The Effect of Angular Opening on the Dynamics of Relativistic Jets in Hydrodynamics

Remi Monceau-Baroux

Centrum voor Plasma-Astrofysica
K.U.Leuven

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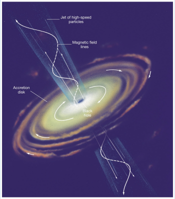
Outline

1. Introduction
2. Framework
3. Discussion of the results
4. Conclusion

What? - Jet from active galactic nucleus (AGN)



- Originates from a massive object like a massive star or a black hole.
- The accretion disk of a massive stellar object releases matter in the form of winds
- Many studies are made to explain how a jet can arise from these winds (see [Blandford & Payne 1982][Bogovalov and Tsinganos 2004])
- Magnetic and pressure driven collimation.

Why? - Some (good) reasons to study AGN jets

- Scenario for galaxy cluster formation - [Dubois et al 2010]
- Predicted galaxy distribution does not match the observed one
- Necessity for a retroactive phenomenon for injection of energy

Opening angle - Direct observations

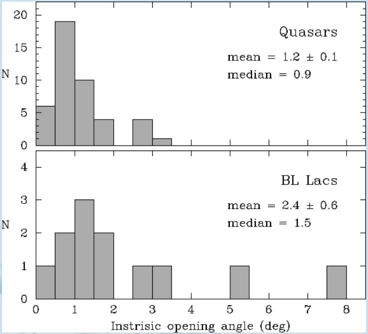


Figure: Distribution of intrinsic opening angle [Pushkarev & Kovalev 2011]

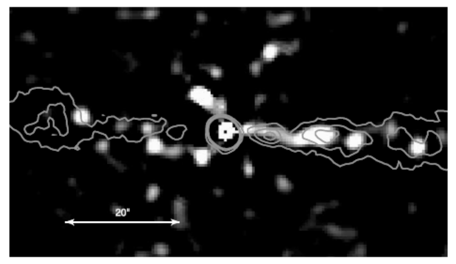
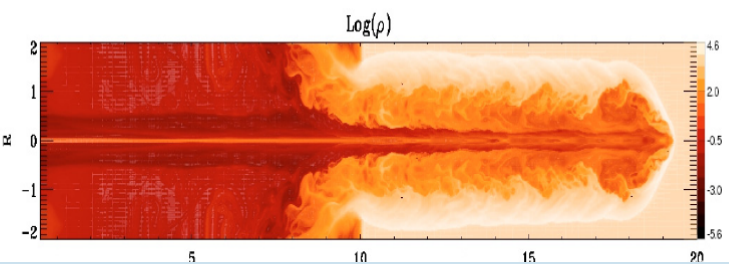


Figure: 0.3 to 5.0 keV CHANDRA image of NGC 4261 (3C 270) after subtracting the diffuse component. The contours correspond to radio emission from a 4.9 GHz VLA observation [Zezas et al 2005]

Energy transfer - Shocks and instabilities



- Interaction with the ISM through front shock - ex: Density jump [Meliani et al 2008]. Kinetic to thermial energy.
- Heating by shocks: internal deceleration of the jet by recolimation shocks. Heating of the ISM.
- Rayleigh Taylor and Kelvin - Helmholtz instabilities: mixing of jet and surroundings of the jets materials.

Outline

Equations of Relativistic Hydrodynamics

Equations of Relativistic Hydrodynamics

1. Continuity Equation

$$\frac{\partial \rho\gamma}{\partial t} + \vec{\nabla}\cdot\rho\gamma\vec{v} = 0 \qquad (1)$$

2. Momentum Equation

$$\frac{\partial \vec{S}}{\partial t} + \vec{\nabla}\cdot(\vec{S}\vec{v}) + \vec{\nabla}p = 0 \qquad (2)$$

3. Energy Equation

$$\frac{\partial \tau}{\partial t} + c^2\vec{\nabla}\cdot(\vec{S} - \rho\gamma\vec{v}) = 0 \qquad (3)$$

1. Momentum Density

$$\vec{S} = \frac{h}{c^2}\gamma^2\rho\vec{v} \qquad (4)$$

2. Specific Enthalpy

$$h = c^2 + \epsilon + \frac{p}{\rho} \qquad (5)$$

3. Energy Density

$$\tau = \rho h\gamma^2 - p - \rho\gamma c^2 \qquad (6)$$

Closure equation - The synge gas equation of state

1. Mathews approximation to the Synge gas equation

$$p = (\frac{\Gamma - 1}{2})\rho(\frac{e}{m_p} - \frac{m_p}{e}) \tag{7}$$

2. Which gives a local effective polytropic index

$$\Gamma_{eff} = \Gamma - \frac{\Gamma - 1}{2}(1 - \frac{m_p^2}{e^2}) \tag{8}$$

Code used for the simulations MPI-AMRVAC

1. homes.esat.kuleuven.be/∼ keppens
2. A code to solve conservation equations of the form

$$\partial_t \vec{U} + \vec{\nabla} \cdot \vec{F}(\vec{U}) = \vec{S}_{phys}(\vec{U}, \partial_i \vec{U}, \partial_i \partial_j \vec{U}, \vec{x}, t) \tag{9}$$

3. Different modules available (ex: HD, MHD, SRHD)
4. Different solvers available (ex: TVDLF, HLLC)
5. Possibility to use libraries to add more physics (ex: gravity, Optical thin radiative cooling)

Adaptive Mesh Refinement and Message Passing Interface

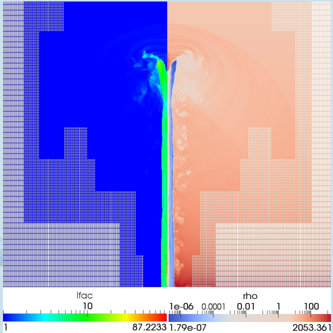


Figure: Example of simulation with adaptive mesh refinement

Adaptive Mesh Refinement - AMR

- Improves computation time by only refining the grid where needed
- Flags are set on different variables
- Typical use of 5 to 8 levels of refinement

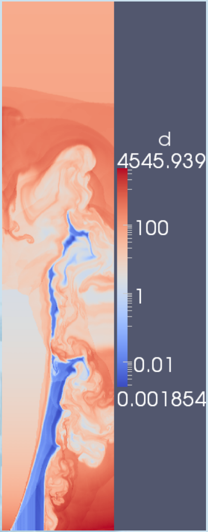
Message Passing Interface - MPI

- The code is using MPI for massive parallelisation
- Division of the space in blocks
- Finite number of blocks per CPU
- Typical use of 20 000 blocks

Computation - some figures

- Base resolution of 300x192, total 5 levels: effective resolution of 4800x3072 (around 2 000 000 grid points at end of simulation)
- Runs simulation: 16 processors for 24 hours
- Without AMR: over a week

Dimensions and Boundary conditions



Dimension

1. Simulations in 2D
2. Axi-symmetry

Boundary conditions

1. 2 transparent (continuous) boundaries
2. 1 axi-symmetry
3. 1 special boundary: source of the jet

Recapitulation of input parameters

Simulation	Density ratio	Opening angle (degrees)	Domain size (pc)	Density profile
A	0.01	5	20x5	uniform
B	0.0001	5	20x5	uniform
C	0.018	0	20x5	King
D	0.018	5	20x5	King
E	0.018	10	20x5	King
F	0.1	0	20x5	King II
G	0.1	5	20x5	King II
H	0.1	10	20x5	King II

Table: Parameters for the simulations.

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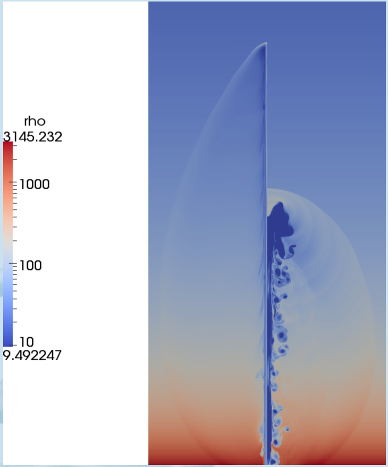
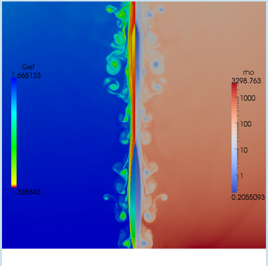
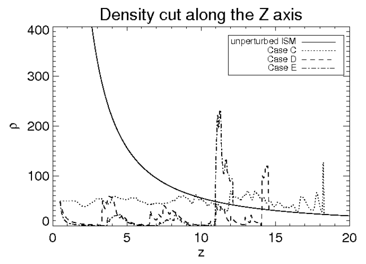
Parametric study - Influence of the opening angle



1. Comparison of 10 degrees of opening angle (Right - Model E) and 0 degree opening angle (Left - Model C)
2. Influence of the opening angle on size of the mixing region and shocked ISM
3. Axial reach of the jet

Density variation along the symmetry axis





1. Shorter pulsation for higher opening angle
2. Possible site for particles accelerations: X-Rays brightening scenario

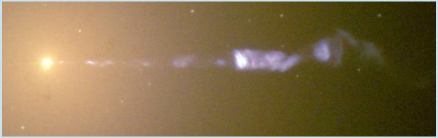
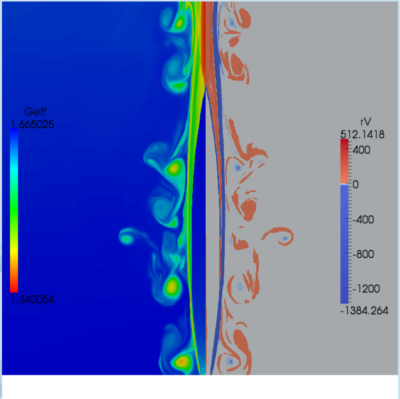


Figure: Image of M87

Formation of a structured beam



1. The head of the jet pushes the ISM over a wider radial distance than the radius of the beam
2. Formation of a low density layer with a rarefaction wave propagating radially
3. Formation of a two components structure for the beam

Formation of a structured beam

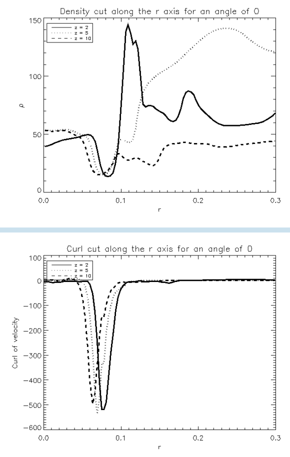


Figure: 1D cut along the radius - 0 degree

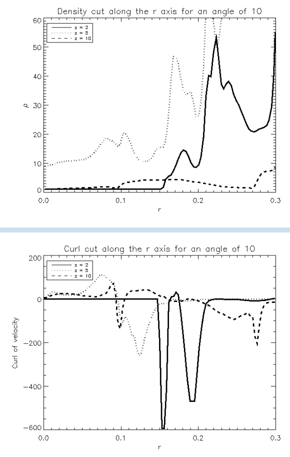
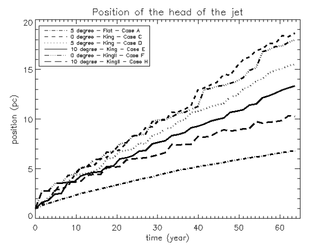
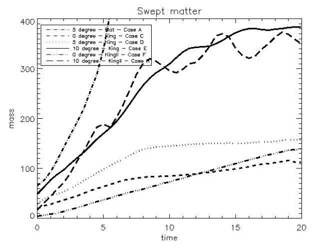


Figure: 1D cut along the radius - 10 degree

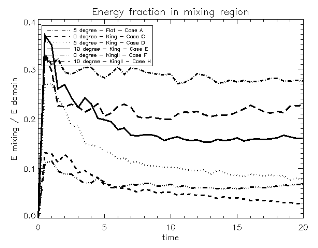
Parametric study - Deceleration of the jet

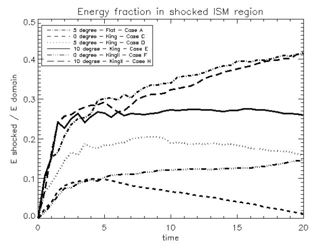


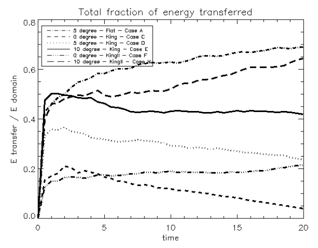


1. Cylindrical geometry propagating freely
2. High deceleration for a flat density profile due to the density ratio
3. Wider angle gives higher deceleration

Parametric study - Energy transfer







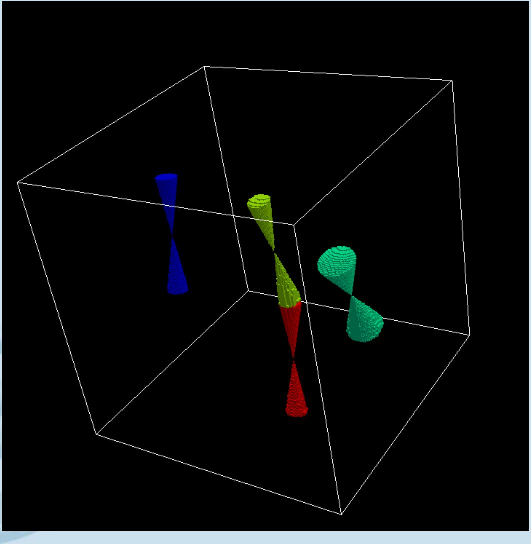
1. Increased energy transfer for wider opening angle
2. Dominance of transfer through shocks in the SISM region for early time

Outline

Conclusion

- While keeping a collimated beam for the jet we show that an angle at the source of the jet changes the dynamics of the jet.
- As the interaction between the jet and the ISM is more important at the head and in the layer where the instabilities develop, this scenario offers a possible mechanism to re-inject more energy into the ISM, and then, help to explain cluster formation.
- For early time of injection of the jet, the transfer of energy is dominated by shocks heating the ISM.

Welcome to the Third Dimension



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Dank u wel