How can jets survive MHD instabilities ?

Hubert Baty
Observatoire Astronomique, 11 Rue de l'université 67000 Strasbourg, France

Rony Keppens
FOM-Institute for Plasma Physics Rijnhuizen, Association Euratom/FOM, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands

Pierre Comte
Institut de mécanique des fluides, 2 Rue Boussingault, 67000 Strasbourg, France

December 3, 2003

Abstract. We present the main findings of two recent studies using high-resolution MHD simulations of supersonic magnetized shear flow layers. First, a strong large-scale coalescence effect partially countered by small-scale reconnection events is shown to dominate the dynamics in a two-dimensional layer subject to Kelvin-Helmholtz (KH) instabilities. Second, an interaction mechanism between two different types of instabilities (KH and current-driven modes) is shown to occur in a cylindrical jet configuration embedded in an helical magnetic field. Finally, we discuss the implications of these results for astrophysical jets survival.

Keywords: Jets – MHD – numerical

1. Introduction

It is to date an open question how astrophysical jets survive MagnetoHydroDynamic (MHD) instabilities (Ferrari 1998). Indeed, there are many examples of observed jets showing a remarkable stability with well collimated flows that propagate over large distances with respect to their radial extents. This is the case of jets emanating from young stellar objects, and from active galactic nuclei for Fanaroff-Riley type II sources. These collimated flows terminate in a strong shock with the external medium and hence, this termination is generally not due to the development of internal instabilities.

On the other hand, MHD stability theory 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 observed long-term coherence in the jet. This is the case of Kelvin-Helmholtz (KH) instabilities that are seen to disrupt supersonic jets in high resolution MHD simulations. This is mostly evident in three dimensional (3D) hydrodynamics where a strong turbulent transition characterizes the disruption (Bodo et al. 1998).

Generally, collimated astrophysical jets are magnetized although the dominant contribution to the jet energy is the kinetic one. However, the results on jet survival in MHD simulations are much less clear. While the presence of a weak longitudinal magnetic field seems to have a negligible effect as compared to a pure hydrodynamic configuration, an azimuthal field provides a substantial stabilization (Hardee et al. 1997, Rosen et al. 1999). Thus, a full understanding of the role played by the magnetic field in non linear MHD is of prime importance. This article focuses on particular aspects of the full problem: namely, the magnetic reconnection and large-scale coalescence effects associated with the development of KH modes, and the mutual interaction between two different types of MHD instabilities. Other attempts to stabilize highly supersonic jets invoke jet densities much higher than that of the surrounding medium and/or favorable radiative effects (Downes et Ray 1998, Micono et al. 2000, Stone et al. 1997), but these complications are are beyond the scope of the present paper.

The paper is organized as follows. The main results on the development of KH instabilities occuring in a two-dimensional (2D) magnetized shear flow layer are presented in Section 2. In particular, configurations allowing the growth and mutual interaction of many linearly dominant wavelengths along the layer are examined. In Section 3, we focus on the interplay beween KH and current-driven (CD) instabilities occuring in a cylindrical jet configuration. Finally, we discuss the consequences of these results in the context of astrophysical jets survival.

2. Magnetic reconnection and large-scale coalescence along a 2D shear flow layer

We summarize here the essential findings of the work by Baty *et al.* (2003), which may play a role for the large-scale coherence of magnetized jet flows.

2.1. Physical model and numerical procedure

We consider a very simple 2D configuration in order to model the interface separating the jet from the surrounding medium. The fluid moves along the longitudinal direction x with a velocity given by

$$v_x(y) = \frac{V}{2} \tanh\left(\frac{y}{a}\right), \tag{1}$$

where a is the half-width of the shear layer situated at $y = 0$. The y direction is the cross-stream, transverse direction. This single shear

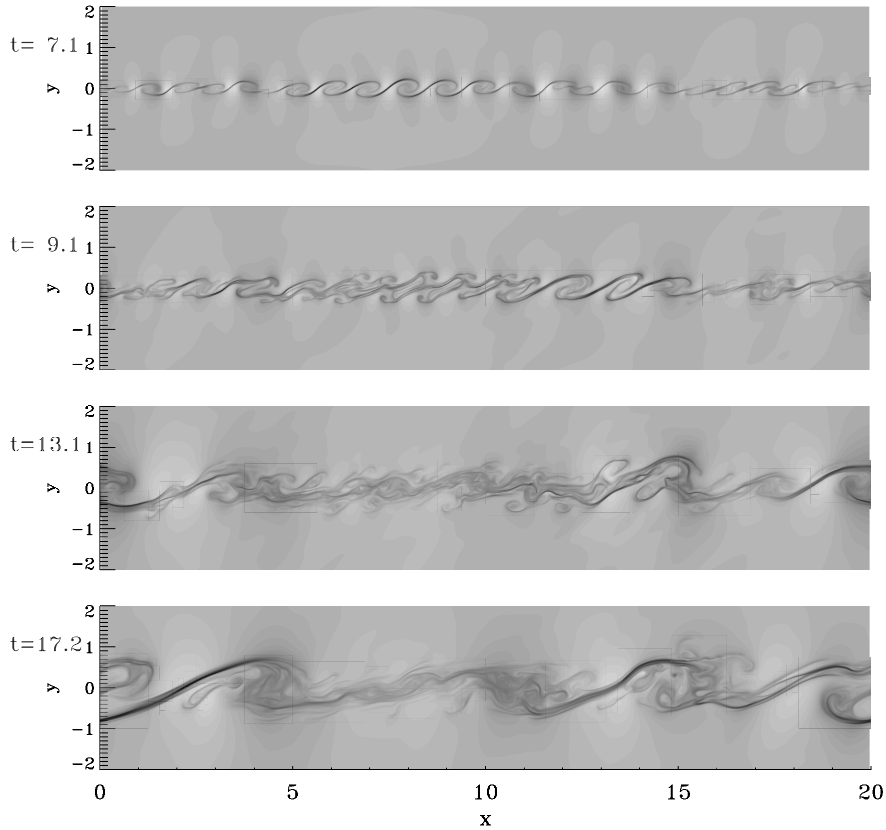

Figure 1. Grey-scale images of the density distribution of a weak field transonic layer ($M_s = 1$) with $M_A = 7$. The contour levels are normalized using a linear scale, and dark regions correspond to low values. Only a part in y of the full grid is shown, and times are indicated at left.

flow layer is embedded in a magnetic field that is aligned with the flow with a uniform strength given by $B_x = B_0$. The initial thermal pressure P, the density ρ, and consequently the sound speed $c_s = (\gamma p/\rho)^{1/2}$ are assumed uniform. In the present study, we fix a and the dimensions of the computational domain $L_x \times 2L_y$ can vary from case to case.

As the kinetic and magnetic Reynolds numbers are supposed to be very large in astrophysical jet environments, the ideal MHD model is considered. Thus, we solve the full set of non linear ideal MHD equations as an initial value problem. The above mentioned configuration is perturbed with a well chosen small amplitude velocity field. For our simulations, we use the general finite-volume based Versatile Advection Code VAC (Tóth 1996) and its recent grid-adaptive variant AMRVAC (Keppens *et al.* 2003). All simulations make use of a second order accurate shock capturing method employing a Roe-type approximate

Riemann solver, namely an explicit one-step total variation diminishing (TVD) scheme with minmod limiting on the characteristic waves. The solenoidal constraint on the magnetic field $\nabla \cdot \mathbf{B} = \mathbf{0}$ is handled by a projection scheme in VAC and by a diffusive source term treatment in AMRVAC. We assume periodicity along the longitudinal direction, and we use free outflow boundaries on the lateral sides at $y = \pm L_y$.

2.2. Magnetic reconnection for the linearly dominant KH mode in the disruptive regime

We have extended results previously obtained for the subsonic/transonic regime ($M_s \leq 1$) to a 'supersonic' flow layer with $M_s \geq 1$ (Frank et al. 1996, Jones et al. 1997). Note that the sonic Mach number is $M_s = V/C_s$ in our definition. A domain length $L_x \simeq \lambda_m$ is chosen, where λ_m is the longitudinal wavelength of the linearly fastest growing mode, in order to follow the development of the linearly dominant KH instability. We have performed VAC simulations at a maximum (uniform) resolution of 400×800 grid cells. The nonlinear evolution of an isolated KH billow for a sonic Mach number $M_s = 1.4$ layer is in many respects similar to its transonic counterpart (Mach $M_s = 1$). In particular, the disruptive regime (relevant for astrophysical jets) where locally amplified, initially weak magnetic fields, control the nonlinear saturation process is found for Alfvén Mach numbers $4 \lesssim M_A \lesssim 30$ (where $M_A = V/V_a$, and V_a is the Alfvén speed). The most notable difference is that higher density contrasts and fast MHD shocklet structures are observed for this slightly supersonic regime $M_s = 1.4$. For $M_s >> 1$ cases, the dominant instability changes character having both a low linear growth rate and a low saturation level, making thus the highly supersonic regime not dangerous for the integrity of the flow.

Slightly beyond the KH saturation, a magnetic reconnection process is triggered due to magnetic reversals, leading to the release of the perturbed energy during the further disruption of the billow. In this disruptive regime, the evolution ends up in a relaxed state with an enlarged (in the cross stream direction) central flow layer of heated and lower density plasma. The disruption of the background flow is consequently weak because it is limited to a region surrounding the initial layer.

2.3. Large-scale coalescence for extended domains

Large-scale coalescence is excluded in configurations having small L_x length values. Thus, we have performed simulations for configurations having extended domain dimensions. Thanks to AMRVAC with a local resolution of 1600×1600, a maximum value of L_x allowing the

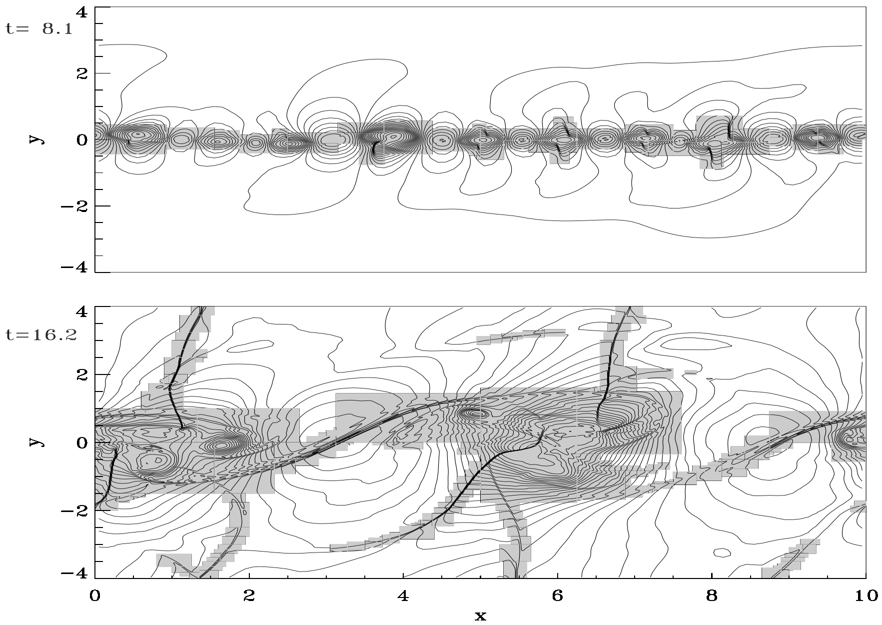

Figure 2. Contour levels of the density for 2 snapshots in the evolution of a supersonic layer $M_s = 1.4$ with $M_A = 100$. Also indicated is the location of the finest level grids in the grid-adaptive simulations: note how the shock fronts are fully captured at the highest resolution.

initial growth of 22 linearly dominant longitudinal wavelengths has been obtained. A strong process of large-scale coalescence has been found, whatever the magnetic field regime. It proceeds through continuous pairing/merging events between adjacent vortices up to the point where a final large-scale structure reaches the domain dimensions. This trend towards large scales is also accompanied by magnetic reconnection events that are able to partially disrupt the vortices at different stages of the evolution, releasing thus a non negligible part of the perturbed energy. The evolutions as seen in density images of transonic and supersonic layers are shown in Figures 1 and 2, respectively.

3. Interplay between Kelvin-Helmholtz and current-driven instabilities

More details about the results of this section can be found in Baty & Keppens (2002). Again, we restrict ourselves to the main findings relevant for astrophysical jets.

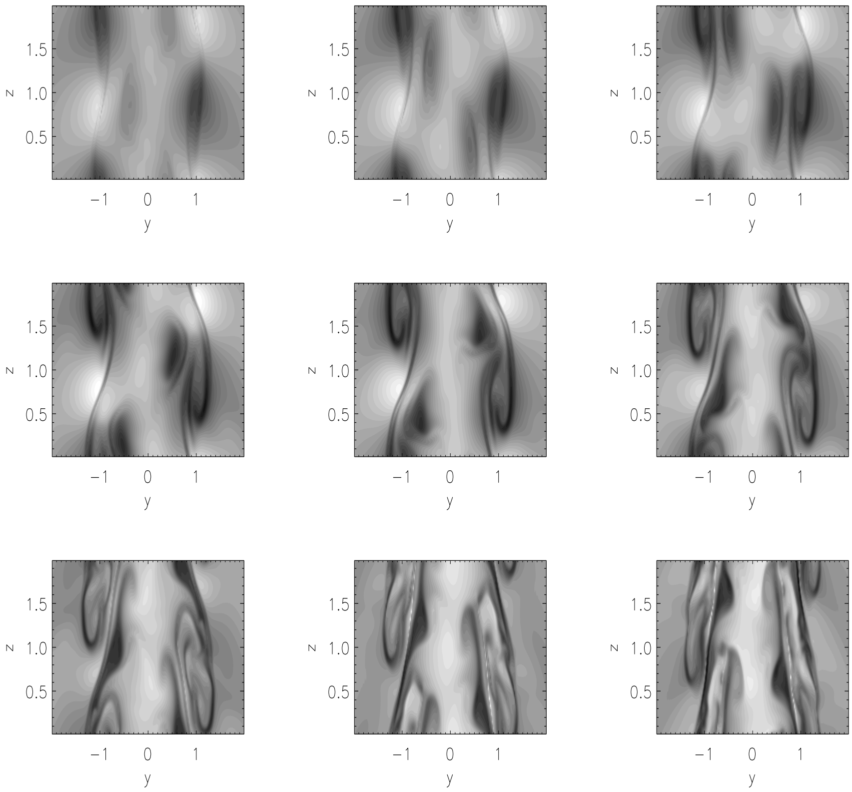

Figure 3. Grey scale images of the density distribution in the $y - z$ plane (using a 2D cut at $x = 0$) of a 3D jet evolution with simultaneous development of a KH and a CD instability. The times are $t = 6.5, 7, 7.5, 8, 8.5, 9, 9.5, 10, 10.5$, running from left to right and top to bottom.

3.1. Physical model and numerical procedure

We consider a 3D magnetized cylindrical jet configuration. The flow is axial, sheared in the radial direction (an hyperbolic tangent form similar to Equation 1 is assumed), and is embedded in an helical magnetic field. A sligthly supersonic regime is investigated with sonic and fast magnetosonic Mach numbers equal to 1.26 and 1.24 on axis, respectively. The strength of the axial field component is chosen to be weak, in accord with the 'disruptive regime' (Ryu et al. 2000). Using the VAC code with a resolution of $200 \times 200 \times 100$ grid cells, we follow the time evolution of a periodic section of the flow. We take an axial length equal to the linearly dominant axial wavelength $L_z \simeq \lambda_m$, where the jet surface is perturbed at $m = \pm 1$ azimuthal mode numbers.

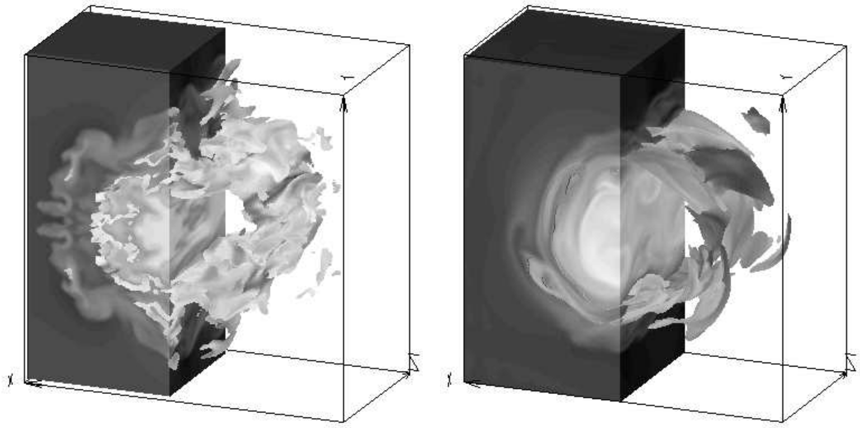

Figure 4. The 3D jet structure at the end of the simulations for jets in a pure axial (left), and in helical (right) magnetic field. Shown is the axial velocity V_z on various cross-sections, and an isosurface $V_z = 0$ corresponding to the jet boundary.

3.2. Results

A $m = -1$ KH surface mode linearly develops dominating the $m = +1$ KH one, in agreement with results obtained using an independent ideal stability code. This lifted degeneracy, due to the presence of the helical field, leads nonlinearly to clear morphological differences in the jet deformation as compared to uniformly magnetized axial configurations. As predicted by stability results, a $m = -1$ CD instability also develops linearly inside the jet core for configurations having sufficiently twisted magnetic field lines (Appl et al. 2000). As time proceeds, this magnetic mode interacts with the KH vortical structures and significantly affects the further nonlinear evolution. This can be clearly seen in Figure 3. The magnetic field deformation induced by the CD instability provides a stabilizing effect through the resulting changes in the azimuthal component B_θ: at the time of KH saturation, the helical field component is locally amplified at the jet surface, hampering the further KH development. This saturates the KH vortices in the vicinity of the jet surface. Beyond saturation, the subsequent disruptive effect on the flow is weaker than in cases having similar uniform and helical magnetic field configurations without CD mode, as illustrated in Figure 4.

4. Discussion

We have presented two examples of configurations in which initially weak magnetic fields ultimately control the non linear dynamics of unstable shear flow layers.

First, magnetic reconnection events are able to partially release the perturbed magnetic energy in the nonlinear development of KH instabilities that affect a 2D magnetized shear flow layer, even in the presence of a strong large-scale coalescence. The long-term disruptive effect on the flow is thereby weaker compared to a 3D purely hydrodynamic configuration. Second, the presence of CD instabilities developing in the jet core can aid in jet survival. Indeed, they can interact with surface KH modes leading to a low saturation level of KH vortices situated at the jet interface. The subsequent disruption of the flow is weaker compared to a similar configuration without CD modes.

For the sake of understanding the essential physics and clearly separate cause and effect, idealized configurations have been assumed in these two studies. In order to reach definite conclusions on the role played by the magnetic field in astrophysical jet survival, more realistic configurations need to be investigated. This especially includes higher supersonic regimes and more complex velocity and/or magnetic field profiles. Nevertheless, such more realistic simulations will quite likely demonstrate that opposing trends to small-scale reconnection and large-scale coalescence, as well as a variety of coexisting hydrodynamic (KH) and magnetic (CD) instabilities can give rise to 3D nonlinear jet dynamics which is less susceptible to disruption.

Acknowledgements

This work was supported in part by the European Community's Human Potential Programme under contract HPRN-CT-2000-00153, PLATON.

References

Appl, S., Lery, T., and Baty, H.:2000, A&A, **355**, 818.
Baty, H., and Keppens, R.:2002, ApJ **580**, 800
Baty, H., Keppens, R., and Comte, P.:2003, Phys. Plasmas, **10**(12), 4661.
Bodo, G., Rossi, P., Massaglia, S., Ferrari, A., Malagoli, A., and Rosner, R: 1998, A&A, **333**, 1117
Downes, T.P., and Ray, T.P. 1998: A&A, **331**, 1130
Ferrari, A. 1998, Annual Rev. Astrophys., **36**, 539
Frank, A., Jones, T. W., Ryu, D., and Gaalaas, J. B.:1996, ApJ **460**, 777
Hardee, P. E., Clarke, D. A., and Rosen, A.:1997, ApJ **485**, 533
Jones, T. W., Gaalaas, J. B., Ryu, D., and Frank, A.:1997, ApJ **482**, 230
Keppens, R., Nool, M., Tóth ,G., and Goedbloed, J. P.:2003, Comput. Physics Comm. **153**, 317
Micono, M., Bodo, G., Massaglia, S., Rossi, P., Ferrari, A., and Rosner, R.:2000, A&A **360**, 795
Rosen, A., Hardee, P. E., Clarke, D. A., and Johnson, A.:1999, ApJ **510**, 136
Ryu, D., Jones, T.W., and Frank, A.: 2000, ApJ **545**, 475.
Stone, J.M., Xu, J., and Hardee, P. E.:1997, ApJ **483**, 136
Tóth, G.: 1996, Astrophys. Lett. Commun. **34**, 245