Peculiar morphologies of extended extragalactic radio sources from numerical simulations

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Among the extragalactic radio sources there are objects with unusual morphologies. We investigated the possibility that the propagation of jets in a stratified distribution of density may produce such effects. A numerical setup was worked out and hydrodynamical 2D simulations were performed using the PLUTO code. We carried out a parametric study of a jet launched along the main axis of the mass distribution in order to obtain important sideways features.

Introduction

Active galaxies have active nuclei (AGN) in their cores, which are compact regions with a luminosity much higher than normal over a wide range of the electromagnetic spectrum. Early observations of twin lobes of extended radio sources, which were later associated with galaxies at cosmological distances, provided an evidence of highly collimated jets leading to the conclusion that such jets are huge in size, up to megaparsecs, and are highly energetic. The energy release is beyond that which can be attributed to normal processes from stars, interstellar medium and their interaction, therefore the primary source of energy is considered to be a result of mass accretion onto a supermassive black hole in the center of the host galaxy. A typical example of such objects is Cygnus A radio galaxy (see [3] for details).

The classification of extended radio sources is made based on observational characteristics. The main categories are (see e. g. [6]):
- Seyfert galaxies (type I and II)
- Radio galaxies (Fanaroff-Riley or FR I and II types)
- Quasars (radioloud and radioquiet)
- Blazars.

Radio galaxies with moderate emission lead to distortions observed in FR II jets. These distortions can be classified as follows:
- C-shaped, or C mirror-symmetric, when the two jets bend in the same direction;
- X or Z-shaped, center-symmetric, when the jets bend in opposite directions, making up to about 7% of FR II radio sources. Some of them also have a diffuse emission along the second axis [1].

The generally accepted origin of such relativistic jets is the central supermassive black hole, surrounded by an accretion disc, which gives rise to two opposite jets. The variety of morphologies can be explained if one considers different positions of the source axis with regard to our line of sight. These jets are believed to be made up of a mixture of electrons and positrons/protons, highly collimated due to pressure confinement and having supersonic outflow velocities. The extreme regions of the jets are large structures, so called cocoons, which correspond to the observed lobes of radio emission. The appearance of these cocoons is different for the FR I and FR II sources, in terms of the position of the region of emission maximum.

Setting up the problem

The peculiar morphologies observed in extragalactic radio sources are yet to be fully understood, but in the case of many X-shaped radio sources there is a strong dependence on the properties of a host galaxy. These sources tend to be located in elliptical galaxies, with the jet axis close to the main axis of the density

Table 1: Ratio between the jet's dimension on y and x axis for different combinations of parameters.

simulation	M:	100	100	100	150	150	150	150	200	200	200	200
	ν:	0.01	0.005	0.001	0.01	0.005	0.001	0.0005	0.01	0.005	0.001	0.0005
Δ y/Δ x		3.33	2.85	2	3.33	3.07	2.22	1.81	1.9	3.08	2.22	2

distribution. For the present study we performed numerical 2D hydro-dynamical simulations by means of `PLUTO` code [5].

This code 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, and it can be applied in different modes, i.e., classical, relativistic unmagnetized, and magnetized flows. The code is structured in a modular way, allowing a new module 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 `C` programming language and can run on either single processor or parallel machines. The code has already been successfully applied for stellar and extragalactic jets. For the performed simulations we used a cylindrical symmetry on a uniform grid, with 256×256 integration cells. The results were then plotted and their characteristics were analyzed using `Interactive Data Language` (`IDL`).

The supersonic jet was inserted along the main axis of the ellipsoidal stratified medium, described by a King density distribution [4], that best describes elliptical galaxies which are the hosts of such jets. The parameters that characterize a jet are the Mach number M with respect to the sound speed in the external medium (100, 150 and 200) and ν — the ratio between the jet density and the density of the external gas distribution in the central point (0.01, 0.001, 0.005 and 0.0005). A conclusion that could be drawn from the simulations performed in the last decades was that the jets are underdensed with respect to the ambient medium. Both jets of a pair were simulated, with slightly different velocities, in order to avoid the numerical reflection effects in the symmetry plane.

Results and conclusions

Using all possible combinations of the considered parameters, we performed 12 simulations. (For a typical example of the density distribution see Figure 1, right). The evolution in the normalized time is presented

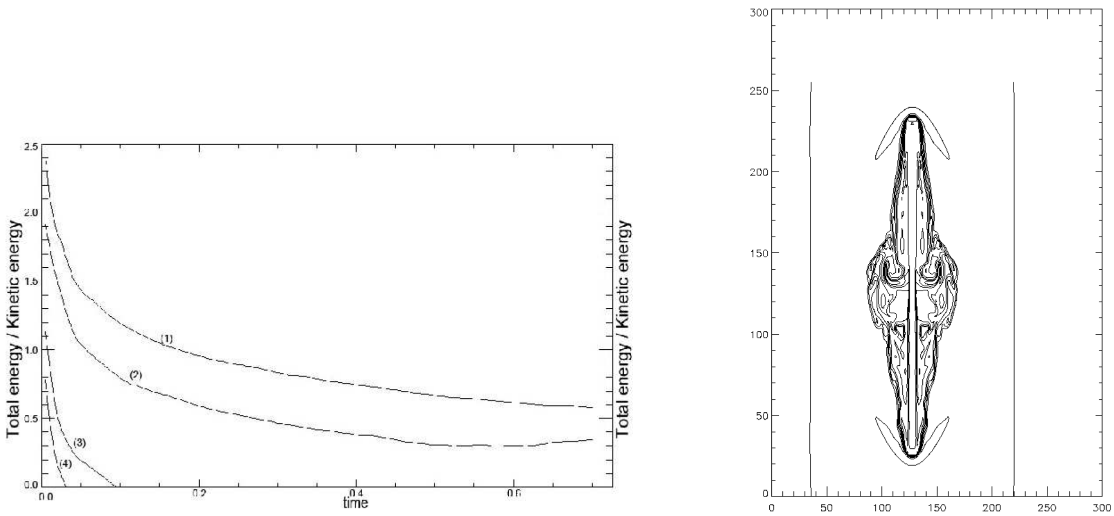

Figure 1: *Left*: Total energy to kinetic energy ratio for M=100 and different values of ν: 0.0005(1), 0.001(2), 0.005(3), 0.01(4). *Right*: Density distribution of a typical jet.

Table 2: Ratio between the jet's dimension on y and x axis taken at different time steps for a given simulated jet.

$\Delta y/\Delta x$	1.66	1.4	1.66	1.44	1.5	1.33	1.58	1.5	1.53	1.62	1.56	1.5	1.52	1.59
Frame	10	20	30	40	50	60	70	80	90	100	110	120	130	140

for each of them, up to the moment the jet head exits the defined domain, as well as the evolution in time of the ratio between the total energy and the kinetic energy.

Comparative approach of the ratio between the total energy and the kinetic energy for a given Mach number leads to the conclusion that this ratio decreases with the decrease of the density ratio. (See Figure 1, left) The reason why such a behavior is present is due to the fact that with the increase of density ratio higher amounts of matter are set in motion, and the velocity gradient along the jet decreases (as the heavier matter transports momentum more efficiently), leading to the increase of kinetic energy ratio to the total energy.

For each simulation we computed the ratio between the jet's dimensions on y and x (Z and R axis in cylindrical coordinates); we found that generally this ratio has similar values for a given density ratio (See Table 1).

Taking this ratio at different time steps for one given jet we founded similar values, all within the range $1.4 - 1.66$. These values can be used for characterizing the structure, which means that the jet is stable for a given set of parameters (See Table 2).

The sample of 9 X-shaped radio sources with sufficient extension of the secondary axis and reliable observations of the host galaxies by HST is presented and discussed in [1]. Recently, a new set of X-shaped radio sources candidates was proposed in [2], although not for all of them optical counterparts of relevant quality are available.

Based on the performed simulations we can conclude that:

- The morphology of the jet depends greatly on the considered parameters.
- A jet launched along (or very close to) the main axis of the host galaxy's mass distribution may produce important sideways features, that might correspond to the "wings" of the X-shaped structures observed.
- The possibility to get "wing-like" structures increases for fast, low-density jets.
- The ratio between the total energy and the kinetic energy also varies with the given parameters — steeper decrease with increased Mach numbers.

This work is thus a further proof for the validity of the hypothesis proposed in [1], on the formation of the X-shaped radio sources due to a particular geometrical configuration of the collimated ejection axis and the host galaxy.

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