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Simulating peculiar X-shaped extragalactic radio sources

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Peculiar morphologies have been observed among extragalactic radio sources, which present important sideways features that are yet to be explained. After obtaining the region in the parameter space for which the intended lateral extensions appear, further 2D simulations using `PLUTO` code were performed. For some selected sets of parameters the effect of resolution on the simulated morphology, and the effect of a toroidal magnetic field on the propagation of the simulated jet in the stratified medium, were considered.

Key words: jets, x-shaped, radio galaxy

INTRODUCTION

Early observations in radio wavelengths have provided evidence of extended sources outside our galaxy, spanning over regions ranging from a few kilo parsecs (kpc) to a few mega parsecs (Mpc). These were associated with source galaxies to which they were connected by highly collimated jets. The central propelling engine of the jet is widely accepted to be the accretion of material around a supermassive black hole.

Since the first observations of radio sources, a classification based on the radio characteristics has been made in order to distinguish between the different objects [3]: Seyfert galaxies (type I and II), Radio galaxies (Fanaroff-Riley I and II – FR I and FR II), Quasars (radio-loud and radio-quiet) and Blazars.

The Unified Model brings a simplification, considering that the observed morphologies are only a matter of perspective, the system at work always being a supermassive black hole with its accretion disc and jets. These can drive to different morphologies depending on the angle between the direction of the observed system with respect to our line of sight.

The jet is believed to consist of a mixture of electrons and protons/positrons, highly collimated due to external pressure confinement, with supersonic (sometimes even relativistic) outflow velocities. The outer regions of the jets, the so-called cocoons, are large structures corresponding to the observed lobes in radio maps, with important differences between the FR I and FR II in terms of overall appearance and position of the peak emission area.

Among the observed radio galaxies with moderate emissions there are some that present significant distortions in the FR II jet. Based on the symmetry of the distortion we have C-shaped sources (C mirror-symmetric) and X or Z-shaped sources (center-symmetric). About 7% of the FR II sources have been classified as X-shaped. A sample of 9 X-shaped radio sources with important extension on the secondary axis and relevant observations of the host galaxies by HST is presented and discussed by Capetti in his paper [1]. A study by Cheung have brought a new set of about 100 X-shaped radio sources candidates from the FIRST survey data (see [2]). Recent 3D simulations have been performed by Hodges-Kluck & Reynolds [4] using the ZEUS code, leading to simulated morphologies that have a high resemblance to those observed.

In this study we will focus on the X-shaped sources and try to numerically model their morphologies through Magnetohydrodynamics simulations. The simulation setup, code and model used are presented in Section 2. Section 3 contains the summary of the simulations performed and the results of the numerical study. Conclusions and perspectives for future work are presented in Section 4.

THE SIMULATIONS

Employing the back-flow model proposed by Capetti [1] and the `PLUTO` simulation software [7], two dimensional Hydro-Dynamical (HD) [8] and Magneto-Hydro-Dynamical (MHD) simulations were performed in a cylindrical symmetry on a uniform integration grid. The results of the simulations were then analyzed using standard and custom `IDL` (Interactive Data Language) routines.

The `PLUTO` code, used for performing these simulations, is a multi-physics, multi-algorithm, high-resolution code, suitable for time-dependent, explicit computations of highly supersonic flows in the presence of strong discontinuities. It can be employed under different regimes, i.e., classical, relativistic unmagnetized, and magnetized flows. The code struc-

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ture is modular, allowing new modules to be easily incorporated. This flexibility turns out to be quite important, since many aspects of computational fluid dynamics are still in rapid development. Besides, the advantage offered by a multiphysics, multisolver code is also to supply the user with the most appropriate algorithms and, at the same time, provide interscheme comparison for a better verification of the simulation results. `PLUTO` is entirely written in the C programming language and can run on either a single processor or parallel machines. The code has already been successfully employed in the context of stellar and extragalactic jets.

The cylindrical jet is introduced along the main axis of a King ellipsoidal distribution [5], in the central part. For the HD simulations the parameters used were: Mach number M (representing the speed of the jet in units of the sound speed in the external medium), and the ratio between the jet density and the density of the external gas distribution in the central point, denoted by ν. The `MACH-UP` and `MACH-LOW` parameters refer to the speeds of the two components of the jet, inserted in the upwards and downwards directions, respectively. These insertion speeds were set to be slightly different in order to avoid unwanted numerical reflection effects at the lower boundary of the integration domain, and at the insertion point.

Table 1: Simulation parameters.

name	value
MACH-UP	102
MACH-LOW	−100
ν	0.0005
Bz	0.13

Table 2: Normalization units.

name	value	units
Density	$1.66{\cdot}10^{-24}$	g/cm^3
Pressure	$4.75{\cdot}10^{-8}$	dyne/cm^2
Velocity	$1.69{\cdot}10^{8}$	cm/s
Time	$1.82{\cdot}10^{15}$	s
Magnetic field	7.72·10−4	G

In the case of the MHD simulations, the toroidal magnetic field strength was also taken into account. The magnetic field vector, set to be perpendicular on the 2D simulation plane (resulting in the so-called 2.5D simulation) with various absolute values below 1mG, is inserted together with the jet matter, at the lower boundary of the domain. Then, it is let to evolve in a self-consistent manner together with the plasma. As the jets are pressure-confined, no external fields are considered. A summary of the parameters can be found in Table 1. From these parameters, normalized with convenient units (found in Table 2), the parameters in physical units may be computed.

RESULTS

In a previous stage of our study, with the results summarized in [6], we tried to find the region in the parameter space for which the jet develops important sideway features. In order to achieve this, we performed twelve 2D simulations on a 256x256 integration grid with all possible combinations of values of the considered parameters (M=(100, 150 and 200) and ν=(0.01, 0.001, 0.005 and 0.0005)). We concluded that in order to obtain the desired results we needed a low value for the Mach number M, as well as for the density ratio ν. In other words, the very light (underdense) and not too fast jets are more likely to develop a "butterfly" structure.

We then performed the simulations for the selected sets of parameters at different resolutions in order to see the effects on the results, with a focus on numerical viscosity. The resolutions used were 128×256, 256×512, 384×768, 512×1024, 1024×2048, and 2048×4096 integration cells. We simulated only half (with respect to the jet axis in 2D) of the two opposing jets, as due to the cylindrical symmetry, the second part of the jet would be nearly identical. This technique also added the advantage of reducing the time needed for the high resolution simulations. By increasing the resolution, the turbulences in the flow were better defined, and up to a point, more important sideway features developed.

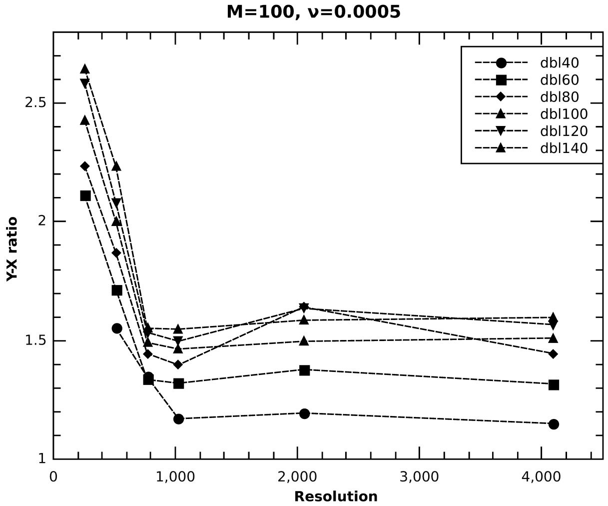

Fig. 1: Lateral extension as a function of the simulated resolution.

A clear asymptotic behavior with increasing resolution can be inferred from Figure 1, which stabilizes at more evolved stages. This image represents the case where highly extended wings do form. With increasing resolution, the values of the Y/X ratio converge towards 1.5 for this simulated jet. Furthermore, a division between "adequate" ($\geqslant$ 768) and "non-adequate" ($<$ 768) resolutions for this kind of simulations can be inferred from Figure 2. By adequate it is meant that the increase in resolution does not bring further information on the jet. Figure 3 (left side) presents a sample of such a simulation performed on an uniform grid with 512×1024 integration cells. The contour map was obtained using a logarithmic display of the density values at the last evolutionary step of the simulation.

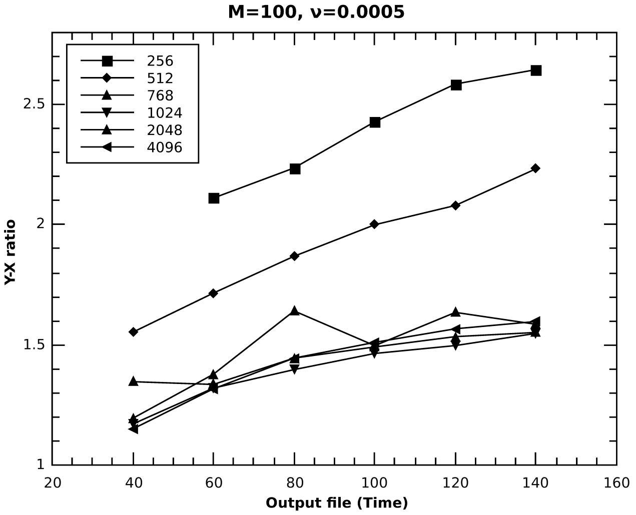

Fig. 2: Evolution of the sideways features.

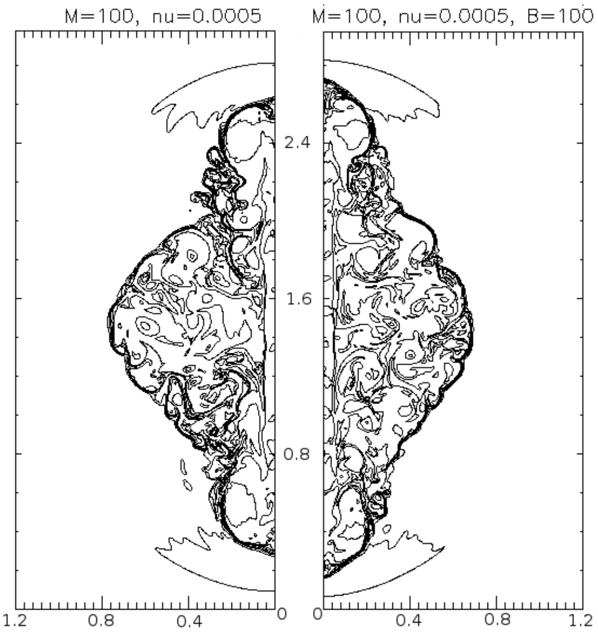

Fig. 3: Density distribution with no magnetic field(left) and with magnetic field (right).

As during its propagation through the intergalactic medium the jet is influenced by the magnetic field, simulations were performed taking it into account. We have applied a toroidal magnetic field of different strengths at the point of insertion and allowed it to evolve along with the jet. We then analyzed the effect it had on the resulting structure. For the performed simulations we employed an MHD model and ran simulations considering different values for the toroidal magnetic field: 0, 50, 100 and 220 μG.

As expected, with the increase in magnetic field, the collimation of the jet also increases, reducing the possibility of formation of notable sideways features. In Figure 3 (right side), we have the same parameters as in the resolution simulation, aside from the fact that a magnetic field is applied around the point of insertion of the jet. As it can be clearly observed, the sideways extension is greatly decreased when compared to the HD simulation. For displaying this result, we also used a logarithmic contour map of the density values at the last evolutionary step of the simulation. At the same evolutionary point, there is an increase in the Y/X ratio for increasing magnetic field, due to increased collimation forces, particularly a higher Lorentz force (see Figure 4). In time, the Y/X ratio continues to increase for the jet matter due to the fact that the outflow in the wings is directly limited by the toroidal magnetic field (see Figure 5).

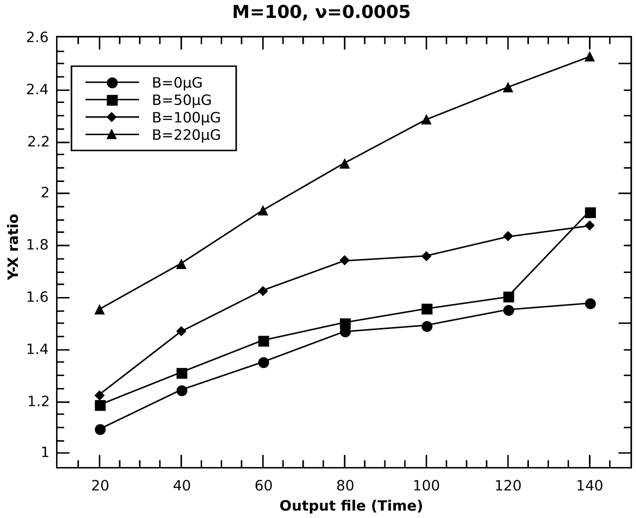

Fig. 4: Lateral extension as a function of the simulated magnetic field.

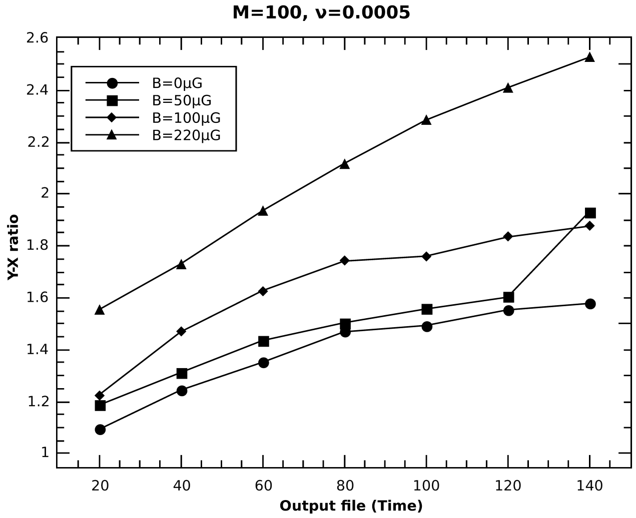

Fig. 5: Evolution of the sideways features when the magnetic field is considered.

CONCLUSIONS AND FUTURE DEVELOPMENT

After performing and analyzing the simulations with different considered parameters, we can conclude that increasing the resolution indeed gives rise to more turbulence as the numerical viscosity decreases. Therefore careful consideration is needed when selecting the resolution, as it may introduce unwanted effects and prolong the simulation time while bringing no new information. When applying a magentic field to the simulation, chances of sideways features development decrease with increasing magnetic field strength. Values of about $100\,\mu$G were proven to be the most suitable, as they preserve the sideways extensions and maintain a magnetic field strength similar to that supported by theory for such sources.

This work will continue with simulations of the jets in 3D. As a result we will be able to use an additional parameter, the angle between the direction of propagation of the jet and the main axis of the ellipsoidal distribution. The final goal is to obtain morphologies that resemble those observed in radio maps. Additionally, we will try to estimate the emission of the simulated jets and compare the values with those retrieved from observational data.

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