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X-SHAPED RADIO SOURCES – ADVANCES IN INTERPRETATION*

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Abstract. In continuation of the work of Capetti et al. [1], the present work investigates the X-shaped morphologies of extragalactic radio sources and tries to establish the area in parameter space where such morphologies form. The main objective is to verify the new proposed interpretation for the X-shaped structures formation, by 2D numerical simulations. Also, some recent observations of three of the sources in our sample are discussed.

Key words: AGN, extragalactic radio sources, X-shaped, numerical simulations, observations.

1. INTRODUCTION

The classification of extragalactic radio sources is still subject of discussions, but a widely accepted classification exists and is based on observational characteristics. The main categories are (growing radio power): Seyfert galaxies (type I and II), Radio galaxies (FR I and FR II), and Quasars (radio and radio-quiet). A fourth category is formed by the variable sources - Blazars (BL Lacs and OVV).

Unified models were proposed for the Active Galactic Nuclei (AGN) that are the sites of the observed extragalactic radio sources. These models are based on the existence of a supermassive black hole (with mass $>10^8\ M_{\mathrm{Sun}}$) at the center of the host galaxy. The black hole is surrounded by an unresolved accretion disk and a dust torus, and two opposite jets are produced. The various morphologies observed are determined by different positions of our line of sight with respect to the direction of the jets axis and by the power of the source. According to this

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interpretation, the radio galaxies are AGNs of high power viewed from a direction close to the perpendicular on the jets - the central emission is obscured by the dust torus, and extended radio-emitting lobes are visible.

The radio galaxies are classified in two groups, based on the power of their radio emission [5]: FR I and FR II. Morphologic differences exist between these two classes.

The jets terminate in large structures – the cocoons – that correspond to the lobes of radio emission. The structure of the cocoon (Fig. 1) was described by Massaglia et al. [9].

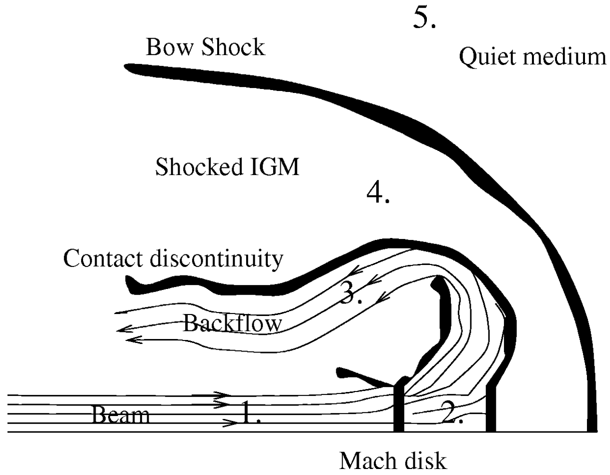

Fig. 1 – Cocoon structure.

The overpressure factors inside the cocoon sustain the collimation of the jet (the observed collimation angles are below 15°). The cocoon generates along the jet shock waves that compress it.

In numerical simulations, structures like the radio emitting lobes observed in radio galaxies form for densities of the jet matter much below the densities of the external medium. The hot spots of radio emission correspond to the Mach disk.

Less powerful sources have more complex structures.

The distortions observed in FR II jets can be classified in:

C mirror-symmetric, or C-shaped, when the two jets bend in the same direction;

C center-symmetric, or X or Z-shaped, when the jets bend in opposite directions.

About 7% of the FR II radio sources are X-shaped, having also a pair of secondary radio lobes. Usually, the radio power of these sources is not very high, being at the lower limit for the FR II.

The composition of extragalactic jets is not well known, although there are observational clues (polarization measurements) that support the electron-positron hypothesis.

Jets seem to be pressure-confined along their length. The flow velocities are supersonic at large scales, and even relativistic at parsec-scales (Kpc for FR II). Velocity measurements are difficult due to the absence of emission/absorption lines. The jet radius increases thousands times leaving the inner core, but after that it re-collimates to a conical structure.

The parameters that characterize a jet are the Mach number M with respect to the sound speed in the external medium and ν – the ratio between the jet density and the density of the external gas distribution in the central point.

The mechanism of radio emission in radio galaxies is the synchrotron radiation from accelerated charged particles. The bow shock propagating through the ambient medium creates a compressed region where particle acceleration, and thus radio emission, occurs (Fermi's mechanism). The density profiles obtained in numerical simulations correspond to luminosity profiles and can be compared with observations.

Several interpretations were made for the formation of X-shaped radio sources: backflow and buoyancy [8], conical precession, reorientation of the jet axis. However, none could explain all the observational aspects.

2. THE SAMPLE

Our test sample is the one used by Capetti et al. [1], and consists of 9 FR II radio galaxies, selected from the literature on the basis of the high extension of the secondary radio lobes (Table 1).

Table 1

Sample sources. Offset between the main optical axis and the radio wings

Name	Optical	Wings	Offset	Radio
3C 52	55	-65	60	25
3C 63	80	-45	55	30
3C 136.1	-80	10	90	-70
3C 192	-85	60	55	-55
3C 223.1	40	-40	80	15
3C 315	35	-45	80	10
3C 403	35	-50	85	85
4C 12.03	-25	-70	85	15
4C 32.25	90	-5	85	60

The new interpretation of the origin of X-shaped radio sources is based on two remarks:

- The angle between the main axis of the mass distribution in the external medium and the main jets axis avoids small values, with an average of 75º.
- The X-shaped radio sources appear in host galaxies of high ellipticity.

Capetti et al. [1] suggested that the "butterfly" morphologies appear naturally in some peculiar geometrical situations. They performed some 2D simulations, and demonstrated that in a ellipsoidal stratified medium, if a supersonic jet is introduced along the main axis of the gas distribution, the bow shock expands also sideways at great speeds because of the higher density gradient in that direction. This way the secondary jets (the "wings") form.

The simulated structures could be identified as X-shaped sources for a wide range of view angles. However, such structures do not form for any jet parameters, so a study of the area in the parameter space where they develop was needed, and was performed during this work.

3. 2D SIMULATIONS

The 2D hydrodynamic simulations were performed in cylindrical symmetry on a uniform grid of 512×512 integration cells in one quadrant of the *r-z* space. The *r-z* profile is obtained by symmetry. 19 simulations were performed, employing about 10000 processor-hours at the Turin Observatory computer cluster and CINECA Bologna.

The jet is aligned to the gas distribution's major axis (constraint imposed by the cylindrical symmetry). Dense jets never form X-shaped structures, while light jets do form such structures for high velocities (e.g., Fig. 2, 3).

As resulted from the 2D simulations, the "wings" form for high velocities $M \geq 60$ and low densities $\nu \leq 0.003$ (Fig. 4).

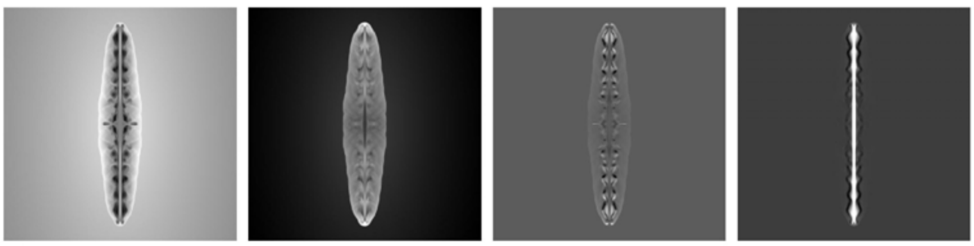

Fig. 2 – 2D Simulation. $M = 100$, $\nu = 0.1$. Density (log), pressure, v_r, v_z profiles.

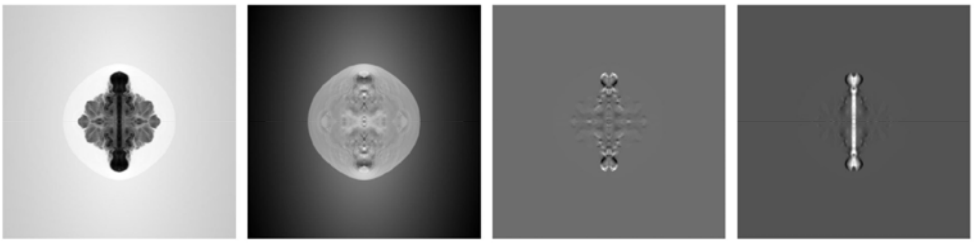

Fig. 3 – 2D Simulation. M = 200, ν = 0.0001. Density (log), pressure, v_r, v_z profiles.

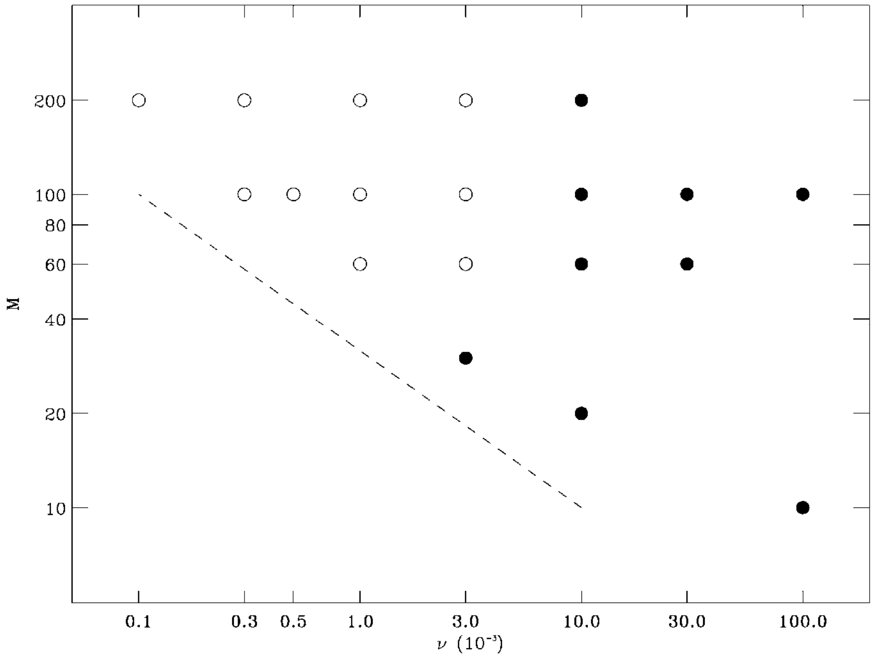

Fig. 4 – Parameter space – open circles represent the formation of X-shaped morphologies.

For low Mach numbers (10, 20, 30) butterfly structures do not form at all, because for low densities the velocity becomes subsonic with respect to the jet medium. It is an observational constraint (the existence of knots and filaments in jets) that the jets should be supersonic.

4. NEW OBSERVATIONAL DATA

New observational data came during 2005 from X-ray (Chandra) for 3C 403 and low frequency radio (GMRT) observations for 3C 136.1 and 3C 223.1.

The Chandra observation was the first in X-ray of an X-shaped FRII radio galaxy [7]. X-ray emission was detected from several radio knots.

The X-ray isophotes of the hot gas of the central galaxy are highly elliptical and aligned with optical isophotes, and this supports the hypothesis that X-shaped morphologies appear as consequence of the propagation of jets through asymmetric density distributions.

The 3C 136.1 and 3C 223.1 observations were done at GMRT in low-frequency (210-640MHz) [3, 4].

3C 136.1 has a spectral index of 0.61 ± 0.01 in the active lobes and 0.76–0.71 in the wings. This is consistent with most of the formation scenarios, which predict flatter spectra in the active radio lobes.

The results for 3C 223.1 were surprising. A spectral index of 1.08 ± 0.01 was observed in the active lobes, and 0.37–0.62 in the wings. A steeper spectrum in the active lobes than in the wings is hard to account in current formation models. One possible explanation could be that the wings are in the process of becoming active lobes.

5. CONCLUSIONS

Depending on their speed and density, some of the simulated jets form extended secondary structures. The resulting morphologies, viewed from different angles, are similar to the observed X-shaped sources. It may be concluded that the formation of X-shaped structures can be due to a particular geometrical configuration, as described above.

We have found, in the M-v parameter space, a zone where X-shaped morphologies form.

Further 3D simulations are to be performed in order to fully understand the dependence of the wings extension with the angle between the jets and the main axis of the gas distribution.

The X-ray data on 3C 403 is consistent with the theory of the formation of X-shaped structures in asymmetrical density distributions.

In most formation scenarios for the X-shaped radio sources, the spectral index of the wings should be higher than that of primary lobes. The new GMRT observational data for 3C 136.1 is consistent with the Capetti et al. [1] interpretation on the X-shaped radio sources formation. However, it is not easy to explain the results of low frequency radio investigation of 3C 223.1. A possible explanation would be that the wings are in the process of becoming main lobes.

A high-resolution radio survey on the entire X-shaped sample is in progress at GMRT, and will be of valuable aid in selecting between the different formation scenarios.

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