluating the maximum propagation angle to which the decay instability (of the parallel propagating pump Alfvén wave) operates.

Starting point and motivation

- Former numerical studies, e.g., Matteini et al., 2010, Gao et al, 2013, discovered a broad perpendicular spectrum of Alfvén and density fluctuations developing at the decay of a large-amplitude Alfvén pump wave with linear polarization.
- Recent 3-D hybrid simulations show a similar perpendicular spectrum of daughter waves resulted from the decay of a field-aligned Alfvén wave with circular (left-hand) polarization.
- Here a former Hall-MHD analytic approach is used to check whether the solutions of the dispersion equation can or cannot drive a perpendicular spectrum of daughter waves in accordance with the prediction of the 3-D hybrid simulation.



Schematic representation of the wave resonance conditions for the oblique decay of a field-aligned Alfvén wave (Comişel et al., 2019).

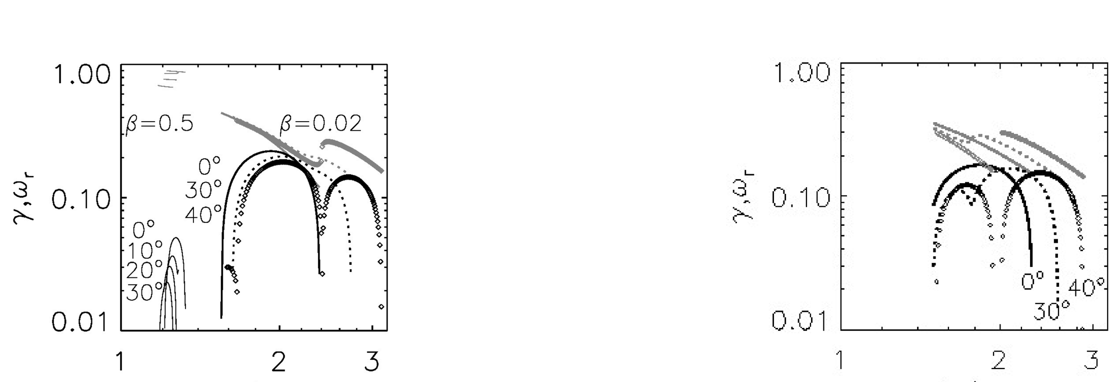
Analytic dispersion analysis

Viñas and Goldstein, 1991 2-D analytic model:

- Two-fluid plasma model together with the generalized Ohm's law.
- Dispersive effects driven by the ion inertia and Hall term.
- 3-wave coupling of the large-amplitude field-aligned Alfvén pump wave ($\mathbf{k}_0$, ω_0) with a density perturbation ($\mathbf{k}$, ω) conducting to parallel- and obliquely- propagating side-band daughter waves:

$$\mathbf{k}^{\pm} = \mathbf{k} \pm \mathbf{k}_0 \qquad \omega^{\pm} = \omega \pm \omega_0$$

- Dispersion equation numerically solved by using Mathematica software.



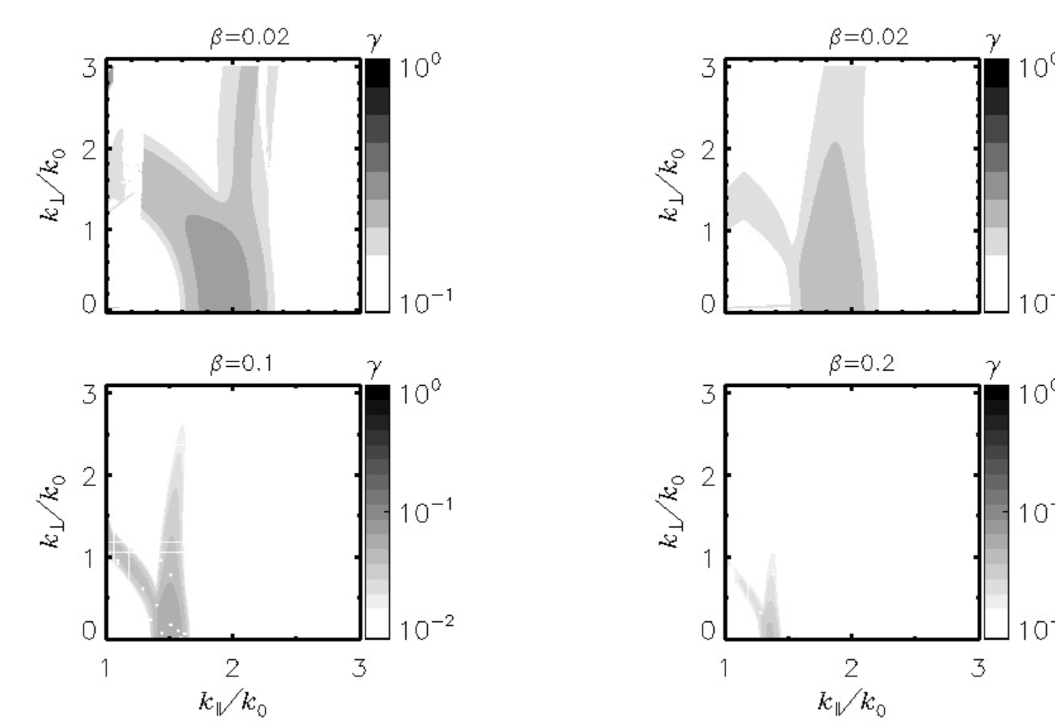
Solutions of the dispersion equation (growth rates in black and frequencies in gray) versus normalized wavenumber for right-handed (panel left) and left-handed (panel right) polarized Alfvén pump waves at propagation angles 0°, 30°, and 40° and plasma beta 0.02.
Left panel also shows the result obtained for right-hand polarization and plasma beta 0.5.

References

Comişel, H., Narita, Y., and Motschmann, U., Ann. Geophys. 37, 835-842, 2019.
Comişel, H., Narita, Y., and Motschmann, U., Earth, Planets and Space, 72:32, 2020.
Comişel, H., Narita, Y., and Motschmann, U., submitted to Ann. Geophys, 2020.
Gao, X., Lu, Q., Li, X., Shan, L., and Wang., Phys. Plasmas 20, 072902, 2013.
Ghosh, S. , Viñas, A.F., and Goldstein, M. L., J. Geophys. Res. 98, 1993.
Matteini, L., Landi, S., Del Zanna, L., Velli, M., Hellinger, P., Geophys. Res. Lett., 37, L20101, 2010.
Müller, J., Simon, S., Motschmann, U., et al., Comp. Phys. Comm. 182, 2011.
Viñas, A.F., and Goldstein M.L., J. Plasma Phys., 46, pp. 107-127, & pp. 129-152, 1991.

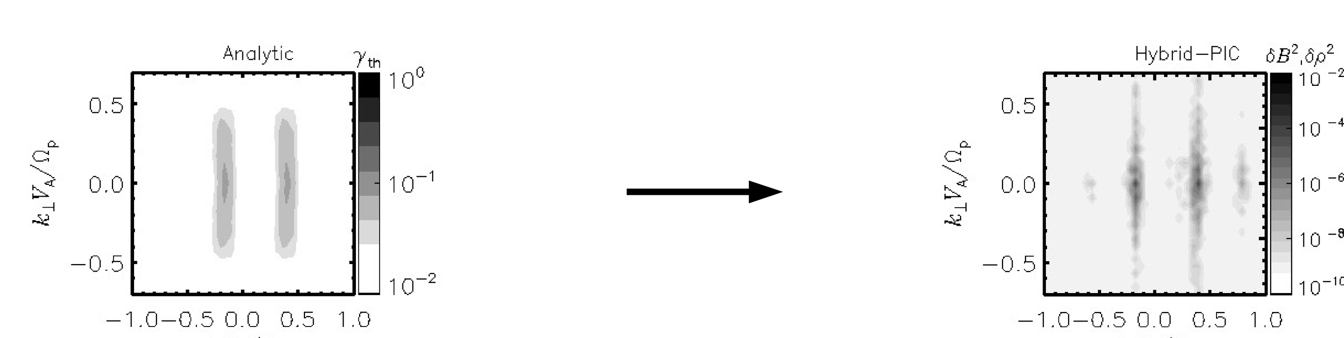
Map of the growth rates

- Diagrams of the growth rates versus the wavenumber and propagation angle are replaced by 2-D wavenumber distributions to be compared with corresponding wavevector spectrum of density and magnetic field fluctuations.
- Perpendicular-shape spectral pattern is seen as a wavevector signature of decay instability in low-beta plasma.



Top: Map of the growth rates in the parallel and perpendicular wavenumber domain for the right-handed (panel left) and left-handed (panel right) polarized Alfvén pump waves at plasma beta 0.02.
Bottom: Growth rates for the left-handed polarized Alfvén pump waves at larger values of plasma beta: 0.1 (panel left) and 0.2 (panel right).

Analytic analysis versus simulation



Comişel et al., (submitted) Comişel et al., 2019

Comparison between the extended map of the growth rates in the wavevector domain (left) and 2-D wavenumber spectrum of density and magnetic field fluctuations (right) from hybrid simulations.

Numerical setup of the 3-D hybrid-PIC simulation used in Comişel et al., 2019:

- A.I.K.E.F hybrid code (Müller et al., 2011).
- Simulation box: L=288d_i & 288x288x288 grid points
- N=500 particles/cell
- Pump wave: $k_{0||}V_A/\Omega_p$=0.21, ω_0/Ω_p=0.19
- Amplitude of the pump wave: $\delta B/B_0$=0.20
- Polarization: circular left-hand (LH)
- Plasma beta: $\beta_i = \beta_e$=0.01

Conclusions

1. The analytic model developed by Viñas and Goldstein, 1991, prescribes that circularly polarized Alfvén waves decay into parallel- and obliquely- propagating daughter waves in low beta plasmas.

2. The growth rates plotted in the two-dimensional domain of the wavevector parallel and perpendicular to the mean magnetic field evince a displacement of the solutions into a perpendicular branch predominant for both left- and right- hand polarization and an "arc"- shape branch which is stronger for the right-handed polarized Alfvén pump waves.

3. The oblique decay significantly decreases at beta values larger than 0.1.

4. The theoretical prediction for left-handed polarized Alfvén pump waves is consistent with the wavevector spectrum of density and magnetic field fluctuations resulted from 3-D hybrid simulations.

5. The growth-rate maps conveniently obtained for various values of the plasma parameters can be used as predictions for further numerical simulations or in-situ measurements.