

## Magnetohydrodynamic instabilities in astrophysical jets

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### Abstract

Astrophysical jets are usually well collimated flows that are observed to propagate over very large distances with respect to their radial extents. It is to date an open question how these supersonic jets survive instabilities. First, using the ideal MHD framework, we present a recent stability analysis of flows embedded in different current-carrying magnetic configurations that are representative of astrophysical jets. The results show that Kelvin-Helmholtz modes remain strongly unstable even in presence of a strong magnetic field (i.e. for Alfvén Mach numbers of order unity). Moreover, magnetic instabilities driven by the density current parallel to the magnetic field are also strongly unstable when the characteristic magnetic pitch length is substantially smaller than the jet radius. In addition, we present nonlinear MHD simulation results illustrating how initially even weak magnetic fields can ultimately control the nonlinear dynamics of unstable shear flow layers (through magnetic reconnection events), and showing how the interplay between current-driven and Kelvin-Helmholtz modes could help to reduce the flow disruption. These various results highlight the role played by the magnetic field and provide important clues to understand the large-scale flow coherence and survival in observed astrophysical jets.

### Motivation

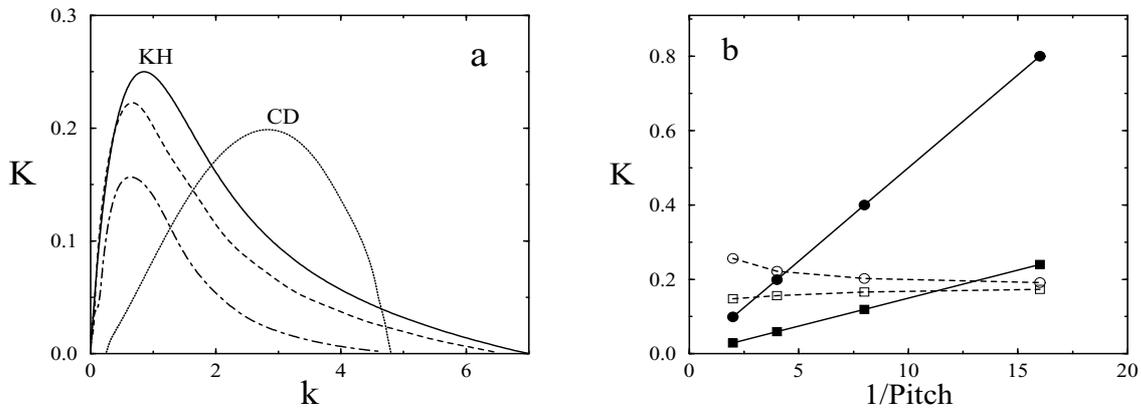
There are many examples of observed astrophysical jets showing a remarkable stability with well collimated flows that propagate over very large distances with respect to their radial extents. This is the case of jets emanating from young stellar objects, and from active galactic nuclei. As these supersonic flows generally terminate in a strong shock with the external medium, this termination is not due to the development of internal instabilities. On the other hand, the magnetohydrodynamic (MHD) theory (confirmed by nonlinear simulations) predicts the development of many destructive modes on a time scale that is too fast by more than one order of magnitude to account for the observations. Thus, it is to date an open question how astrophysical jets survive MHD instabilities.

### MHD stability of current-carrying jets

Most of the previous studies have assumed flows embedded in a purely uniform magnetic field aligned with the plasma velocity, except in Ref. [1] where a linear force-free helical field known as the Bessel Function Model (BFM) is considered. Such magnetic configuration carrying an electrical current is the natural outcome of jets launched by a

magnetocentrifugal mechanism from an accretion disk [2]. The toroidal magnetic field component also provides the collimation of the flow in a self consistent way.

Using the ideal MHD framework, we present a recent stability analysis of trans-magnetosonic/supermagnetosonic flows embedded in general current-carrying magnetic field configurations (see Ref. [3] for the details). We focus on  $m = \pm 1$  ( $m$  being the azimuthal wave number) helical modes of hot flows (with approximate equipartition between thermal and magnetic energies), as  $m = \pm 1$  instabilities are believed to be the most dangerous ones for the integrity of the jets. Two types of instabilities are simultaneously present, with magnetic current-driven (CD) modes dominating the Kelvin-Helmholtz (KH) ones when the magnetic pitch length parameter  $P_i$  (that is a measure of the helicity of the field lines) is approximately smaller than  $0.1R_j$  ( $R_j$  being the jet radius). In the supermagnetosonic regime, the enhanced stability of KH modes due to the presence of the electrical current is much weaker than previously obtained for cold flows embedded in the BFM configuration [1]. Moreover, current-carrying modes of transmagnetosonic flows appear to be more unstable than their current-free counterpart. We have also shown that KH instabilities remain present for rather strong magnetic field (Alfvén Mach number  $M_A$  of order unity). Finally, as the growth length  $1/K$  deduced from this study is roughly a few times the jet radius, we conclude that the presence of the electrical current is not able to substantially stabilize the MHD instabilities. In order to understand the remarkable stability of observed jets, it is necessary to carry nonlinear MHD simulations using these linear results as an important guideline.



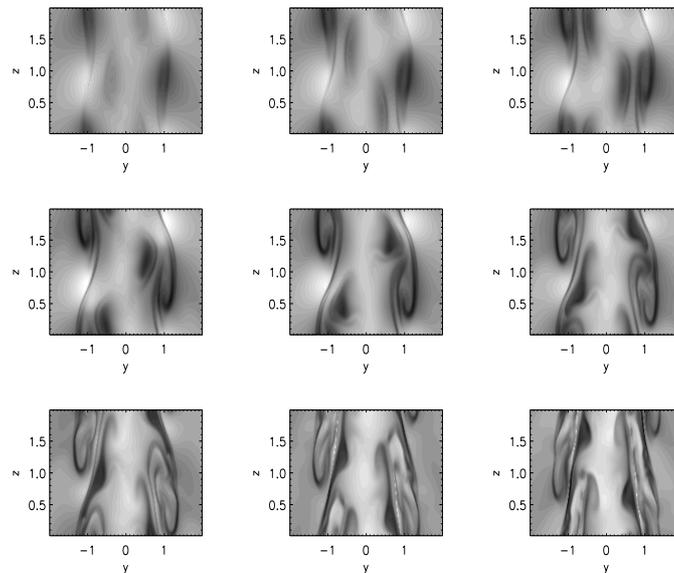
The figure (a) shows the spatial growth rate  $K$  as a function of the axial wavenumber  $k$  for  $m = \pm 1$  instability branches. Flows having a fast magnetosonic Mach number  $M_f = 3$  are taken. A current-carrying case is considered :  $m = -1$  KH mode (dashed),  $m = +1$  KH mode (dash-dotted),  $m = -1$  CD mode (dotted line). A current-free case is also considered ( $m = \pm 1$  KH branch in plain line) for comparison. The figure (b) shows the maximum spatial growth rate as the function of the inverse pitch for CD (filled circles and squares) and KH modes (nonfilled circles and squares) of current-carrying cases. Note that  $R_j = 1$  in our units.

## Nonlinear MHD simulations

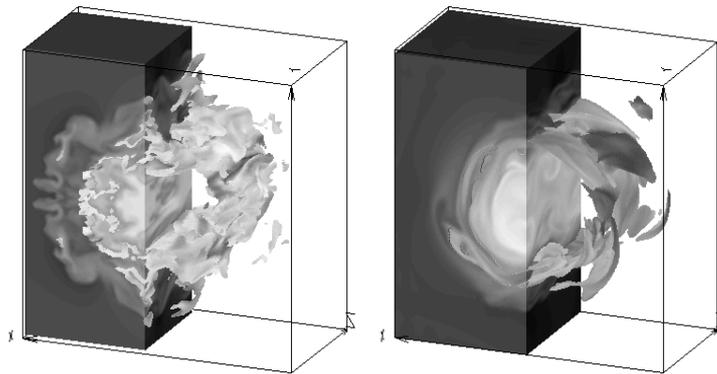
We present two examples of configurations in which initially weak magnetic fields ( $M_A \gg 1$ ) ultimately control the nonlinear dynamics of unstable shear flow layers. To that end, we use the Versatile Advection Code (VAC), that is a finite-volume based shock capturing code, to solve the full set of nonlinear MHD equations as an initial value problem.

Thanks to a grid-adaptive version of VAC, we have followed the growth of many KH vortices developping at the interface of a single two dimensional transonic shear flow layer, which was embedded in a weak uniform magnetic field aligned with the flow (see Ref. [4]). A strong process of large-scale coalescence has been found. It proceeds through continuous pairing/merging between adjacent KH vortices up to the point where a final large-scale structure reaches the domain dimensions. This trend towards large scales is accompanied by magnetic reconnection events that are able to partially disrupt the vortices at different stages of the evolution (thus releasing a non negligible part of the perturbed energy), leading to an enlarged (in the cross stream direction) flow layer of heated and lower density plasma. The extension of these results to a 2D slab jet is actually under current investigation.

Second, a three dimensional magnetized cylindrical jet configuration is considered (see Ref [5]). The flow is assumed to be axial, sheared in the radial direction with an hyperbolic tangent form, and is embedded in an helical magnetic field. We take a periodic domain with an axial length equal to the linearly dominant axial wavelengths (neglecting coalescence effect in this study), and the jet surface is perturbed at  $m = \pm 1$  azimuthal mode numbers. As predicted by stability theory, a  $m = -1$  KH mode develops at the interface, while the jet core is affected by the growth of a  $m = -1$  CD instability (see the KH vortices in the figure below). As time proceeds, an interplay between both instabilities is observed. Finally, the subsequent disruptive effect on the flow is shown to be weaker than in similar magnetized configurations without CD mode.



Grey scale images of the density distribution in the  $y - z$  plane (2D cut at  $x = 0$ ), at different times running from left to right and top to bottom.



The 3D jet structure at the end of the simulations for jets in a pure axial (left) and in helical (right) magnetic field. Shown is the axial velocity on various cross-sections and an isosurface corresponding to the jet boundary.

## Conclusion

Astrophysical jets are strongly linearly unstable even in presence of a moderately strong helical magnetic field. In particular, they are liable to KH and CD modes (with the same importance) that can grow on a fast time-scale. The role of the magnetic field (via its geometry) appears to be crucial during the non-linear evolution, being able to weaken the disruptive effect on the flow. The results will be extended to explore a much wider parameter space with more realistic radial profiles of the flow velocity and magnetic field configuration.

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