# Simulations of jet - environment interactions using the PLUTO code

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Jet - environment interactions can produce interesting astrophysical phenomena that may explain features in jets such as the HST-1 in M87. Using the PLUTO code (v4.0) by A. Mignone et al., we simulate the interaction between a relativistic, magnetized, axisymmetric jet with a selection of different environments, assuming that the poloidal component of the magnetic field is negligible in large distances from the source. Two different simulations are presented: 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 or the Bondiaccretion. A transition in the shape of the jet from parabolic to conical near the Bondi radius was observed by Asada & Nakamura in the case ofM87, which may be connected to pressure variations of the accreting material outside the jet. Consequently, the second case aims to examine whether such pressure variations may be produced by Bondi accretion and thus change the shape of the jet.

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|---|---|---|
| Subject : | : | oral |
| Topics | : | Plasmaphysics |
| Topics | : | Astrophysics |
| Topics | : | Numerical simulations |

*Accretion and Outflows throughout the scales, 1-3 October, Lyon, France*

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# Aknowledgements


- Collaborators: N. Vlahakis & G. Katsoulakos - K. Sapountzis
- T. Matsakos
- State Scholarship Foundation

# Outline

1. Introduction
   - A glimpse of M87

# Outline

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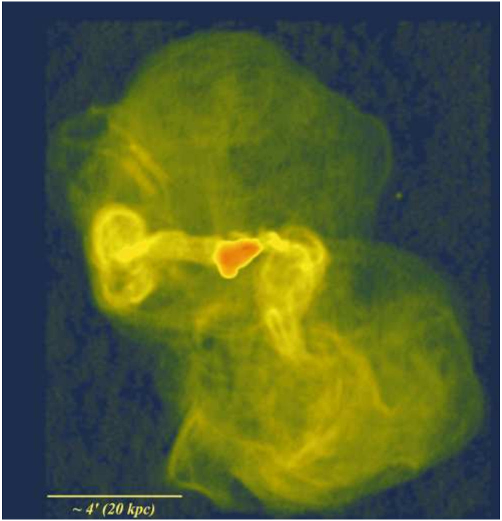


M87 at 90cm, (Owen et al. 2000)

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- Mass: 3.2 to 6.6 $\cdot 10^9 M_\odot$

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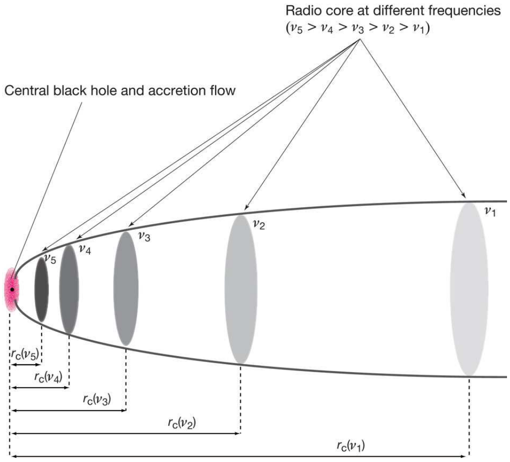
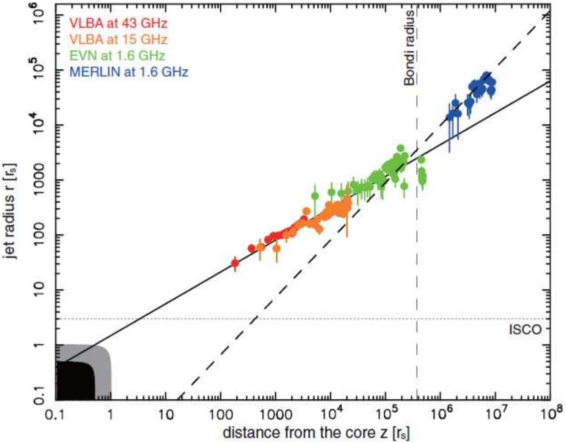
- Mass: 3.2 to 6.6 $\cdot 10^9 M_\odot \rightarrow 1mas = 0.081pc = 140R_S$
- Viewing angle of inner jet regions: $10^o - 19^o$ to the line of sight
- HST-1: Luminous region at $\sim 0.9$ arcsec from core




Core of the M87 jet with frequency (Hada et al. 2011)




Jet radius with deprojected distance from core (in Schwarzschild radii, Asada & Nakamura, 2012)

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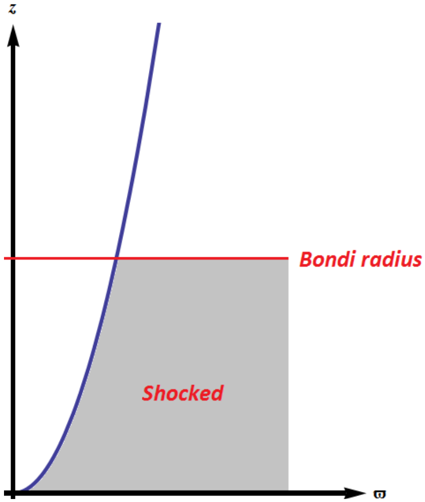
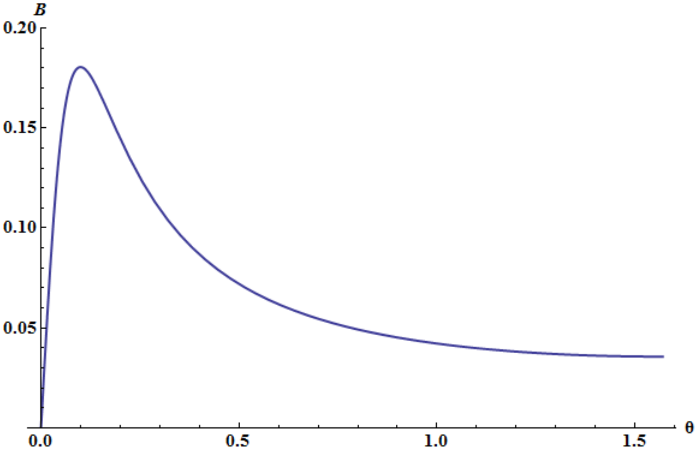
- **Simulations of both the jet and the Bondi accretion**


z
Bondi radius
Shocked
ϖ

# Setting up the jet

- Initial Lorentz factor: $\gamma = 5$
- Maximum magnetization: $\sigma = 4$
- Density: defined by $\sigma = \left.\frac{B^2}{\gamma^2 \rho}\right|_{\theta=\theta_1}$
- Thermal pressure: polytropic with $\Gamma = 5/3, c_s = 0.1$

Magnetic field with angle: bell-shaped $B_\phi(r,\theta) = B_o \frac{sin\theta}{1+\left(\frac{sin\theta}{sin0.1}\right)^2} \frac{1}{r}$



# Modifying the integrals

Assuming axisymmetry and time independence, we may partially integrate the ideal MHD equations:

- Mass flux to magnetic field flux ratio:

$$\Psi_A = \Psi(A) = \frac{4\pi\gamma\rho_o V_p}{B_p}$$

- Field angular velocity:

$$\Omega = \Omega(A) = \frac{V_\phi}{\varpi} - \frac{V_p}{\varpi}\frac{B_\phi}{B_p}$$

- Total specific angular momentum:

$$L = L(A) = \xi\gamma\varpi V_\phi - \frac{\varpi B_\phi}{\Psi_A}$$

- Total energy to mass flux ratio:

$$\mu = \mu(A) = \xi\gamma - \frac{\varpi \Omega B_\phi}{\Psi_A c^2}$$

- Adiabat:

$$Q = Q(A) = \frac{P}{\rho_o^\Gamma}$$

Assuming no poloidal component is used, the integrals may be expressed as:

- Specific angular momentum:

$$L = \xi\gamma r sin(\theta) V_\phi = \xi\gamma\varpi V_\phi$$

- Angular velocity function:

$$\Phi = -\frac{B_\phi}{4\pi\gamma\rho_o c r sin(\theta)} = -\frac{B_\phi}{4\pi\gamma\rho_o c\varpi}$$

- Total energy to mass flux ratio:

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

# Acceleration

Using the integrals:

**Wind equation** (velocity along a field line):

$$\frac{\mu^2}{\xi^2}\frac{G^2\left(1-M^2-x_A^2\right)^2-x_A^2\left(G^2-M^2-x^2\right)}{G^2\left(1-M^2-x^2\right)}=1+\left[\frac{\sigma_M M^2\varpi\vec{\nabla}A}{\xi x^2 A}\right]^2$$

$x$ cylindrical radius (normalized to the light cylinder), $x_A$ its value on Alfvén surface, $G = {}^{x}/_{x_A}$, $\sigma_M = A\Omega^2/\Psi_A c^3$

**Transfield equation** (shape of a field line):

$$\Big[x^2\Big(\vec{\nabla}A\Big)^2\frac{\mathrm{d}ln(\frac{x_A}{\varpi_A})}{\mathrm{d}A}-\bar{L}A\Big(1-M^2-x^2\Big)\Big]\Big(\frac{\vec{\nabla}A}{\varpi}\Big)$$
$$+\Big[\frac{2x_A^2}{\varpi_A^3 G}\Big(\vec{\nabla}A\Big)^2+\frac{\mu^2 x_A^6 A^2}{\varpi_A^5\sigma_M^2 M^2 G^3}\Big(\frac{G^2-M^2-x^2}{1-M^2-x^2}\Big)^2\Big]\hat{\varpi}\cdot\vec{\nabla}A$$
$$-\frac{M^2}{2}\vec{\nabla}\Big[\Big(\frac{\vec{\nabla}A}{\varpi}\Big)^2\Big]\cdot\vec{\nabla}A-\frac{\Gamma-1}{\Gamma}\vec{\nabla}\Big[\frac{\xi\big(\xi-1\big)}{M^2}\frac{A^2x_A^4}{\sigma_M^2\varpi_A^4}\Big]\cdot\vec{\nabla}A$$
$$-\frac{1}{2\varpi^2}\vec{\nabla}\Big[\frac{\mu^2A^2x_A^6}{\sigma_M^2\varpi_A^2}\Big(\frac{1-G^2}{1-M^2-x^2}\Big)^2\Big]\cdot\vec{\nabla}A=0$$

- Steady state MHD equations after partial integration: wind & transfield
- Solutions depend on Alfvénic Mach number and magnetic flux function
- Wind equation solutions depend on the bunching function $S = \varpi|\nabla A|/A = \varpi^2 B_p/A$

$$\mu^2 \frac{G^2(1-M^2-x_A^2)^2 - x_A^2(G^2-M^2-x^2)}{G^2(1-M^2-x^2)^2} = 1 + \left(\frac{\sigma_M M^2 \varpi \nabla A}{x^2 A}\right)^2$$

Desirable form of $S$?

- Using the integrals:

$$\frac{d\gamma}{dx} = \gamma^2 \sigma_M (\gamma^2 - 1)^{1/2} \frac{{}^{dS}/_{dx}}{\mu - \gamma^3}$$

For an accelerated flow:

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- ...and of course the shape of the jet

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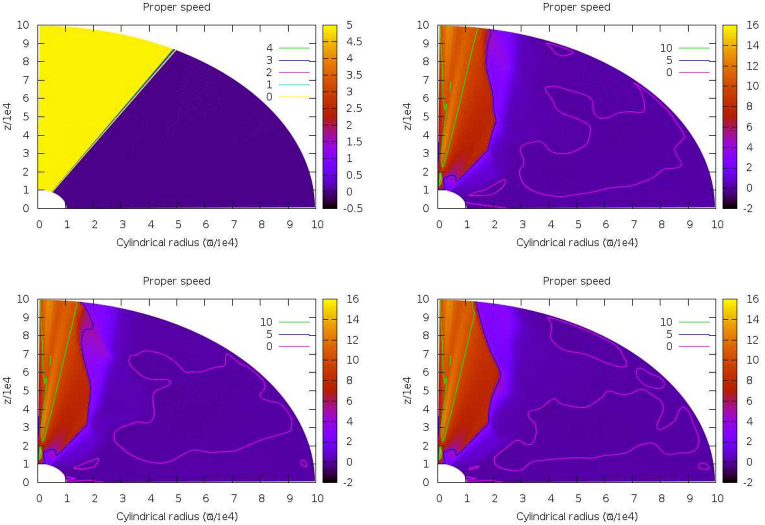
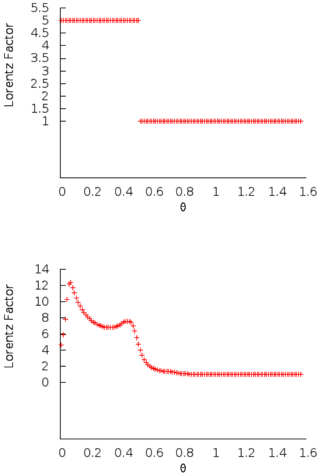
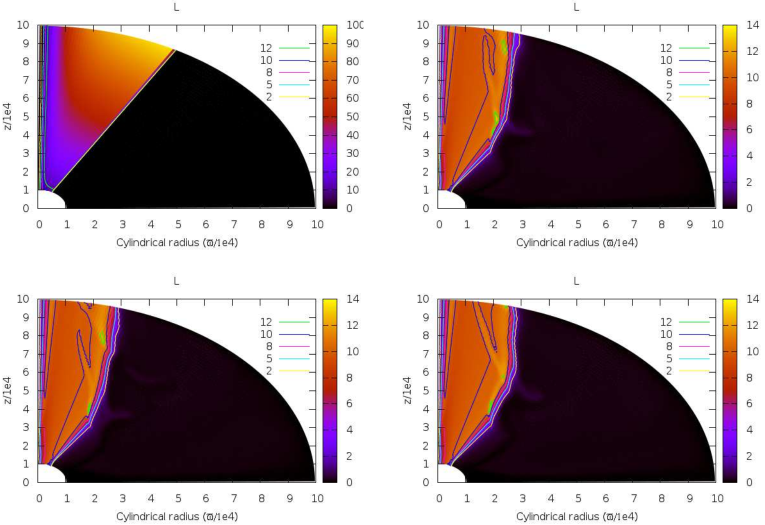



Proper speed at 0, 1, 10 and 20 sound crossing times




Lorentz factor with $\theta$ in 0, 1, 10 and 20 sound crossing times ($r \sim 3 \cdot 10^4$)

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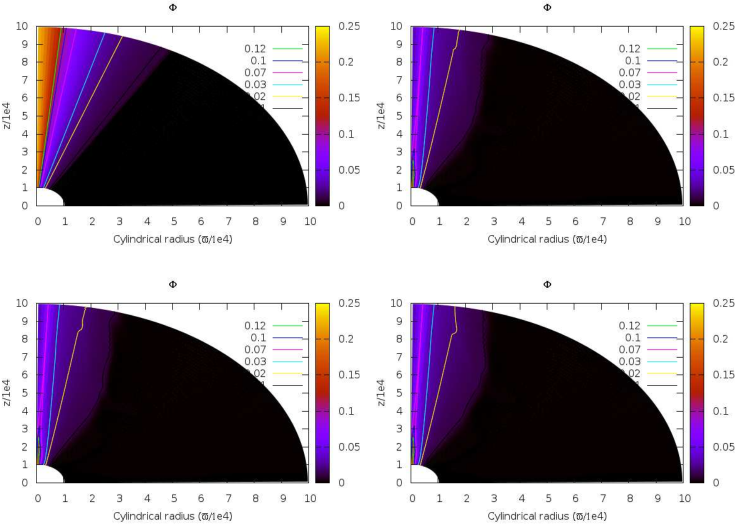


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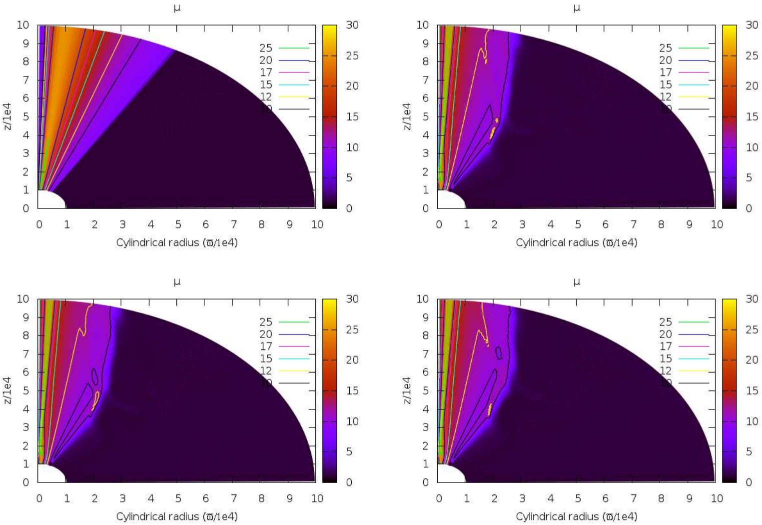
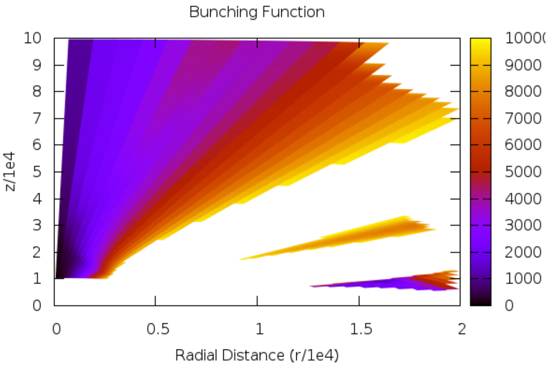
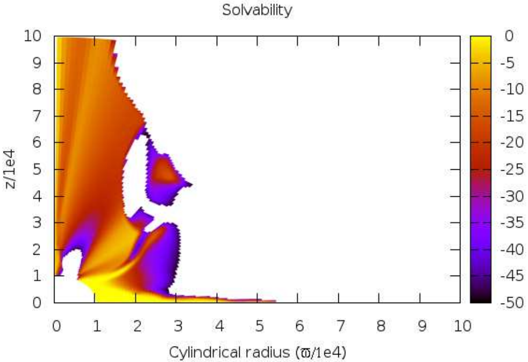



$\mu$ integral in 0, 1, 10 and 20 sound crossing times

# Acceleration efficiency

- Theoretical maximum of $\gamma$: $\gamma_{max} = \gamma(\sigma + 1) = 25$
- Result: $\gamma_f = 15$
- Acceleration efficiency $\alpha \simeq 60\%$


Bunching Function
10
9
8
7
6
5
4
3
2
1
0
z/1e4
0
0.5
1
1.5
2
Radial Distance (r/1e4)
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0




Solvability ($\frac{\varpi B_\phi}{\gamma}$)

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- Probable rarefaction acceleration

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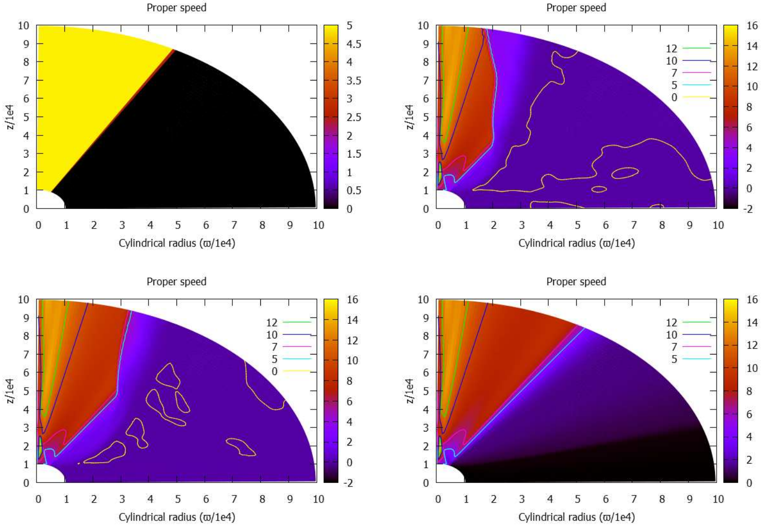
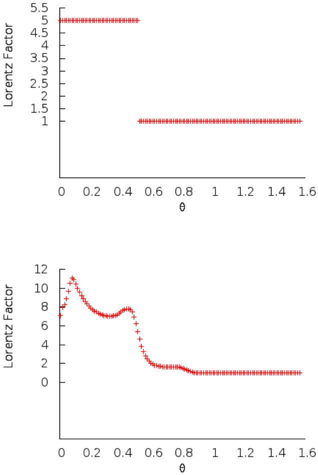
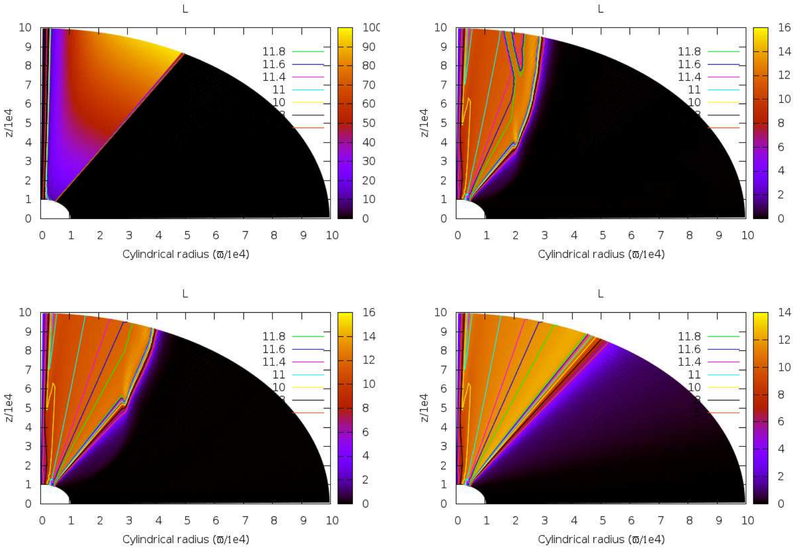
**But:** No shock to provide the necessary pressure gradient



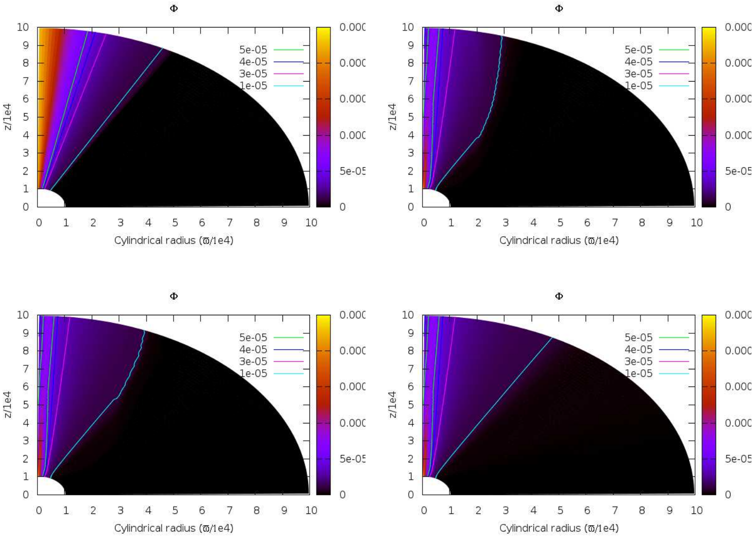

Proper speed 0, 1, 2.5 10 sound crossing times



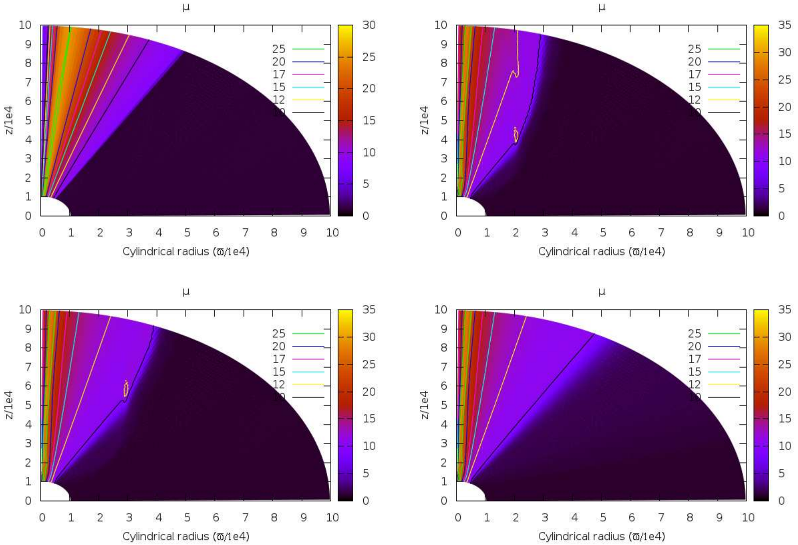

Lorentz factor to $\theta$ for 0, 1, 2.5 and 10 sound crossing times $(3 \cdot 10^4)$




L integral at 0, 1, 2.5 and 10 sound crossing times



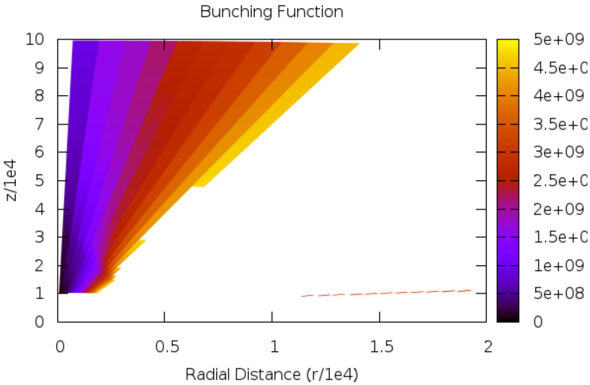

$\Phi$ integral at 0, 1, 2.5 and 10 sound crossing times




$\mu$ integral at 0, 1, 2.5  10 sound crossing times

# Acceleration efficiency

- Theoretical maximum of $\gamma$: $\gamma_{max} = \gamma(\sigma + 1) = 25$
- Results: $\gamma$: $\gamma_f = 14$
- Acceleration efficiency $\alpha \simeq 56\%$


Bunching Function
z/1e4
Radial Distance (r/1e4)
0
1
2
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6
7
8
9
10
0
0.5
1
1.5
2
5e+09
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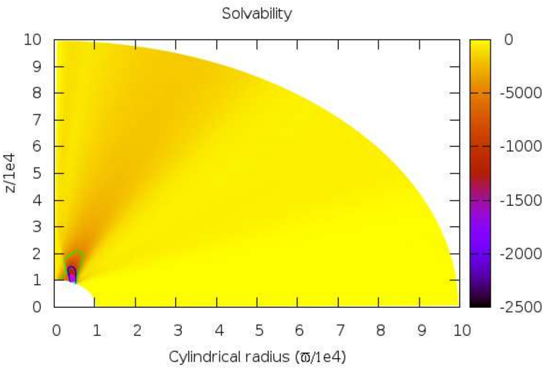
4e+09
3.5e+0
3e+09
2.5e+0
2e+09
1.5e+0
1e+09
5e+08
0


Solvability
10
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8
7
6
5
4
3
2
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0
z/1e4
0
1
2
3
4
5
6
7
8
9
10
Cylindrical radius (ϖ/1e4)
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-1000
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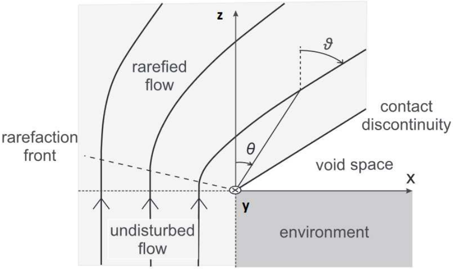
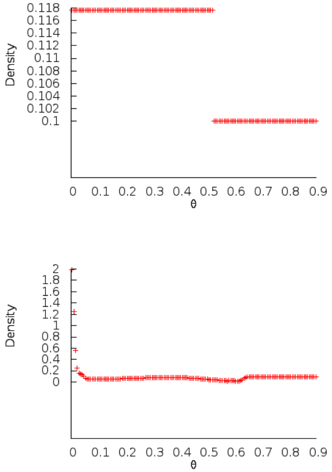
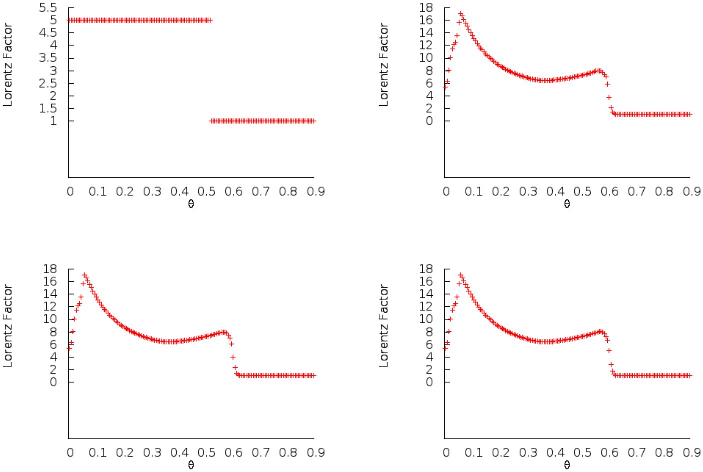
- Jet interior in agreement with other simulations & theory
- Probable rarefaction acceleration even with different environment!




- Examine environment with $\rho_{env} = \frac{\rho_j}{10}$
- Neglect gravity (GM=0)
- Mantain the same configuration for the jet




Density with $\theta$ in 0, 1, 5 and 8 light crossing times ($r \simeq 3 \cdot 10^4$)




Lorentz factor to $\theta$ in 0, 1, 5 and 8 light crossing times ($r \simeq 3 \cdot 10^4$)

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An accreting environment with a pressure gradient, which would result in changing the shape of the jet

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- The Bondi accretion scenario is unclear (interacting region, boundary conditions)

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**Our Results:**

- Jet - environment interaction clearly affects the shape of the jet
- The Bondi accretion scenario is unclear (interacting region, boundary conditions)
- In both cases, the inner jet does not change

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An accreting environment with a pressure gradient, which would result in changing the shape of the jet

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An accreting environment with a pressure gradient, which would result in changing the shape of the jet

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- Both scenarios indicate a probable rarefaction acceleration in the interacting region

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