The Multimessenger Chakra of Blazar Jets
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Understanding the interplay between jets and ISM for winged radio galaxies

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Abstract. In this work, we investigate the formation and early evolution phase of X-shaped radio galaxies using the Back-flow model. We show how the X-like winged morphology evolves over time in a tri-axial ambient medium, naturally. At this early stage of formation, we demonstrated that both the pair of jet lobes are actively pushing the ambient material out of their path of propagation, forming (X-ray) cavities that are surrounded by a shocked shell (X-ray bright rims) of swept materials. We also noticed how turbulent the wing is in comparison to the active lobe, generating sites of random shocks, indicating that the wings are not passively evolving structures. This study demonstrated that the ambiguous morphology observed in jets is also imprinted over the ambient medium, providing an alternative perspective in understanding the underlying physical process causing such ambiguities. Finally, we indicate that shearing instabilities cause mixing of ambient material at the shearing interface.

Keywords. Galaxies: jets, galaxies: active, Magnetohydrodynamics (MHD), Methods: numerical

1. Introduction

Extended radio galaxies show the presence of jets that emanate from the central Active Galactic Nuclei (AGN) and travel over a distance that can range from several hundreds of kilo-parsecs to a few mega-parsecs. As they travel through the heavy ambient medium (galactic, group, or cluster), they push aside the material that is circumjacent to them, which results in the formation of cavity regions. When studied using X-ray telescopes, an X-ray dip region (the cavities) is found to be surrounded by a bright X-ray envelope, also known as the rims. This phenomenon is caused by the expanding cocoon's shock-wave that has been generated by the backflow of materials of the inflating powerful (FR-II like) jets. Because of this, the jet is able to deposit a significant quantity of energy into the surroundings through the processes of heating, work done, shock waves, and turbulence (Cielo et al. 2018). The flow axis of bidirectional jets is typically predetermined by the spin axis of the supermassive blackhole (SMBH). As a result of this, it is not surprising to come across a pair of cavities that correspond with the flow of the straight, bidirectional jet. Recent findings with deep exposure maps, on the other hand, have shown X-ray cavities that have a high degree of complexity. For instance, Ubertoshi et al. (2022) reported two pairs of cavities that were equally spaced and positioned at a right angle to one another (see also Bogdan et al. 2014). A more complicated illustration can be seen in the Perseus Galaxy Cluster, which reveals off-axis cavities, rims, and intricate pressure waves (see also Ubertoshi et al. (2022) for RBS 797 galaxy cluster). An in-depth investigation has revealed that in each of the instances, the jets have most certainly deviated from the straight course that was anticipated for them, either as a result of jet precession or jet re-orientation into a different direction. These are some intriguing cases, and only a few of these sources have been thoroughly investigated. In general, it is apparent that the ambiguities noticed in the jet morphology also have an impact on the surrounding medium, which are highly intertwined. In this study, we will discuss the origin and evolution of a sub-class of unusual winged radio galaxies, and how they interact with its circumjacent medium. These galaxies exhibit two sets of jet lobes that are positioned at an angle to each other, raising X-like morphology (also known as X-shaped radio galaxies; XRGs).

The XRGs have a pair of lobes known as active lobes, which are mainly identified by the jet hotspots or by indications of active jet activity. The other pair of jet lobes has been identified as the secondary lobe, which was previously thought to evolve passively. Recent observations and simulation works, however, have provided evidence to the contrary. Due to their complex morphology and intrinsic properties, the formation process of such galaxies is still being debated. The mechanism of their formation can be broadly classified into two types (Gopal-Krishna et al. 2012): (a) back-flow model (in which the asymmetric ambient medium curves the back-flowing material in a different direction, producing an X-like structure) and (b) spin flip model (in which the initial jet ejection axis of the central SMBH is forced to change direction due to a BH-BH merger). We will use the back-flow model to generate the XRGs numerically, as it can naturally explain several key characteristics observed in these galaxies (Capetti et al. 2002). The primary goal of this work would be to demonstrate the formation and evolution of such galaxies based on the diverted back-flow scenario, as well as to demonstrate whether or not these RGs exhibit any signs of enhanced interaction with their surrounding ambient medium.

2. Simulation Setup

In order to perform the numerical simulation, we used the relativistic magneto-hydrodynamic (RMHD) module of PLUTO code (Mignone et al. 2007).
We started with an ellipsoidal (tri-axial) galaxy by employing the King's density profile (Cavaliere & Fusco-Femiano 1976), which is defined (in the Cartesian system) as

$$\rho = \frac{\rho_0}{(1 + x^2/a^2 + y^2/b^2 + z^2/c^2)^{\frac{3}{4}}} \tag{1}$$

where ρ_0 is the density at the centre of the galaxy (set to 1 amu/cc) and a, b and c are the effective core radius (4/3, 8/3 and 1 kpc, respectively) which make the density profile tri-axial. The galaxy has an initial isothermal atmosphere, whose static equilibrium is maintained by a gravity profile determined using the hydro-static equilibrium equation. We have introduced a jet nozzle at the centre of this distribution (i.e., at the galaxy centre) that will continuously inject bi-directional relativistic jets (radius 200 pc) having Lorentz factor $\Gamma = 5$ and which is under-densed as $10^{-6}\rho_0$. A B-field of toroidal nature is injected along with the jet which is defined as $B_x = -B_t r sin\vartheta$ and $B_y = B_t r cos\vartheta$, where r and ϑ are the polar coordinates in the perpendicular plane to the jet ejection axis, and B_x, B_y are the components of the field defined in that plane. The value of B_t is constant and is set to 100 μG. The parameter values are adopted from the study of Rossi et al. (2017) for the initial configuration, which have broader observational relevance. We simulate a 3D Cartesian domain having size $(16 \times 32 \times 16)$ kpc, distributed in $192 \times 384 \times 192$ grids, where y-axis is the jet propagation axis.

3. Jet-environment interaction & wing formation

At the initial time of jet propagation, the jet struggles to pierce the dense ambient medium, forming an ellipsoidal cocoon in which the jet cannot be identified individually. But, after a Mega-year of evolution, it extends beyond the core of the galaxy and begins

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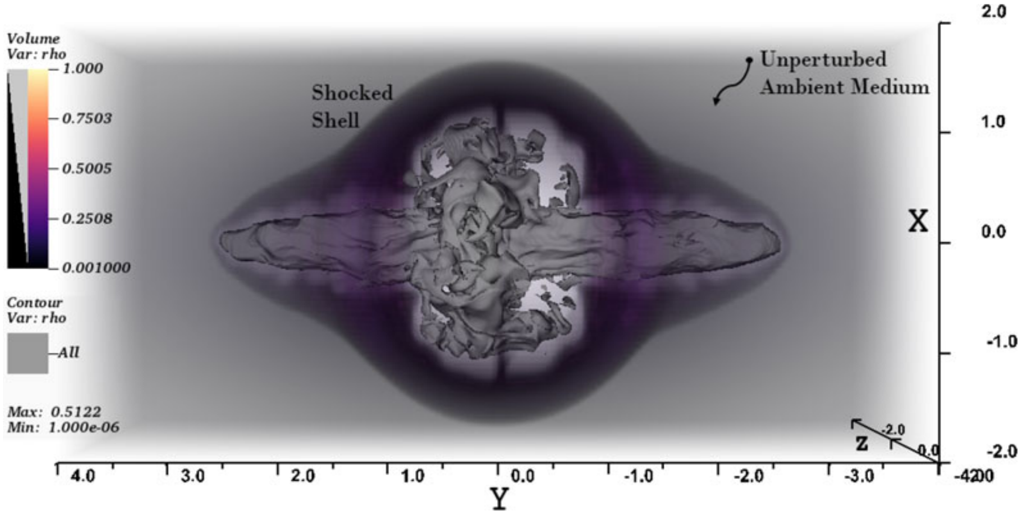

Figure 1. Volume rendered image of the simulated 3D density distribution, showing the jet-ambient medium configuration, indicating their highly interactive nature. The jet material here is represented with gray colored contour, which is overlaid with the ambient material indicated by the magenta color bar. Here, unit density is 1 amu/cc and unit length is 4 kpc.

to propagate rapidly. As the jet still remains underdense, it continues to generate a steady back-flow of matter from the unstable jet head. The asymmetric ambient medium further exerts additional force on the plasma material as it flows back towards the centre. This is the pressure gradient force that is higher along the minor axis of the galaxy. As a result of this force, the back-flowing plasma material diverts in the lateral direction, forming a structure that looks like a wing. We ran the simulation up to 4 Myr, just to investigate the early formation phase of such galaxies. At this stage, the active jet lobe still drills through the dense galactic medium with little decollimation. Therefore, the formed structure is expected to expand as it is for a significant course of it's evolution, which illustrates how XRGs with sizes of ∼100 kpc may have grown based on the Back-flow model. At this stage, the formed cocoon is still over-pressured and thus capable of removing the matter surrounding it (i.e., the ambient gas).

This is illustrated in Fig. 1, which is a volume rendered image of the density distribution of the jet-ambient system at time 3.9 Myr. It can be seen that the active jet is drilling through along the y-axis, concurrently with the construction of a wing structure, both of which are pushing the surrounding material away and producing a shell of over-density region. When observed with X-ray imaging telescopes with typical band ranges of 1-10 kev, we will see a cavity region and a bright rim (2D representation of the 3D shell structure) surrounding the cavities. It would be interesting to note that the ambiguities that are linked with the jet are produced by an underlying physical process, and the size and shape of the cavity region is expected to depend on these ambiguities. This can further be investigated in understanding the difference between various mechanisms that produces jet anomalies. In this regard, Fig. 2 shows the amount of volume the cocoon occupies within our simulated box at 3.9 Myr, as well as a comparison to the volume of an ellipsoid with a major axis of 16 kpc. This indicates how much fraction of the triaxial galaxy is disturbed by the newly-formed XRG. The small scale dips observed in the curve are due to the loss of cocoon volume caused by the mixing of jet-ambient material at the shear surfaces (due to shearing instabilities).

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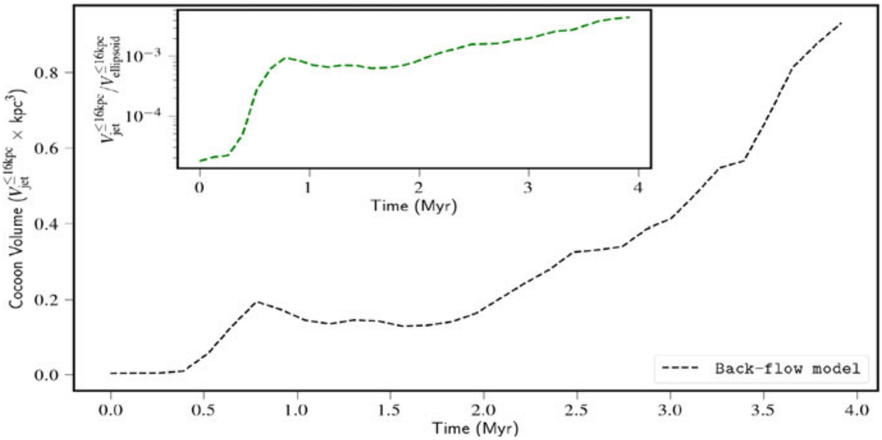

Figure 2. Evolution of the cocoon volume (in physical unit) and its comparison with the volume of an ellipsoid having a major axis of 16 kpc. This will give us an idea of how much of the ambient medium is affected by the inflated jet.

Lastly, we would like to highlight the turbulent wing structure that has been nicely captured in the volume rendered image in Fig. 1. The wing appeared more turbulent than the active lobe, producing sites of random shocks that in turn play a significant role in energizing the cooling particles, affecting it's emission signature. This has also been studied in Giri et al. (2022), using the evolution of passive particles.

4. Summary

In this work, we first showcase how a back-flow model can naturally form an X-like winged structure in a tri-axial medium. The primary motivation here was to demonstrate the enhanced interaction observed between such an unusual jetted system and its immediate ambient medium. The interaction caused by the expanding over-pressured cocoon pushes the surrounding matter aside, resulting in a shell-like shocked structure. When observed using imaging X-ray telescopes, such systems produce an X-ray cavity region at the center, surrounded by a bright rim of enhanced emission, which is a 2D representation of the 3D shocked shell shown here. We also demonstrate how turbulent the wing is, generating random shock sites, indicating that wings are actively evolving structures, at least in this early formation phase. Turbulence and shock sites observed in the wing play an important role in re-energizing the cooled particles, influencing their emission signature. Finally, we indicate that shearing instabilities cause significant mixing of jet material with the ambient material on the shear surface.

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