Emission modelling of numerical hydrodynamical simulations with application to active galactic nuclei jets

IP van der Westhuizen, B van Soelen and PJ Meintjes

Department of Physics, University of the Free State, Bloemfontein, 9301, SA

E-mail: vanderwesthuizenip@ufs.ac.za

Abstract. Active Galactic Nuclei, such as quasars and blazars, are highly variable over intra-day to year time scales. The regions that produce this variability have been the topic of many recent studies, especially in the investigation of correlation between multi-wavelength components from radio to gamma-rays. In this study a simulation of an idealistic relativistic hydrodynamical jet propagating through a uniform background medium is presented. This simulation is created with the use of the numerical code PLUTO ver 4.2 which uses high resolution shock capturing algorithms to evolve the fluid dynamic partial differential equations with time. In order to investigate possible causes of variable emission in the simulation a post processing emission code is developed to compute intensity maps of the hydrodynamic computational environment. The code is designed to model the synchrotron self-absorption spectrum in the radio regime for each cell. This emission is calculated using the emission and absorption coefficients, which are then integrated along a fixed line of sight to produce simulated intensity maps of the relativistic jet. Using the intensity maps we can investigate regions of variable emission as well as the respective time scales on which they occur. In this paper we present the initial results and intensity maps produced by the emission code as well as the planned future development of the project. The tools which are being developed for this hydrodynamic model can be applied to a range of other transient sources, such as X-ray and γ-ray binaries, to investigate the different emission components produced by such sources.

1. Introduction

Observational studies of jets from Active Galactic Nuclei (AGN) have revealed a complex system of both stationary and moving emission regions inside AGN sources [1]. These emission regions have been associated with shock fronts inside the relativistic jet and produce variability on both short, intra-day, as well as longer time-scales. AGN sources emit radiation over a wide range of the electromagnetic spectrum, from radio to gamma rays, with low energy region of the spectrum being dominated by synchrotron radiation produced by relativistic electrons inside the jet [2].

In order to investigate the production and propagation of shock fronts and other structures inside highly relativistic jets that may lead to the observed characteristics many studies have turned to numerical simulations using fluid dynamics to evolve jet-like environments with time [3]. Such simulations have revealed complex interaction between the relativistic jet material and the surrounding medium as well as the internal structure [4, 5]. The physical characteristics, such as the density, velocity and pressure, calculated by hydrodynamic simulations are, however, not directly related to the emission we receive from these sources. In order to produce emission

Table 1. Variables used in the set up of the initial conditions for the preliminary RHD jet simulation.

Parameter		Value (arbitrary units)
Lorentz factor	Γ	10
Density ratio	η	10^{-3}
Jet density	ρ_b	0.1
Ambient density	ρ_{am}	100
Mach number	M_b	3.0
Adiabatic index	γ_{ad}	5/3

maps from the numerical simulations, that are comparable to observational data, the emission mechanisms of such sources as well as the relativistic effects must be taken into account [2].

In this paper we present the results of ideal numerical hydrodynamic simulations of a relativistic jet evolved using the PLUTO open source code. We also present intensity maps calculated by a radiative code which computes emission based on properties of each computational cell and integrates the calculated emission along a user defined line of sight. In section 2 we will discuss the numerical environment used to run the relativistic hydrodynamic (RHD) simulations, while section 3 will focus on the emission modelling of these simulations. Section 4 summarizes the current results followed by a conclusion in section 5.

2. Numerical simulation of relativistic outflows

A RHD simulation of an AGN jet can be achieved by setting up a fluid environment on a structured mesh grid. On this mesh grid quantities such as density, pressure and velocity are assigned to each cell. The environment can then be evolved with time by numerically solving the fluid dynamical conservation equations. In this study we considered an ideal relativistic outflow, with no viscosity, injected into a uniform medium. For this simulation the magnetic field was considered to be dynamically unimportant and we, therefore, chose a purely relativistic hydrodynamic solver. To calculate the internal energy density of the fluid the ideal caloric equation of state was used,

$$e = \frac{p}{\rho(\gamma_{ad} - 1)}, \tag{1}$$

where e is the internal energy, p is the pressure, ρ is the density and $\gamma_{ad} = C_p/C_v$ is the adiabatic index of the fluid [5].

The 3D environment of the simulation was set up on a Cartesian mesh grid consisting of $64 \times 64 \times 64$ length units. The units of the simulation was chosen as arbitrary to avoid large truncation errors, which may occur if the computed values are very small. Initially a uniform rest background medium was assigned to the grid, while a nozzle was defined on the $z = 0$ boundary to inject relativistic outflow material into the computational domain. The radius of the nozzle was set to 1 length unit and less dense jet material was injected at a steady rate with $\Gamma = 10$. The density of the injected material was normalized such that $\Gamma\rho_{jet} = 1$. For the environment we assumed a pressure matched (PM) model to collimate the outflow material. The pressure of the medium was chosen such that the injected material was supersonic. A complete list of the initial parameters for the simulation is given in table 1. The environment was evolved numerically with time using PLUTO *ver 4.2* Open source code [6]. This grid base code is designed for supersonic flows containing contact discontinuities and uses high resolution shock capturing schemes. The code was set up to use piecewise parabolic interpolation along with the HLLC Riemann solver [7] and characteristic trace time stepping. The simulation was run on the UFS high performance cluster (HPC) at a resolution of 8 points per unit length.

3. Post-processing emission modelling

In order to produce emission maps of the numerically simulated environment post-processing emission modelling code is being designed in Python. The code determines the synchrotron emission (j_v^{sy}) and absorption (α_v^{sy}) coefficients for each cell based on a delta-approximation model [8] given by

$$j_\nu^{sy} = \frac{4}{9}\left(\frac{q^2}{mc^2}\right)^2 u_B \nu^{\frac{1}{2}} \nu_0^{\frac{-3}{2}} n\left(\sqrt{\frac{\nu}{\nu_0}}\right), \tag{2}$$

$$\alpha_\nu^{sy} = \frac{2}{9}\frac{p+2}{m\nu^2}\left(\frac{q^2}{mc^2}\right)^2 u_B \nu_0^{-1} n\left(\sqrt{\frac{\nu}{\nu_0}}\right), \tag{3}$$

where,

$$\nu_0 = \frac{3qB}{4\pi mc} \tag{4}$$

Here q is the charge of the radiating particle (assumed to be electrons), m is the mass of the radiating particle, c is the speed of light, u_B is the magnetic field energy density, ν is the frequency in the co-moving frame and $n(\gamma)$ is the particle spectrum [2]. To calculate the coefficients it was assumed that the jet material had a power law particle distribution with spectral index $p = 2$. The magnetic field energy density was assumed to be proportional to the energy density of the fluid with,

$$u_b = \epsilon_B e \tag{5}$$

where $\epsilon_B = 10^{-3}$ is the B-field equipartition parameter based on [9].

Next the code transforms the coefficients from the co-moving frame to an observer frame with regard to the user defined angle as,

$$j_\nu^{sy} = \frac{j_\nu^{sy'}}{(\Gamma[1-\beta\cos(\psi)])^2}, \tag{6}$$

where j_ν^{sy} is the emission coefficient in the observer frame, $j_\nu^{sy'}$ is the emission coefficient in the co-moving frame, Γ is the Lorentz factor, β the magnitude of the velocity in units of c and $\cos(\psi)$ is the angle between the observer and the velocity of the fluid.

The post-processing code finally determines the change in intensity dI_ν for each cell following

$$\frac{dI_\nu}{ds} = j_\nu^{sy} - \alpha_\nu^{sy} I_\nu, \tag{7}$$

and integrates this change along a user defined line of sight to produce a 2D intensity map. This is illustrated in figure 1.

4. Results

The simulation was run until the head of the outflow crossed the computational domain. Figure 2 displays 2D slices of the xz-plane at the origin, showing the density, pressure and velocity distributions. From these results we note that the outflow remains collimated and highly relativistic throughout the simulation similar to the simulations produced by [4, 5].

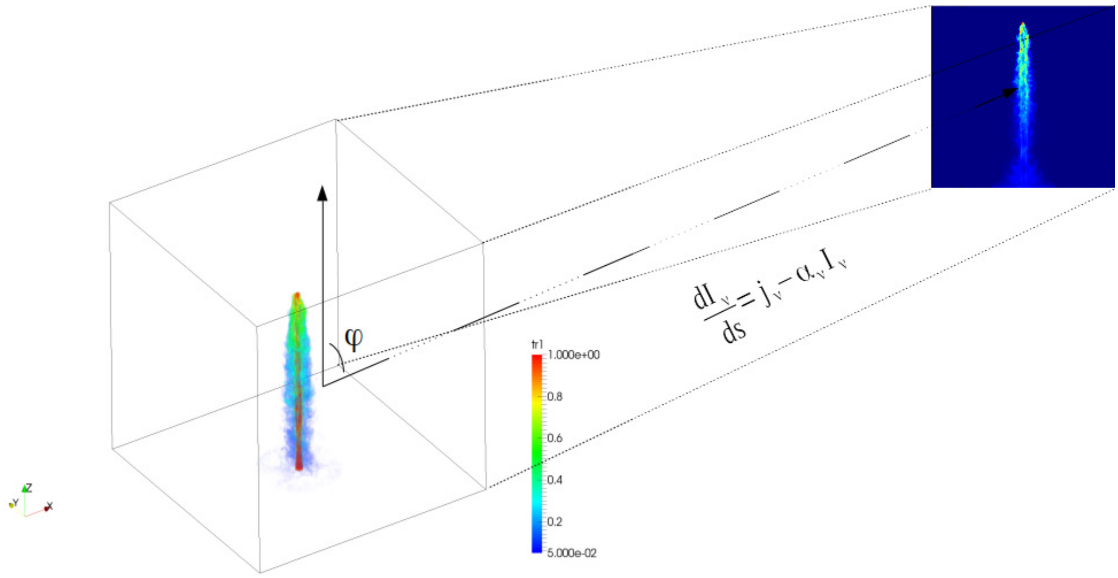

Figure 1. The emission from the 3D fluid dynamic simulation is projected onto a 2D image plane by numerically integrating the change in intensity along a line of site.

Figure 3 displays the calculated intensity maps for three different angles with regards to the propagation direction of the jet. The emission was calculated for a frequency of 12 GHz in the observer frame. In these figures we note that the bow wave structure seen in the density and pressure plots has negligible emission compared to the other structures of the jet. Both the cocoon and the relativistic beam of the jet are initially faint, but increase in brightness with an increase in the z direction closer to the head of the jet. The emission map is dominated by emission at the working surface as well as hotspot regions on the boundary of the relativistic beam. We also note the occurrence of individual asymmetric emission regions close to the head of the jet.

As the viewing angle, ψ, changes from edge-on ($\psi = 90°$) to head-on ($\psi = 0°$) the maximum intensity increases due to Doppler boosting of the fluid moving toward the observer. For example the hotspot regions present in the edge-on system are less prominent at a $\phi = -30°$. This indicates that these regions are located in the cocoon of the jet and are moving at lower velocities compared to the relativistic beam. For the head-on system we obtain a ring type structure with emission of an order of magnitude larger than the edge-on system. The origin of the ring structure is still unknown and further investigation is required to rule out all numerical effects.

5. Discussion and conclusions

A 3D numerical simulation of a relativistic outflow was created and evolved with time using the PLUTO code. The simulation shows a collimated central beam with little deceleration surrounded by an outer cocoon. Intensity maps were computed for the simulation at 12 GHz with a delta approximated synchrotron model. The formation of individual asymmetric emission regions was shown for steady injection model. This suggests that bright emission components can form and propagate in AGN jets without the presence of perturbations in the injection of the outflow. Using these results we will be able to study the propagation of these emission regions further and compare the results to observational data such as [1]. The emission code is still under development with continuous testing and optimization. Future improvements include the addition of a high energy component through an inverse-Compton model, SED modelling, including time of arrival effects and flux calculations. Jet like outflows have been associated with

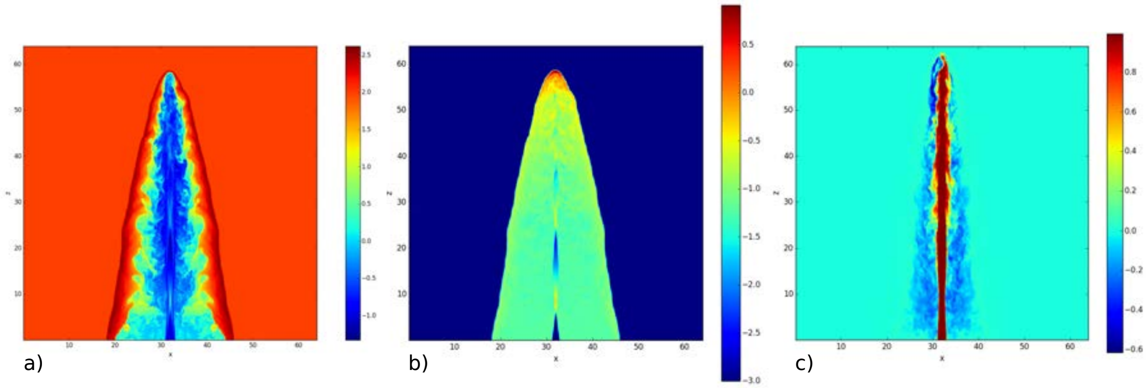

Figure 2. Two dimensional visualizations of the simulation through the xz-plane of the jet, showing a) the density, b) the pressure and c) the velocity component in the z direction. Logarithmic scales are shown for the density and pressure plots in arbitrary units, while the velocity plots have a linear scaling in units of c.

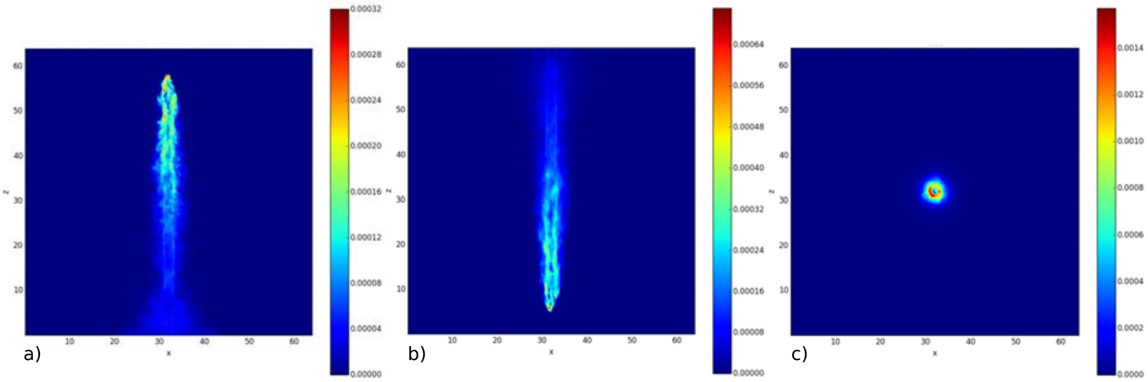

Figure 3. Intensity maps calculated at 12 GHz for different viewing angles a) $\psi = 90°$ b) $\psi = -30°$ c) $\psi = 0°$

many sources such as micro-quasars, young stellar objects (YSO), gamma-ray bursts (GRB's) and X-ray binaries. The code that is being developed for this project can be applied to these sources in future studies.

References

[1] Lister M L, *et al.* 2009 MOJAVE: Monitoring of jets in active galactic nuclei with VLBA experiments. V. Multi-epoch VLBA images *ApJ* **137** 37183729

[2] Böttcher M 2011 Modeling the spectral energy distributions and variability of blazars *2011 Fermi & Jansky: Our Evolving Understanding of AGN* (*preprint arXiv:1205.0539*)

[3] Toro E F 2009 *Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction Third Edition* (Berlin: Springer) Chapter 1 pp 1-40

[4] Rossi P, Mignone A, Bodo G, Massaglia S and Ferrari A 2008 Formation of dynamical structures in relativistic jets: the FRI case *A&A* **488** 795-806

[5] Marti J M, Müller E, Font J A, Ibáñez J M and Marquina 1997 Morphology and dynamics of relativistic jets *ApJ* **479** 151-163

[6] Mignone A, Bodo G, Massaglia S, Matsakos T, Tesileanu O, Zanni C and Ferrari A 2007 PLUTO: a numerical code for computational astrophysics *ApJ* **170** 228-42
[7] Mignone A and Bodo G 2006 An HLLC Riemann solver for relativistic flows - II. Magnetohydrodynamics *MNRAS* **368** 1040-54
[8] Böttcher M, Harris D E and Krawczynski H, 2012 *Relativistic Jets from Active Galactic Nuclei*, Weinheim, Germany: Wiley-VCH Verlag GmbH & Co. KGaA Chapter 3 pp 39-80
[9] Böttcher M and Dermer C 2010 Timing signatures of the internal-shock model for blazars *ApJ* **711** 445-460