INFLUENCE OF INTERNAL ENERGY ON THE STABILITY OF RELATIVISTIC FLOWS

Manuel Perucho[1], Michal Hanasz[2], José María Martí[1], Hélène Sol[3]
[1]*Departament d'Astronomia i Astrofísica. Universitat de València. Burjassot (Spain)*
[2]*Nicolaus Copernicus University. Toruń (Poland)*
[3]*Observatoire de Paris/Meudon (France)*

Abstract A set of simulations concerning the influence of internal energy on the stability of relativistic jets is presented. Results show that perturbations saturate when the amplitude of the velocity perturbation approaches the speed of light limit. Also, contrary to what predicted by linear stability theory, jets with higher specific internal energy appear to be more stable.

1. Introduction

The production of collimated relativistic outflows is common among extragalactic radio sources. The question of why some of these sources produce jets that propagate up to hundreds of kpcs along nine decades in distance scale (as, e.g., Cyg A) whereas others (e.g., 3C31) decollimate and flare after few kpc, arises naturally. To give an answer, the analysis of the nonlinear stability of relativistic flows against the growth of Kelvin-Helmholtz (KH) perturbations emerges as a powerful tool.

Focusing on the relativistic regime, the linear growth of KH perturbations both in the vortex sheet approximation (see Birkinshaw 1991a for a review), and sheared flows (Birkinshaw 1991b, Hanasz & Sol 1996) has been extensively analyzed. However, the nonlinear regime remains practically unexplored with only a couple of papers (i.e., Rosen et al. 1999, Hardee et al. 2001) covering partial aspects of the problem. In the present work, we concentrate on the influence of the specific internal energy in the long term stability of relativistic flows. The reason for this relies on two points: i) it is a genuine relativistic effect and no numerical study has been yet performed for it (Rosen et al. 1999 have reported preliminary results), and ii) a remarkable stability of extremely *hot* jets has been found in simulations (see, e.g., Martí et al. 1997), in contradiction with predictions of linear stability analysis.

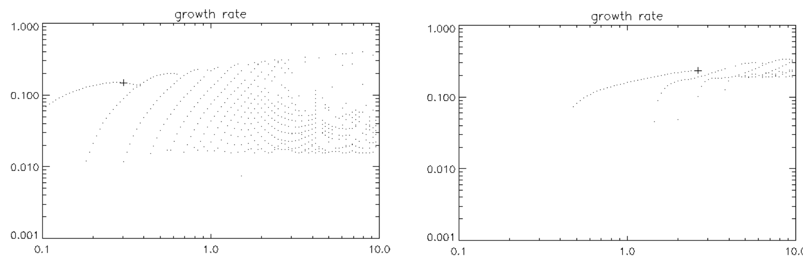

Figure 1. Dispersion relation solutions for models A (left) and D (right) in Table 1. Panels show growth rates in terms of longitudinal wavenumber. Crosses indicate the excited modes.

2. Numerical simulations

We focus on the simplest geometrical configuration of two dimensional planar relativistic flows and apply the temporal stability analysis, i.e., we consider perturbations with real wavenumber and complex frequency, what gives modes which grow in time. For any equilibrium model, the dispersion relation (for symmetric modes in a slab relativistic jet; see, e.g., Hanasz & Sol 1996) is solved numerically for different modes (fundamental, body), getting solutions for real (proper frequency) and imaginary (growth rate) part of frequency as a function of wavenumber. The next step is to choose the mode to excite. In our case, we choose the first body mode with the highest growth rate (see Fig. 1).

We start by generating steady two-dimensional slab jet models. A thin shear layer between the ambient medium and the jet is used to achieve equilibrium. Due to symmetry properties, only half of the jet has to be computed. Reflecting boundary conditions are imposed on the symmetry plane of the flow, whereas periodical conditions are settled on both upstream and downstream boundaries. The steady model is then perturbed according to the selected mode, with an amplitude 10^{-5} the background values. The mode wavelength is used as the grid size in the flow direction. The setup of the simulations is given in Table 1.

The growth of the instability depends critically on the *numerical viscosity* of the algorithm. Hence our first aim was to look for suitable numerical resolutions by comparing numerical and analytical results for the linear regime. Resolution perpendicular to the flow appeared to be essential requiring very high resolutions (400 zones/R_b) and thin shear layers with 40 to 45 zones. A (small) resolution of 16 zones/R_b along the jet was taken as a compromise between accuracy and computational efficiency. Lower transversal resolutions and/or thicker shear layers led to

Table 1. Simulation parameters

Model	P	ϵ_b	ϵ_a	ν	λ
A	$2.55\,10^{-3}$	0.08	$7.65\,10^{-3}$	0.11	20.8
B	0.01	0.42	0.04	0.14	9.80
C	0.2	6.14	0.61	0.44	3.15
D	2.0	60.0	6.0	0.87	2.39

Labels a and b refer to ambient medium and jet, respectively. In all simulations, the density in the jet is $\rho_b = 0.1$, Lorentz factor $W_b = 5.0$, adiabatic exponent $\Gamma_{b,a} = 4/3$. In the table, P is pressure, $\epsilon_{a,b}$ is specific internal energy, ν is the relativistic density ratio $(\rho_b(1{+}\epsilon_b)/\rho_a(1{+}\epsilon_a))$, and λ is the wavelength of the excited mode (first body mode). Throughout the paper, physical quantities are expressed in units of the ambient density, ρ_a, the speed of light, c, and the beam radius, R_b.

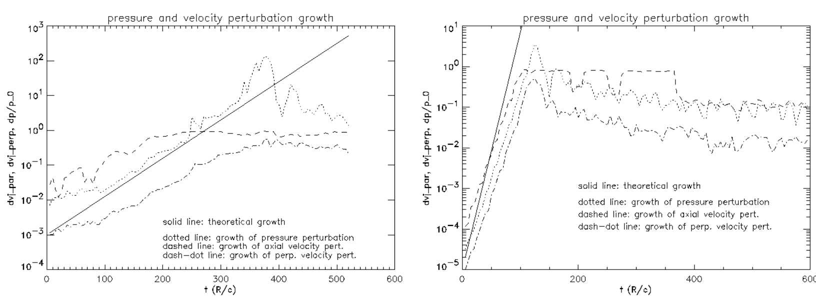

Figure 2. Growth of pressure, axial and perpendicular velocity perturbation for models A (left) and D (right).

non-satisfactory results, with a slow or damped growth. Thinner shear layers gave non-steady initial conditions.

Two phases can be distinguished in all simulations: a phase of linear growth and a mixing phase, separated by the saturation point (Figs. 2, 3). We checked that saturation is reached when the velocity perturbation in the jet reference frame approaches the speed of light (Hanasz 1997). The mixing phase starts after saturation, in connection with the development of a planar shock within the jet flow and a wide shear layer. Disruption may occur besides the mixing phase in some of the models. This phase is characterized by a complete mixing of the ambient and jet materials and an effective spread of the jet's axial momentum into the ambient. In the case of the simulations presented in Table 1, disruption is perceived in models A and B which, according to the linear stability analysis, have smaller growth rates than models C and D.

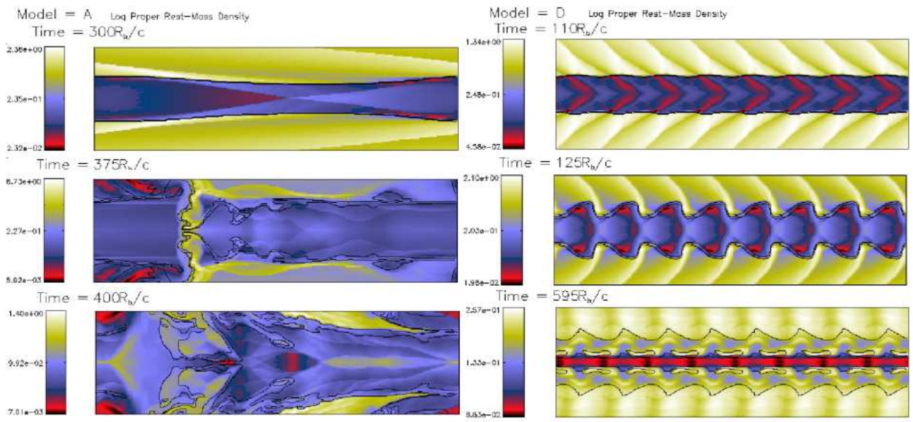

Figure 3. Logarithm of rest mass density in three different instants for models A (left) and D (right). From top to bottom, images correspond to linear phase, mixing phase and disruption (model A), or last image of simulation (model D).

3. Conclusions

Saturation of the growth of perturbations is a very important result (predicted on the basis of post-linear stability analysis by Hanasz 1997). After saturation, disruption is almost immediate, in the cases it occurs. Our results suggest that extremely hot jets are more stable on the long term, contrary to the predictions of the KH linear stability theory. Plots suggest that disruption is related to the pressure amplitude in the saturation point with respect to equilibrium value. It varies from a few in models C and D, to more than two orders of magnitude in models A and B (Fig. 2). The fact that disruption occurs just after saturation suggests that the final fate of the jet must be encoded in the jet properties at the end of the linear phase, however we still have not found such a relation.

References

Birkinshaw M., 1991a, in: Hughes P.A. (ed.), Beams and Jets in Astrophysics (Chap. 6). Cambridge Univ. Press, Cambridge

Birkinshaw M., 1991b, MNRAS 252, 505

Hanasz M., Sol H., 1996, A&A 315, 355

Hanasz M., 1997, in: Ostrowski M., Sikora M., Madejski G., Begelman M. (eds.), Relativistic Jets in AGNs, Kraków, p. 85 (astro-ph 9711275)

Hardee P.E., Hughes P.A., Rosen A., Gomez E.A., 2001, ApJ 555, 744

Martí J.M., Müller E., Font J.A., Ibáñez J.M., Marquina A., 1997, ApJ 479, 151

Rosen A., Hughes P.A., Duncan, G.C., Hardee, P.E., 1999, ApJ 516, 729