# Stability of relativistic two component jets

Dimitrios Millas, Centre for mathematical Plasma Astrophysics,
Department of Mathematics, KU Leuven, 3001 Leuven, Belgium
dimitrios.millas@wis.kuleuven.be

Rony Keppens, Centre for mathematical Plasma Astrophysics,
Department of Mathematics, KU Leuven, 3001 Leuven, Belgium

Zakaria Meliani, LUTH, Observatoire de Paris-Meudon, 92195 Meudon, France

February 15, 2016

**Abstract**

Several observations of astrophysical jets show evidence of a structure in the direction perpendicular to the jet axis, leading to the development of spine & sheath models of jets.
Two-component jets have been already examined for relativistic hydrodynamic jets and relativistic magnetized jets with poloidal magnetic field. These studies focused on a two-component jet consisting of a highly relativistic inner jet and a slower - but still relativistic - outer jet surrounded by an unmagnetized environment. These jets were susceptible to a relativistic Rayleigh-Taylor-type instability, depending on the effective inertia ratio of the two components.
This work is now extended by taking into account the presence of a non-zero toroidal magnetic field. We examine analytically the stability of this configuration and also perform numerical simulations, using MPI-AMRVAC, to compare with the previously studied cases. Depending on the configuration, the toroidal magnetic field might stabilize the previously mentioned case or trigger instabilities on a different time scale. Furthermore, the introduction of a toroidal magnetic field component allows examining different types of relativistic jets (Poynting dominated or matter dominated) by modifying the magnetization parameter. Thus, we can investigate different combinations of matter/ Poynting dominated two-component that will end up (un)stable. Preliminary results, still in the kinetically dominated jet regime, indicate the triggering of additional modes compared to the purely poloidal case.

## 1 Introduction

Observations in multiple wavelengths imply that astrophysical jets are not homogeneous but mostly they display a two component structure. For instance, variability in TeV implies high values of Lorentz factor $\gamma$ and ultra relativistic bulk motion of the jet, whereas radio observations of the parsec scale structure indicate a broad, slow (but still relativistic) motion (Ghisellini et al. 2005). Consequently, at least in terms of velocity, we can distinguish two different regions: a fast inner and a slower outer jet, where the fast component is believed to be lighter than the outer (Giroletti et al. 2004). Similar structure is believed to be present on different scales, from BL Lac to YSO jets (Baccioti et al. 2000). The configuration of the velocity & magnetic field and the energy balance in each component may be important for the evolution and propagation of the jet and may also explain features like the FRI-FRII dichotomy.

## 2 Previous work & Simulations

Two component jets have been previously treated in a number of papers (e.g. Meliani & Keppens 2007,2009, Matsakos et al. 2008). Meliani & Keppens (2007,2009) focused on non-axisymmetric instabilities induced by differential rotation between the two jet components. The evolution of these instabilities was examined in both relativistic hydrodynamic (2007) and magnetohydrodynamic jets (2009). In the second case, a simple configuration of a magnetic field with only non-zero poloidal component was used. We will now extend this work by examining the effects of an additional toroidal field component. The chosen parameters are appropriate for AGN jets. The mechanism can be tested for other astrophysical objects in different scales.

We will follow the overall configuration of the jet and the normalization as described in [1]. We state that the area of interest corresponds to a plane perpendicular to the jet axis, in a distance far from the central engine. In this scenario, the jet is already considered to be accelerated to high values of Lorentz factor and collimated, without examining the contributing mechanisms. Regarding the units, we assume $c = 1$, the unit length is 1pc and a scaling value for the number density is set as $\simeq 10^-3\ cm^{-3}$. The mass is normalized to the proton mass.

First we define the toroidal component of the velocity, which will include a discontinuity between the two jet components. We assign the following rotation profile to the jet, with different values of $\alpha$ for the inner & outer component:

$$V_\phi(R) = \begin{cases} v_{\phi in}\left(\dfrac{R}{R_{in}}\right)^{\alpha_{in}/2}, & R \leq R_{in} \\ v_{\phi out}\left(\dfrac{R}{R_{in}}\right)^{\alpha_{out}/2}, & R > R_{in} \\ 0, & R > R_{out} \end{cases} \tag{1}$$

We assume $\alpha_{in} = 0.5$ for the inner jet and $\alpha_{out} = -2$ for the outer jet. Both components are subsonically rotating , with $v_{\phi in} = 0.01$ and $v_{\phi out} = 0.001$. The relativistic equivalent of Rayleigh's criterion for stability is that the angular momentum flux must increase with the radial distance $R$. The angular momentum flux is given by the formula:

$$I \ = \ \gamma \frac{\rho + \dfrac{\Gamma}{\Gamma - 1}}{p} \rho V_\phi R - \frac{B_p}{\gamma \rho V_p} R B_\phi \tag{2}$$

and thus the inner jet is stable, as $\frac{dI}{dR} > 0$ and the outer jet is marginally stable, as $\frac{dI}{dR} = 0$. The interface between the two components is unstable, as the angular momentum changes significantly at $R = R_{in}$. Regarding the poloidal component of the velocity, we assign a value of Lorentz factor $\gamma_{z,in} = 30$ for the inner jet and $\gamma_{z,out} = 3$ for the outer jet, which are meaningful values for an AGN jet. As the overall velocity of each component is mainly poloidal, the above values are approximately equal to the total Lorentz factor. The jet is surrounded by a static external medium of density $\rho_m = 10^{-2}$ and we assume that the inner jet has a density ($\rho_{in} \simeq 7\rho_{med}$). The density ratio between the two jet components can be calculated using constraints from observations, namely:

- The kinetic luminosity flux for a radio loud galaxy is of the order of $10^{46}$ ergs/s
- The radius of the outer jet, as obtained from observations of nearby AGN (e.g. radio observations of M87, Biretta et al. 2002) is $\sim 0.1$ pc
- The radius of the inner jet is less constrained and can be arbitrarily chosen to be 1/3 of the outer radius

If we allow the inner jet to carry a minimal fraction ($< 1\%$) of the total kinetic luminosity flux, then the density ratio between the components is $\simeq 10^4$. We assume in addition total pressure equilibrium between the two interfaces (inner & outer jet, outer jet & external medium). The effective polytropic index is initially approximately $\frac{4}{3}$ for the inner jet and the external medium and $\frac{5}{3}$ for the outer jet.

We examine two cases: a two component jet with poloidal magnetic field, similar to case B1 of [1] and the same jet including a small toroidal magnetic field component. The poloidal magnetic field is constant in each jet component, with a discontinuity in $R = R_{in}$, as seen in the following equations:

$$B_z(R) = \begin{cases} B_{zin}, & R \leq R_{in} \\ B_{zout}, & R > R_{in} \\ 0, & R > R_{out} \end{cases} \qquad B_\phi(R) = \begin{cases} b_{\phi in}\left(\dfrac{R}{R_{in}}\right)^{\alpha_{in}/2}, & R \leq R_{in} \\ 0, & R > R_{in} \\ 0, & R > R_{out} \end{cases} \tag{3}$$

We define a toroidal component for the magnetic field corresponding to a value of magnetization $\sigma = \frac{B_{\phi in}}{\gamma_{in}^2 \rho_{in}}\Big|_{R=R_{in}} = 10^{-3}$ for the inner jet, while the outer jet still has only poloidal magnetic field. This value of magnetization corresponds to a kinetically dominated jet and the toroidal magnetic field profile is similar to the toroidal velocity profile (3), with $\alpha_{in} = 0.5$. Using (2), we may choose an appropriate value for the magnitude of the inner poloidal field, whereas the value of the outer poloidal field is less constrained. We choose $B_{zin} = 0.5 h_{in} \gamma_{zin} v_{\phi in} \sqrt{\frac{\rho_{in}}{\sigma}}$, where $h_{in}$ is the enthalpy of the inner jet and $B_{zout} = \sqrt{0.001 \gamma_{z,out}^2 \rho_{out}}$. The initial state of the two simulations (velocity, density & pressure) is summarized in Fig. 1.

The simulations are carried out using the relativistic MHD module from the open source, grid adaptive MPI-AMRVAC code ([3],[4]), in 2.5D, assuming translational symmetry along the z-axis. This is justified by the high value of Lorentz factor (in other terms, the flow is supersonic in the z direction) which allows to assume that poloidal instabilities have a low growth rate (or at least much lower than their toroidal counterpart). The computational domain is defined as $-0.3pc < x < 0.3pc$, $-0.3pc < y < 0.3pc$. A base resolution of $200 \times 200$ is used, with 2 levels of AMR (effective resolution $400 \times 400$) in cartesian coordinates. The evolution of the system is described in Figs. 2 and 3, where we show the proper density and average Lorentz factor with time. In the purely poloidal field case, we notice that the Lorentz factor decreases with time and after 1.5 rotation times of the inner jet, the maximum Lorentz factor is decreased to 15. This behaviour is also observed when a toroidal magnetic field component is present, roughly up to 0.8 rotations of the inner jet (which equals 52.24 yrs). When the toroidal component of the magnetic field is non-zero, a mixture of modes is observed and the interface between the outer jet and the external medium is clearly different from the purely poloidal case. Although it is not possible to clearly distinguish the dominant modes, the cartesian setup does favour modes with m=4. This can be clearly observed in the poloidal field case but is less obvious (although the "arms" parallel to x and y axis, thus corresponding to m=4, are wider). No initial perturbation is used in our simulation, but exploring different ways to initialize the mode development may reduce this selection effect.

The evolution of the jet depends on the effective inertia ratio between the two components, namely the value of the expression $\gamma^2 \rho h + B_z^2$, where $\rho$ is the density and $h$ is the specific enthalpy. This is explained following the next steps:

- Momentum equation near equilibrium: $(\gamma^2 \rho h + B_z^2)\left[\frac{\partial}{\partial t} + \vec{V} \cdot \nabla]\vec{V} + \nabla p_{tot} + \vec{V} \cdot \frac{\partial p_{tot}}{\partial t} + ...\right] = 0$
- Ignore temporal variation of total pressure and assume axisymmetry for any velocity perturbation in the direction perpendicular to z axis
- As a first order approximation, we assume that the perturbation speed is potential, $v_\zeta = (\nabla \Psi)_\zeta$ with $\Psi \sim e^{\lambda t - k\zeta}$

Thus we obtain:

$$\lambda^2 \propto (\gamma^2 \rho h + B_z^2)\Big|_{in} - (\gamma^2 \rho h + B_z^2)\Big|_{out} \tag{4}$$

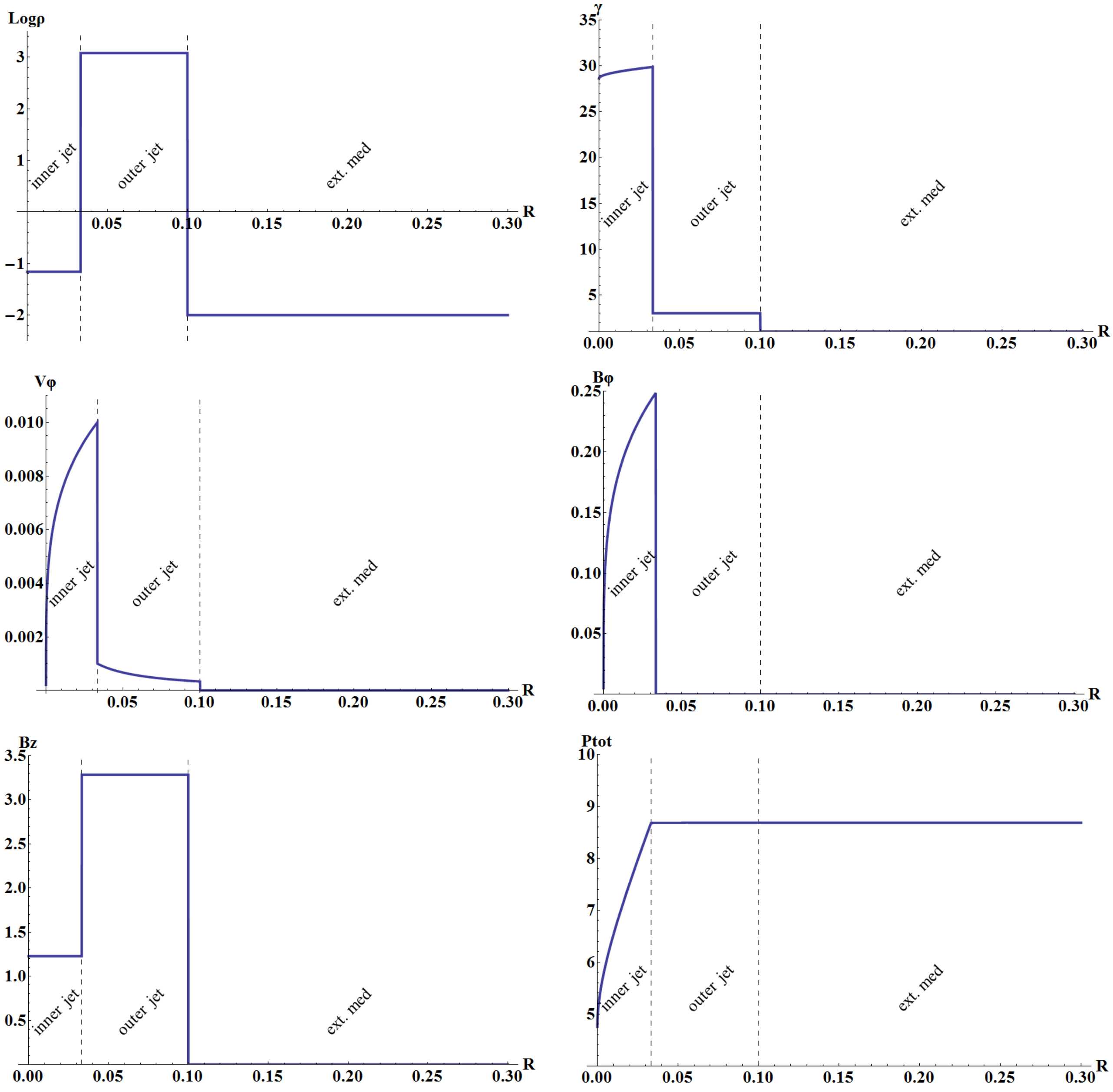


Figure 1: Initial setup of the simulation. Left column: Density, toroidal velocity, poloidal magnetic field. Right column: Lorentz factor, toroidal magnetic field, total pressure. The inner jet extends up to $R_{in} = {}^{0.1}/_{3}$, the outer jet up to $R_{out} = 0.1$.

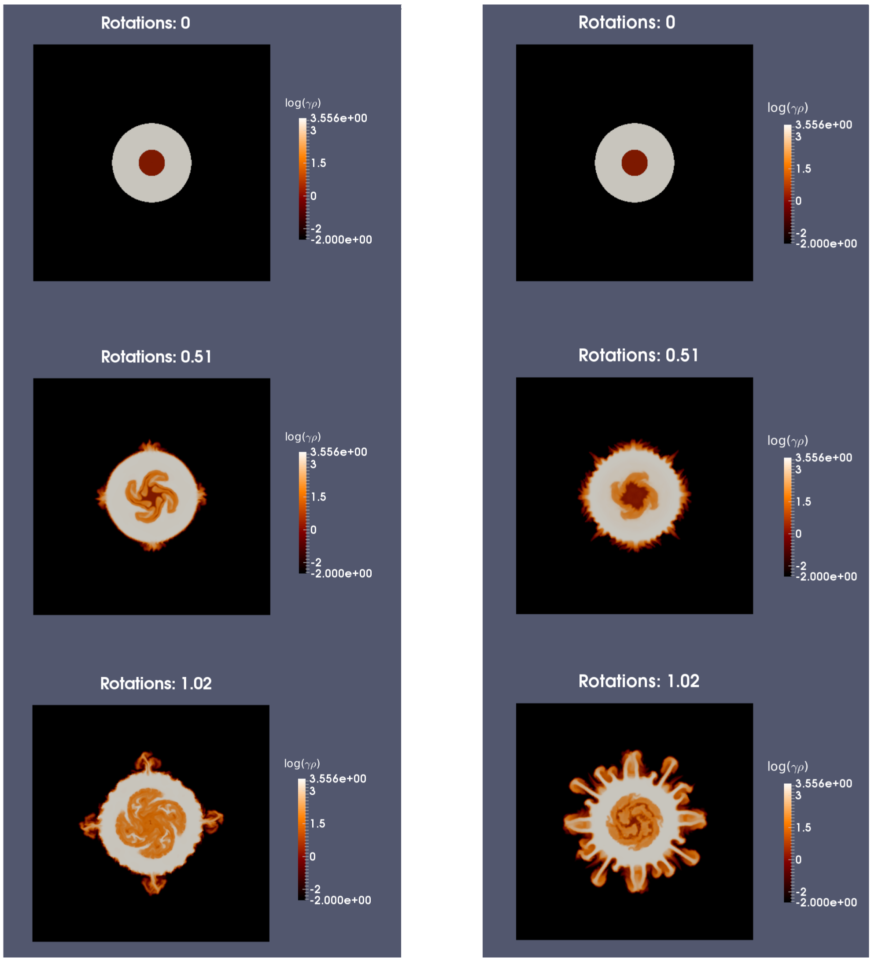


Figure 2: Proper density at 0, 0.5 at 1 rotations of the inner jet (0, 33.3 and 65.3 yrs respectively). The left column corresponds to $B_\phi = 0$ and the right column to $B_\phi \neq 0$

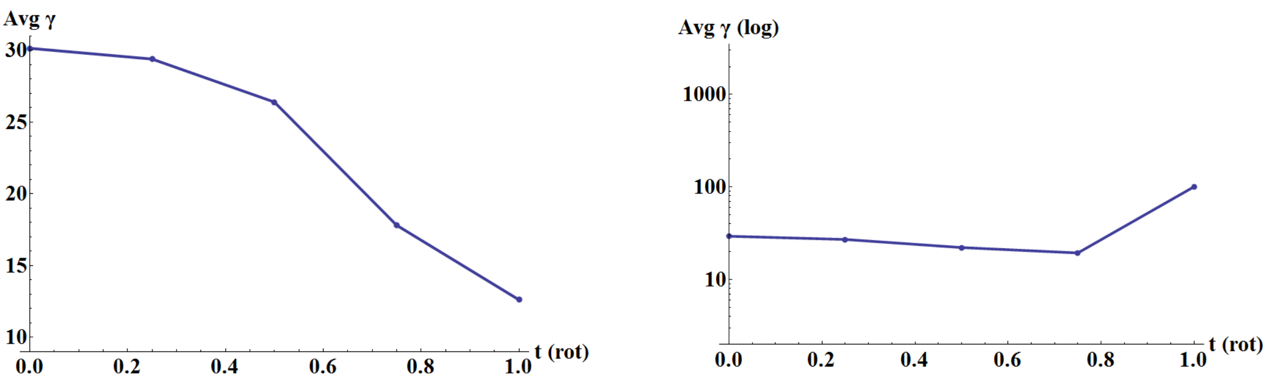


Figure 3: Average Lorentz factor with time (expressed in rotations of the inner jet). The left plot corresponds to $B_\phi = 0$ and the right column to $B_\phi \neq 0$

The dispersion relation of these non-axisymmetric instabilities depends on the difference of effective inertia of the two components. A relativistically enhanced Rayleigh-Taylor type instability ([1]) occurs when the effective inertia of the outer jet is greater than the effective inertia of its inner counterpart: $(\gamma^2\rho h + B_z^2)\Big|_{out} < (\gamma^2\rho h + B_z^2)\Big|_{in}$. In our case, the initial effective inertia ratio (outer vs inner jet) is $\simeq 0.8$, which is consistent with the observed instability.

## 3 Discussion

We examined two cases of two component jets with different magnetic field configuration: a case with purely poloidal magnetic field and a case where a low-$\sigma$ toroidal field is added in the inner jet. In each case, we assume differential rotation and a jump in velocity and density at the interface between the two components.

As expected, the case with zero toroidal field agrees with the results of Meliani & Keppens, 2009. Relativistically enhanced Rayleigh-Taylor type instabilities evolve and the jet decelerates with time. Including low $\sigma$ toroidal field does not stabilize the system, but appears to trigger the instabilities at an earlier moment. The effective inertia ratio (outer jet vs inner jet) in the purely poloidal case is $\sim 0.1$, which is consistent with the development of instabilities. The average Lorentz factor decreases up to 0.8 rotations of the inner jet in both cases, whereas in the second case we observe a significant acceleration. This effect may be present due to rarefaction, although in principle it should not be that prominent. We currently examine this scenario to decide if this is the case or numerical errors are important in our setups.

Future work will focus on analytical studies, which will include previously neglected effects as the curvature of the magnetic field, to produce a better approximation for the dispersion relation of the instabilities when toroidal magnetic field is present. Furthermore, our next simulations will primarily focus on different toroidal magnetic field configurations, and possibly toroidal velocity, mainly with a smooth profile to avoid the steep transition between the two components, while maintaining the jump in density. Later on, 3D simulations will be used to investigate the evolution of these instabilities, in the context of kinetically or Poynting dominated jets, by ejecting a jet with different initial values of $\sigma$. These simulations can also be carried out to explore also the development and/or influence of other types of instabilities, e.g. Kink. Applications in examining the FRI / FRII dichotomy would be possible by adjusting the effective inertia ratio between the two components, thus making the disk wind component much stronger, as required in the case of FRII.

## References

[1] Meliani, Z. and Keppens, R., 2009, ApJ, 705,1594

[2] Meliani, Z. and Keppens, R., 2007, A&A, 475, 785

[3] Keppens et al., 2012, JCP, 231, 718

[4] Porth et al., 2014, ApJS, 214, 4

[5] Ghisellini et al., 2005, A&A, 432, 401

[6] Giroletti, M., et al. 2004, ApJ, 600, 127

[7] Baccioti et al., 2000, ApJ, 576, 222

[8] Matsakos et al., 2008, A&A, 477, 521

[9] Biretta et al., 2002, MNRAS, 46, 239