Simulations of Jet-Environment Interactions

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Abstract

Jet - environment interactions can produce interesting astrophysical phenomena and may be related to features in jets such as the HST-1 in M87. We simulate numerically the interaction between a relativistic, magnetized, axisymmetric jet with a selection of different environments. Two different simulations are shown: the jet interacts with either a static atmosphere (first case) or with accreting material (second case). These interactions are explored by performing magnetohydrodynamic simulations of both the jet and the static atmosphere/Bondi accretion and may provide information about changes in the jet structure. We also examine if conditions which permit rarefaction to appear are created during the interactions and calculate the efficiency of the acceleration to compare with previous works. The simulations are performed using the PLUTO code, v.4.0 (http://plutocode.ph.unito.it).

I. Introduction

The jet of the M87 galaxy is widely studied as it is relatively close to Earth and thus quite easily observed. Observations in different frequencies indicate a transition from parabolic to conical shape, near the Bondi radius (see [1]). This may be the outcome of the interaction between the jet and accreting material in this region, where the hydrodynamic environment is supersonic and a shock may develop. This results in a pressure gradient that affects the shape of the jet.

Assuming that the region of interest is far from the source, we may neglect the poloidal component of the magnetic field. In order to determine the shape of the jet, we need to monitor the fieldlines. This can be done by following the contours of the integrals of motion (in a steady state).

If the poloidal component of the magnetic field is zero, then the integrals are given by the following equations:

$$\mathbf{L} = \xi\gamma\varpi V_{\varphi}$$

$$\Phi = \frac{-B_{\varphi}}{4\pi\gamma\rho_o c\varpi}$$

$$\mu = \xi\gamma + \frac{B_{\varphi}^2}{4\pi\gamma\rho_o c^2}$$

where L is the specific angular momentum, Φ is a function of the angular velocity of the field, μ is the total energy to mass flux ratio, γ is the Lorentz factor, ξ is the specific relativistic enthalpy, ρ_o is the density and ϖ is the cylindrical distance.

We examine the 2.5-dimensional problem (2 dimensions, 3 components) under the assumption of axisymmetry. The simulations are carried out using the RMHD (relativistic MHD) module of the PLUTO code, v.4.0 (see [8]).

II. Relativistic, magnetized jet

We assume a magnetized, relativistic jet with a purely toroidal magnetic field. The toroidal component is selected to be a "bell-shaped" one (see Fig. 1):

$$B_{\varphi}(r,\theta) = B_o \frac{f(\theta)}{f(\theta_o)}\frac{1}{r},\ f(\theta) = \frac{\sin\theta}{1+\left(\frac{\sin\theta}{\sin\theta_1}\right)^2}$$

where θ_o as the angle at which the two different environments are separated and θ_1 is the angle at which the maximum of B_{φ} is located.

This choice of B_{φ} satisfies the following conditions:

- B_{φ} is zero on the z axis
- B_{φ} increases linearly with ϖ near the axis (or the current density is constant)
- After the maximum, the magnetic field decreases, as $1/\varpi$ such that the current density vanishes

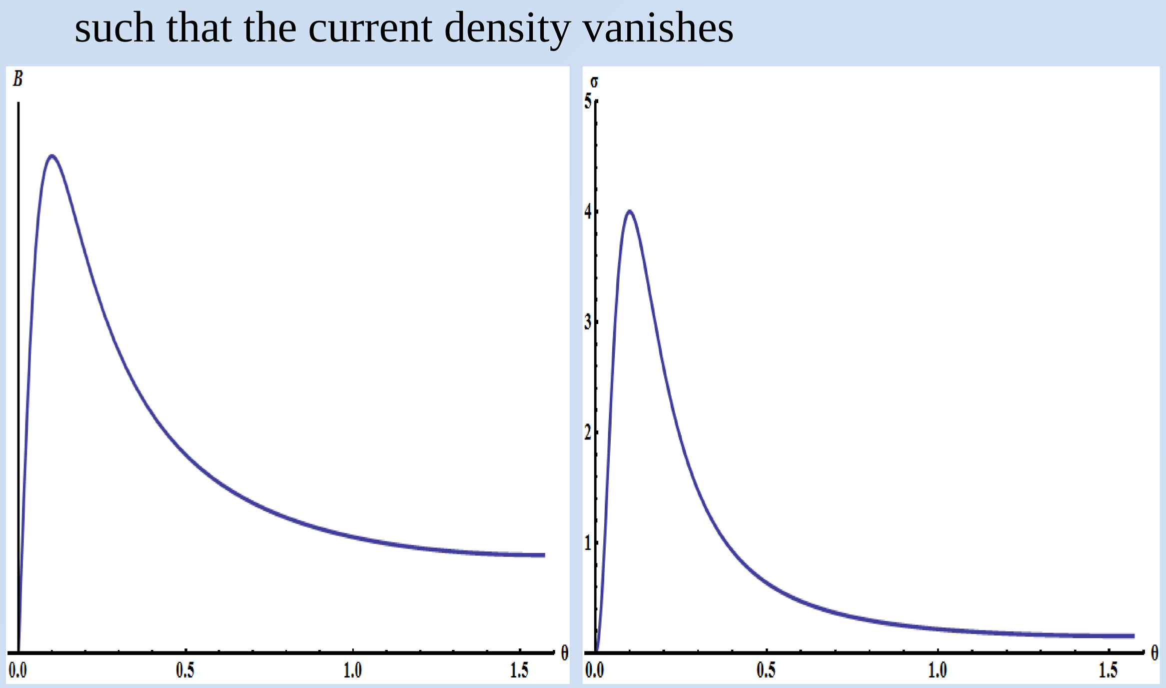


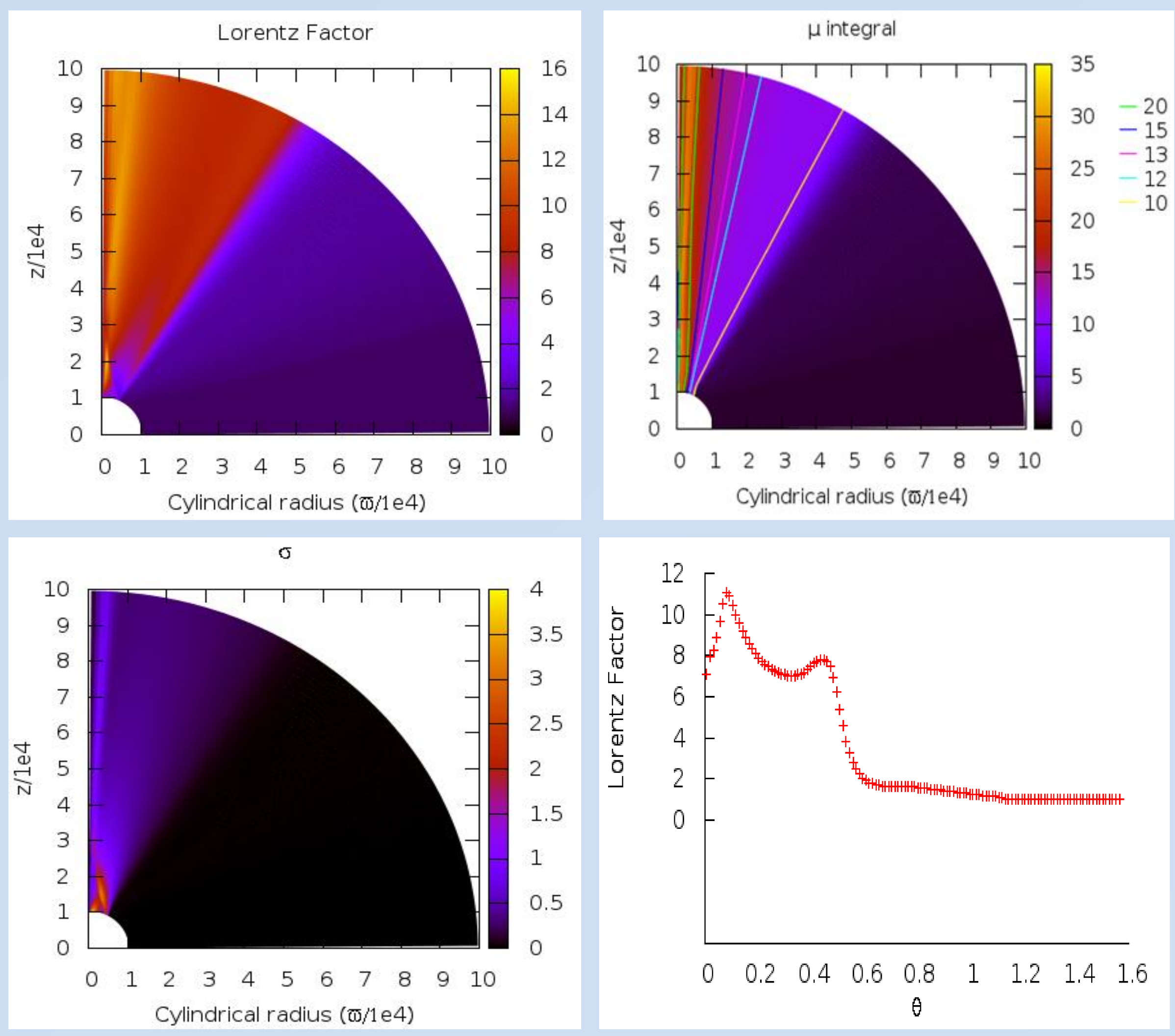
Figure 1: Magnetic field and magnetization (initial configuration) with θ

The jet is ejected with both radial and azimuthal velocity components, with an initial Lorentz factor γ=5 and v_{φ} profile similar to the azimuthal magnetic field profile (the exact profile does not significantly affect the results). The initial maximum value of the magnetization is σ=4 (for θ=θ_1). Density decreases with r as $\rho \propto r^{-2}$ and thermal pressure is obtained from a polytropic law with $\Gamma=5/3$. The sound speed value is selected c_{sj}=0.1c. This selection is necessary to avoid low values of plasma-β that create numerical problems. It results in a relatively high thermal pressure for the jet but still the magnetic pressure is dominant.

III. Jet & Static atmosphere

The simplest choice of environment is a static atmosphere (with the same polytropic index) surrounding the jet. Even though such a scenario is unrealistic for AGN jets, its simplicity helps to familiarize with the interaction between two very different (relativistic & magnetized - non-relativistic & unmagnetized) media.

The jet setup is the one described in the previous section. In order to control the density ratio we assume that the magnetic pressure of the jet and the thermal pressure of the surrounding medium are equal at the lower r-boundary for θ=θ_o. A sound speed value of c_{so}=0.001c is assumed for the surrounding environment (which agrees with X-ray temperatures from observations - e.g see [6],[7]) and results at an initial density contrast between jet and its environment of at least 10^6. In the following figures we present the Lorentz factor γ, the μ integral contours, the magnetization and the distribution of the Lorentz factor γ(θ) at r ~ $3\cdot10^4$ (in light cylinder units R_{lc}, where 1 R_{lc} ~ 5 Schwarzschild radii) after ~10 sound crossing times.



The simulation reaches a steady state. Note than the theoretical maximum value of the Lorentz factor is:

$$\gamma_{max,th} = \mu = \gamma_{in}(\sigma+1)$$

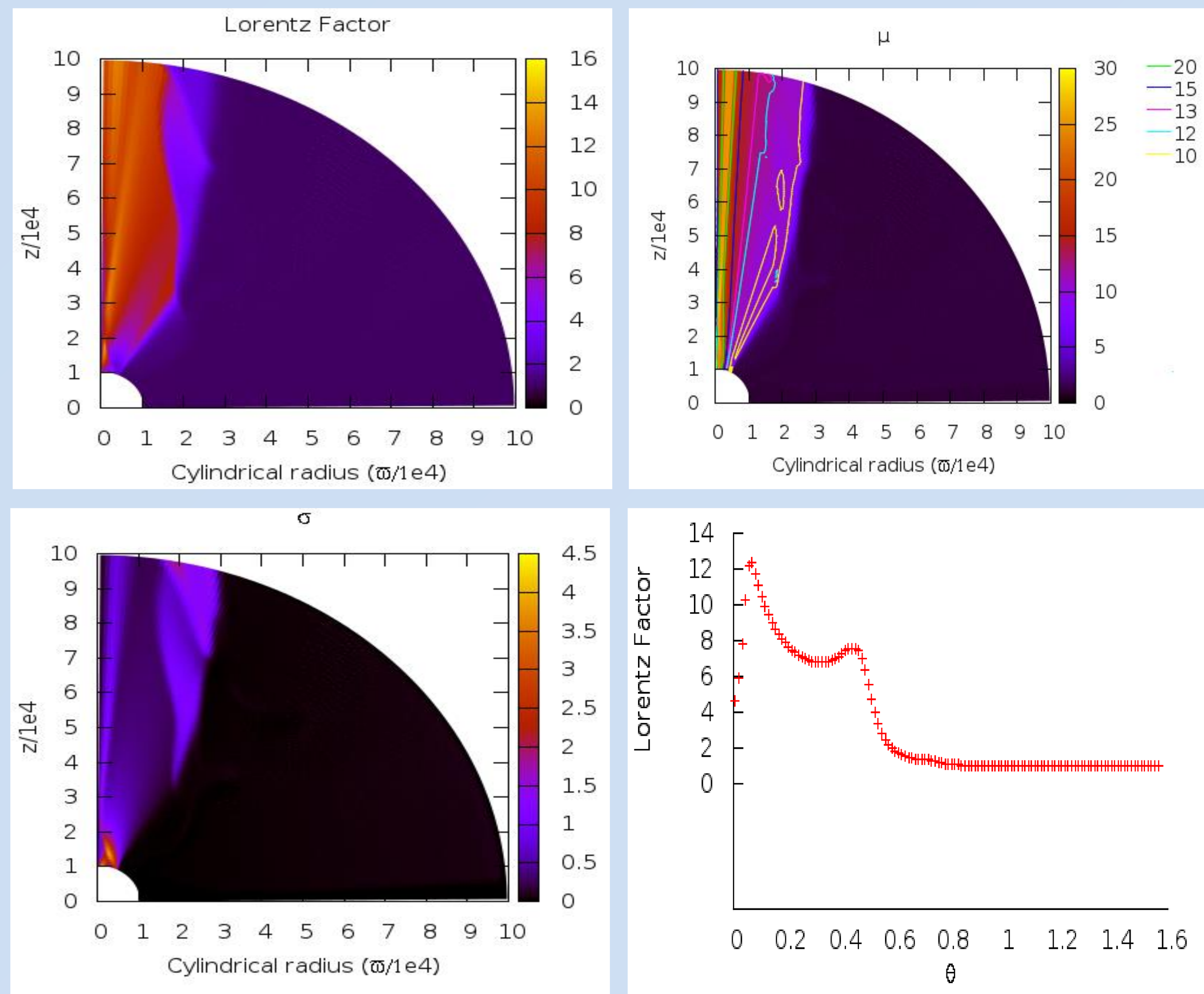
The jet is accelerated up to γ ~15 and as μ=25 the efficiency is about 60%. The inner jet is almost not affected by the interaction with the environment. The fieldlines are approximately parabolic for small values of r near the axis and tend to become radial for high values of r. Fieldlines near the separatrix are radial and remain so for the rest of the simulation.

It is worth mentioning that initially the thermal pressure of the static atmosphere is greater than the magnetic pressure of the jet. The simulation though reaches a steady state in which the jet has clearly expanded. We also note that conditions that favour the development of rarefaction do arise during that interaction. This is evident from the second peak in the γ(θ) plot. Similar results are obtained if the environment is chosen to be of uniform density.

IV. Jet & Bondi Accretion

A more realistic case would be to simulate the interaction between the jet and an accreting (unmagnetized) environment around it.

We use the same setup for the jet and the boundary conditions for the lower r-boundary of the environment are modified in order to produce a shock near the Bondi radius. The upper r-boundary is also modified as we need *outflow* conditions for the magnetized part and *fixed* conditions for the hydrodynamic part. This is achieved by changing between these two choices by examining the magnitude of the magnetic field. The initial density contrast is about 10^5 and the values of Γ, c_{so} are the same as in section III. The following plots represent Lorentz factor γ, the μ integral contours the magnetization and the distribution of the Lorentz factor γ(θ) at r ~ $3\cdot10^4$ after ~10 sound crossing times.



The simulation does not reach a steady state but is rather quasi-periodical (with T ~ 10^5 yrs) and the interaction between the two media is much more complicated. As in the previous case, the efficiency of the acceleration in the inner jet is about 60%. In this case the μ integral cannot be used to exactly follow the fieldlines, but it indicates that in the interaction region the shape of the fieldlines changes (note the μ=10 contour near the Bondi radius, r_B ~$5\cdot10^5$). This change in the shape of the fieldlines (and thus of the jet), while roughly consistent with the observations, is not satisfactory as one would expect the jet to expand at distances greater than the Bondi radius.

The inner jet is not affected by the interaction and once more, conditions that are favourable to rarefaction may develop during the interaction.

	r=10^4	r=10^5	θ=0	θ=$\pi/2$
Static	Fixed	Outflow	Axisymmetric	Eqt. symmetric
Bondi	Fixed	Mixed	Axisymmetric	Eqt. symmetric

Table 1: Boundary conditions for the simulations described in sections III and IV. "Mixed" indicates that outflow conditions are used for the magnetized part and fixed for the hydrodynamic part

VI. Discussion

We examined the interaction between a relativistic, magnetized jet and a hydrodynamic environment. While the interaction with an initially static atmosphere does not produce any significant change in the shape of the fieldlines, an accreting environment is clearly affecting it. In both cases, rarefaction may occur during the interaction, which is something unexpected for AGN jets because of the high density contrast.

In each simulation, the inner jet was largely unaffected by the interaction, regardless of the choice of environment. The final configuration of the magnetic field is still a bell shaped one but quite different from the smooth initial form. This is due to the fact that the transfield momentum equation is not satisfied by the initial conditions. Many already established features for MHD jets are noticed in the inner region of the jet, such as acceleration (efficiency ~ 60%) and collimation. The results are also in agreement with previous works (see [2]-[5]) about the form of the bunching function.

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