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Numerical insights into the propagation of relativistic jets from supermassive black hole inside uniform interstellar medium

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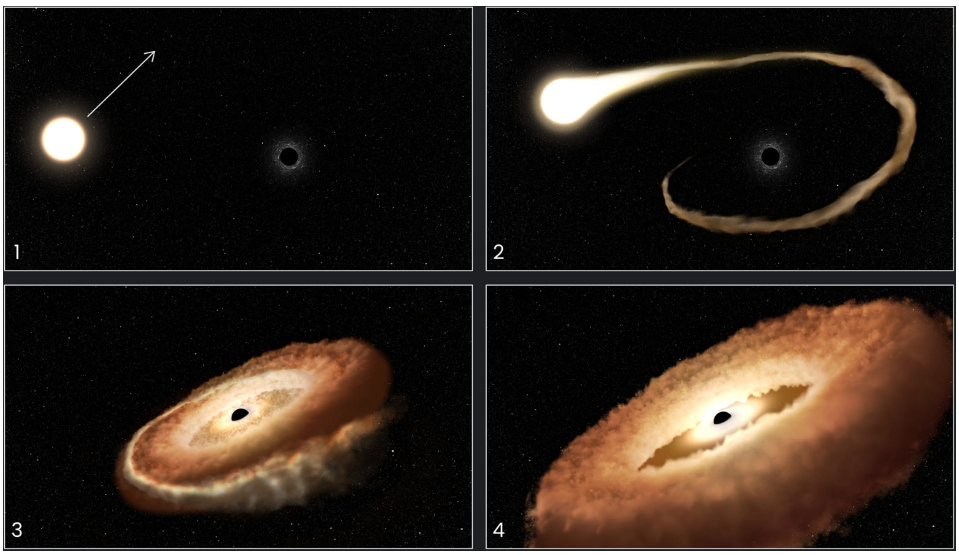
Abstract

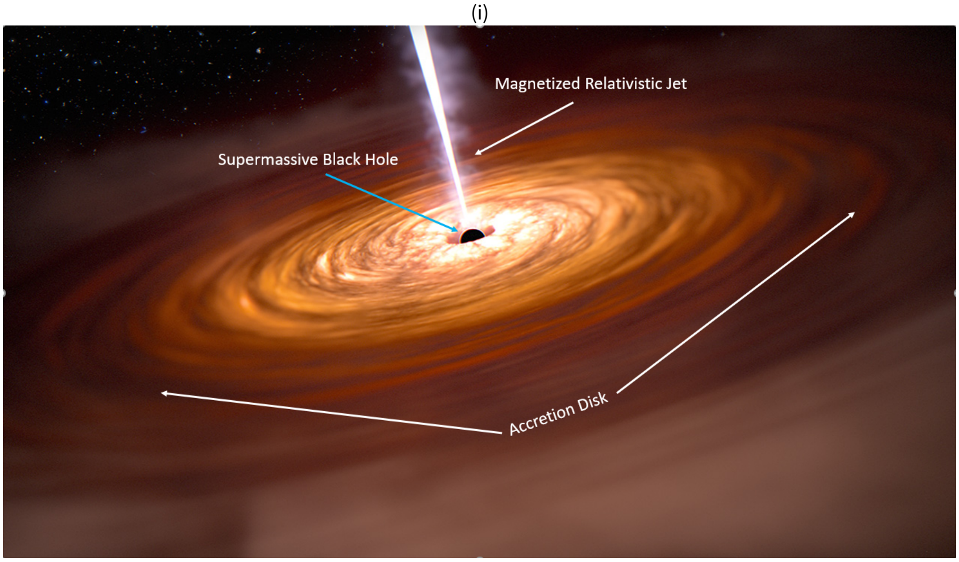
In this present study, the numerical simulation of relativistic astrophysical jet propagation inside an uniform interstellar medium (ISM) has been carried out by solving relativistic magneto-hydrodynamic equations (RMHD) in higher order finite volume method in astrophysics CFD solver[Mignone et al. 2007], which is developed in C programming platform. The relativistic jet is primarily issued from the pole of supermassive black hole inside an active galactic nuclei (AGN). The details flow physics associated to relativistic jet propagation inside the uniform interstellar medium has been thoroughly discussed in this study.

Introduction

Relativistic jets are among the most energetic and enthralling phenomena observed in the universe [Piran 2004; Gaensler and Slane 2006; Hardcastle and Croston 2020; Pasham et al. 2023]. They originate from some of the universe's most compact and potent objects—from the supermassive black holes that fuel active galactic nuclei (AGNs) (see Figure 1, [Gourgouliatos and Komissarov 2018]) to stellar-mass black holes, neutron stars, young stellar objects (YSOs), gamma-ray bursts (GRBs), blazars, microquasars, and more [Piran 2004; Gaensler and Slane 2006; Hardcastle and Croston 2020; Pasham et al. 2023]. The mechanism behind these relativistic jets propagation through both uniform and non-uniform interstellar mediums—or within cluster environments—plays an essential role in the growth and evolution of compact objects. These highly collimated relativistic jet can propagates upto several light year distance at a velocity close to speed of light composing with high energetic particles with higher degree of magnetization. The jets associated with AGNs and YSOs are connected to underdense and overdense respectively, where in the case of underdense jet $\rho_j << \rho_a$ and for overdense jet $\rho_j >> \rho_a$ [Dal Pino 2005]. Active Galactic Nuclei (AGN) are the intensely luminous and small regions at the centers of certain galaxies [refer Figure1]. They are driven by supermassive black holes (positioned at the center of AGN) that pull in surrounding matter, emitting radiation across the entire electromagnetic spectrum, ranging from radio waves to gamma rays. When matter accretes onto a supermassive black hole at the center of an AGN, it is heated to extreme temperatures due to the intense gravitational forces near the singularity point of the black hole [see Figure 1]. As a result, the matter's density decreases significantly, causing the formation of an underdense jet ($\rho_j << \rho_a$), that is launched from the black hole's pole at nearly the speed of light. The precise mechanisms behind jet formation and acceleration are still an ongoing research. However, once these jets are launched, they can travel vast distances across space, carrying tremendous amounts of energy and momentum. This energy is often emitted across the electromagnetic spectrum, ranging from radio wavelengths to high-energy gamma rays, depending on the physical conditions in the jet's environment (such as the type of medium and whether it is uniform or non-uniform). The blazers are capable of emitting relativistic jets with a Lorentz factor (Γ) reaching as high as 40 [Savolainen et al. 2010; Lister et al. 2013]. Mattia et al.[Mattia et al. 2023] investigated the effect on flow features associated with magnetization and electric field in a magnetized relativistic jet due to the presence of both poloidal & toroidal magnetic field distribution at the jet inlet. Del et al.[Del Zanna et al. 2016] investigated the tearing instability within a magnetized relativistic jet emerging from an active galactic nucleus (AGN) through a series of numerical simulations. Several researchers[Qian et al. 2016; Vourellis et al. 2019; Ripperda, Bacchini, and Philippov 2020; Ripperda et al. 2022; Nathanail et al. 2022] performed numerical simulations of the accretion disk and the launching of



(i)



(ii)

Figure 1. (i) Tidal disruptions of star due to presence of black hole (ii) the relativistic jet formation from a black hole during tidal disruptions of star inside an active galactic nuclei (AGN)

relativistic jets from the center of a supermassive black hole. Additionally, Kramer et al.[Kramer and MacDonald 2021] explored the relationship between synchrotron emission and the magnetic field structure during the propagation of relativistic jets through numerical simulations. Numerous relativistic hydrodynamic and magneto-hydrodynamic codes[Mignone et al. 2007; Mignone, Plewa, and Bodo 2005; Seo et al. 2021; Falle and Komissarov 1996; Martı and Müller 1996; Aloy et al. 1999; Zhang and MacFadyen 2006; Radice and Rezzolla 2012; Núñez-de La Rosa and Munz 2016; Del Zanna and Bucciantini 2002; White, Stone, and Gammie 2016; Almgren et al. 2010; Schneider and Robertson 2015] have been developed to investigate the complex flow dynamics associated with relativistic jet propagation through both uniform and non-uniform interstellar medium. The mechanism behind the shock-turbulence interaction [Pal and Roy 2024], effects of jet Lorentz Factor (Γ_j) [Pal, Roy, and Halder 2025], presence of dense cloud [Pal, Roy, and Banerjee 2025] and identification of turbulent structures [Pal and Roy 2025] during relativistic jet propagation through an uniform interstellar medium has been extensively investigated in our previous research work [Pal and Roy 2024; Pal, Roy, and Halder 2025; Pal and Roy 2025; Pal, Roy, and Banerjee 2025].
In this present study, the two-dimensional numerical simulation of axisymmetric relativistic underdense astrophysical jet has been carried out by solving relativistic magneto-hydrodynamic (RMHD) equations in astrophysics [Mignone et al. 2007] cfd solver using higher order finite volume method. The detailed flow features associated with relativistic jet propagation through a uniform interstellar medium has been investigated thoroughly, which was primarily originating from the pole of supermaasive black hole due to accretion of matter on it inside the active galactic nuclei (AGN).

Computational Methodology

In this present study, the direct numerical simulation (DNS) of relativistic jet propagation has been carried out by solving two dimensional axisymmetric non-dimensionalized relativistic magneto-hydrodynamic (RMHD) equations [Mattia et al. 2023] by employing higher order finite volume method in computer code [Mignone et al. 2007] using cylindrical coordinates (r, ϕ, z). The conservative form of Relativistic magneto-hydrodynamic equation (RMHD) described below in vectorial format, which is based on Landau 1971 and Mattia et al. 2023.

$$\frac{\partial D}{\partial t} + \nabla.(D\mathbf{v}) = 0 \tag{1}$$

$$\frac{\partial \mathbf{m}}{\partial t} + \nabla.(w_t\Gamma^2\mathbf{v}\mathbf{v} - \mathbf{b}\mathbf{b} + Ip_t) = \mathbf{f}_g \tag{2}$$

$$\frac{\partial E_t}{\partial t} + \nabla.(\mathbf{m}) = \mathbf{v}.\mathbf{f}_g \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla.(\mathbf{v}\mathbf{B} - \mathbf{B}\mathbf{v}) = 0 \tag{4}$$

Where, $D = \rho\Gamma$; $\mathbf{m} = w_t\Gamma^2\mathbf{v} - b^0\mathbf{b}$ and $E_t = w_t\Gamma^2 - b_0b_0 - p_t$ respectively. The term b^0, $\mathbf{b}$, w_t & p_t can be written as follows; $b^0 = \Gamma\mathbf{v}.\mathbf{B}$; $\mathbf{b} = \frac{\mathbf{B}}{\Gamma} + \Gamma(\mathbf{v}.\mathbf{B})\mathbf{v}$; $w_t = \rho h + \frac{\mathbf{B}^2}{\Gamma^2} + (\mathbf{v}.\mathbf{B})^2$ & $p_t = p + \frac{\mathbf{B}^2/\Gamma^2+(\mathbf{v}.\mathbf{B})^2}{2}$ respectively.Here ρ, p, $\mathbf{v}$, h, E_t and $\mathbf{B}$ are non-dimensionalized density, thermal pressure, velocity vector, specific enthalpy, total energy and magnetic field respectively. $\mathbf{f}_g$ is a acceleration term in the conservative equation. Also, Γ is the Lorentz Factor, which can be written as $\Gamma = \frac{1}{\sqrt{1-\mathbf{v}.\mathbf{v}}}$. The velocity vector ($\mathbf{v}$) and spatial coordinates (r, z) are non-dimensionalized based on speed of light (i.e.,$C \equiv 1$ in non-dimensional form; $C = 3 \times 10^8 m/s$ in dimensional form) and 1kpc (1kpc$\equiv$ 3262 light years) respectively. Which gives the unit-reference time scale t_0 = 3262 years ($t_0 = \frac{L_0}{C}$). The density ρ, thermal pressure p and $\mathbf{B}$ are non-dimensionalized based on density of proton. ρC^2 and $\sqrt{4\pi\rho C^2}$ respectively. For the present numerical study the flow is assumed to be thermally perfect relativistic magnetized fluid flow [Mattia et al. 2023]. The Taub equation of state [Taub 1948] is usually used to model this thermally perfect relativistic fluid, where the Synge expression [Synge 1957] is used to capture the variation of specific heat ratio

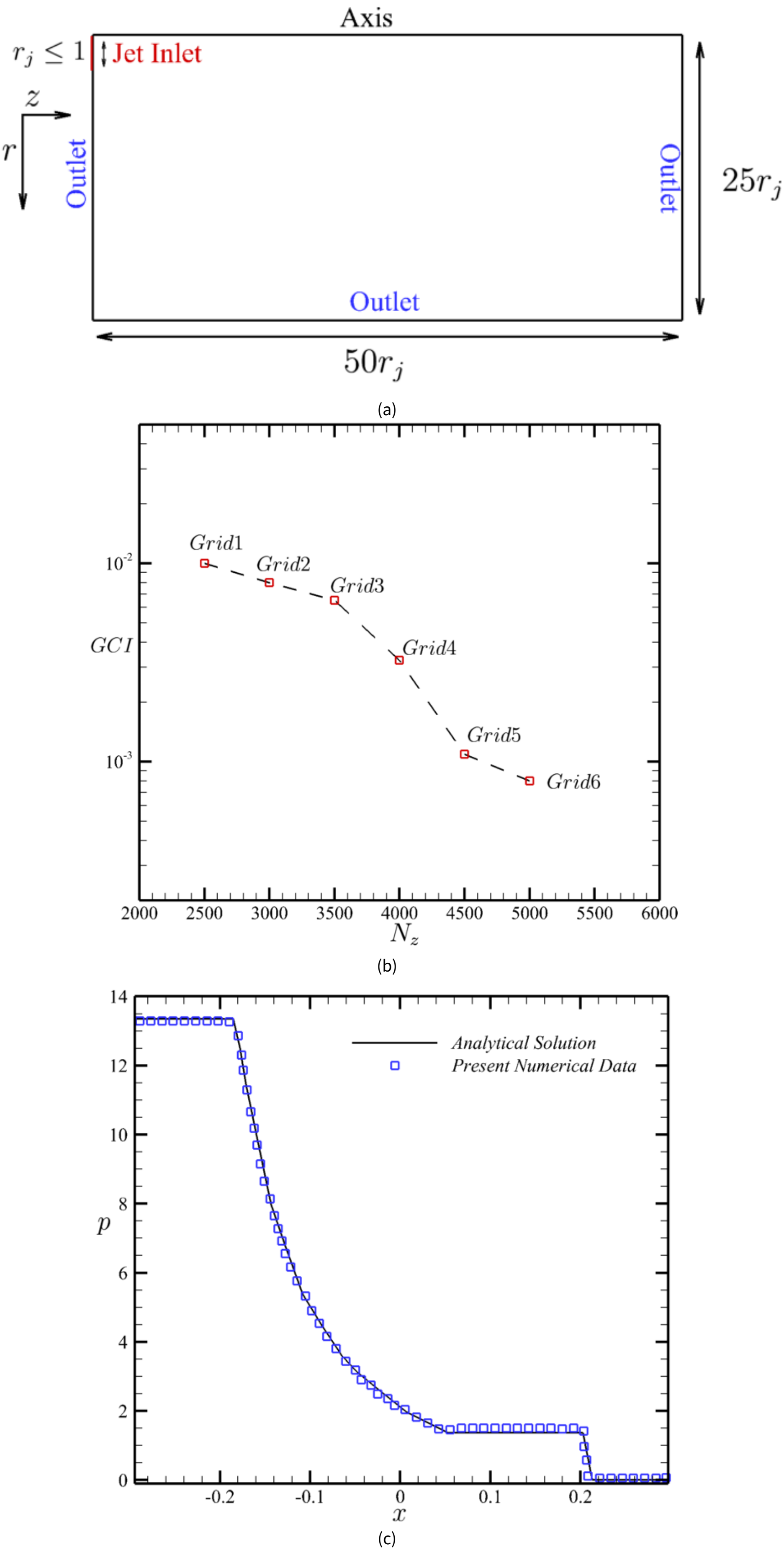


Figure 2. (a) Computational domain, (b) Grid-convergence-index, (c) Numerical validation

(γ) with respect to absolute temperature (T). However, in the present study, the equation of state proposed by Mignone et al. [Mignone and McKinney 2007] is used to model the thermally perfect relativistic fluid, because it is based on a simple quadratic polynomial function and less computationally expensive without compromising the accuracy. The value of specific heat for the current problem is taken as $\gamma = \frac{4}{3}$; in order to capture the high temperature effects.
The unsteady non-dimensional compressible RMHD equations have been solved in the present study by employing a higher order finite volume method in PLUTO[Mignone et al. 2007] solver, where the numerical scheme is based on the HLLC Riemann solver[Eleuterio Francisco Toro 1992; Eleuterio F Toro 2019]. The numerical study by Mignone et al.[Mignone and Bodo 2005, 2006] confirms that HLLC Riemann solver is capable of solving these kind of high speed relativistic fluid flow problems by maintaining numerical stability. In the present study the convective flux calculation at cell interface has been done by using 3rd order WENO scheme[Yamaleev and Carpenter 2009]. A monotonized central difference limiter has been imposed to clip off all the spurious oscillations near the vicinity of the shock waves, which has low diffusivity. A low storage explicit four stage 3rd order Runge-Kutta time integration method is employed to get the elements of the conservative matrix at each timestep. The non-dimensional timestep for the current numerical study is chosen as Δt=5 $\times$ 10^{-6}, which maintains the CFL number 0.25 during the simulation runtime.
The computational domain for the present study is chosen based on the numerical study by Mattia et al.[Mattia et al. 2023] in a two dimensional cylindrical coordinate system as shown in Figure2(a). Where the span of the computational domain is $r \in [0, 25r_j]$ and $z \in [0, 50r_j]$, moreover r_j is the radius of the jet at inlet. The magnetic field structure is same as Mignone et al.[Mignone, Ugliano, and Bodo 2009] & Mattia et al.[Mattia et al. 2023]. The toroidal magnetic field distribution can be written as $B_\Phi(r) = \Gamma_j b_m \min\left(\frac{r}{r_m}, \frac{r_m}{r}\right), 0 \leq r \leq r_j$; Here $r_m = r_j/2$ is the radius where the toroidal field attains its maximum value, $\Gamma_j b_m$. The b_m is determined by $b_m = \sqrt{\frac{4p_j\sigma_\Phi}{(r_m/r_j)^2[1-4\log(r_m/r_j)-2\sigma_\Phi]}}$. The value of p_j is recovered by imposing Mach number $M = v_j\sqrt{\frac{\rho_j}{\gamma p_j} + \frac{1}{\gamma-1}}$; the Mach number for current numerical study is maintained as $M = 6$. By maintaining radial momentum equilibrium, the thermal pressure distribution inside the jet $p(r)$, which can be written as $p(r) = p_j + b_m^2\left[1-\min\left(\frac{r^2}{r_m^2}, 1\right)\right]$; The poloidal magnetic field distribution can be written as $B_z = \sqrt{\sigma_z[(r_m/r_j)^2 b_m^2 + 2p_j]}$; σ_z & σ_Φ are two magnetization parameters, where the the values of σ_z & σ_Φ are 0.7 and 0.3 respectively for current numerical simulation. The boundary condition for the jet inlet is given as (for $r_j \leq 1$) $\rho_j = 1$ and (v_r, v_Φ, v_z)=(0.0,0.0,v_j). The velocity of relativistic jet will $v_j = 0.9977$ for $\Gamma_j = 10.0$, which means that the relativistic jet issues at a velocity of 99.77% of speed of light. Also, the boundary condition at the outlet is maintained as $\frac{\partial p}{\partial n} = 0$, $\frac{\partial}{\partial n}(v_r, v_\Phi, v_z) = 0$ and $\frac{\partial \rho}{\partial n} = 0$. At $t = 0$, ambient initialized with $\rho_a = 10^3\rho_j$, $p_a = 1$ and (v_r, v_Φ, v_z)=(0.0,0.0,0.0).
A block-structured quadrilateral uniform ($\Delta r = \Delta z$) mesh has been generated by maintaining an aspect ratio of one. Total six grids are taken to check the convergence of the numerical solution obtained by them, which are Grid1 (1250 $\times$ 2500), Grid2 (1500 $\times$ 3000), Grid3 (1750 $\times$ 3500), Grid4 (2000 $\times$ 4000), Grid5 (2250 $\times$ 4500) & Grid6 (2500 $\times$ 5000) respectively. In order to check the convergence of the computational solution, a grid independence study involving the above grids have been conducted by employing Grid-Convergence-Index (GCI) theory, which was originally proposed by Roache [Roache 1994, 1997]. The Richardson extrapolation [Richardson 1911] theory is employed to perform the grid refinement tests. The mathematical formula for GCI is given as $GCI = \frac{C_s|\epsilon|}{r^p-1}$; where $\epsilon = \frac{f_2-f_1}{f_1}$ is known as relative error (f_2 and f_1 are the solutions of coarser and finer grid respectively), C_s is the factor of safety, r is the ratio of coarser grid to finer grid

spacing, p is the order of accuracy of the numerical scheme. Roache [Roache 1994] figured out that GCI is capable of obtaining the conservative estimate of the relative error to the unknown "exact" solution. It may be noted that the average relative error of the computational solution obtained by Grid6 (2500×5000) is less than 0.08%, with respect to the unknown "exact" solution as shown in Figure 2(b). The computational convergence for Grid6 is maximum, where the GCI for Grid6 is equivalent to 8×10^{-5}. It may be noted that average relative error of numerical solution obtained through the Grid6 will have less than 0.08 % error with respect to the unknown "exact" solution as shown in Figure2(b). Based on this grid independence study, the Grid6 is chosen to perform this numerical study. Also, the numerical validation ensures that the present numerical data is well matched with analytical solution of streamwise thermal pressure distribution of two-dimensional relativistic shock tube problem [Rosswog 2015] as shown in Figure2(c).

Results & Discussion

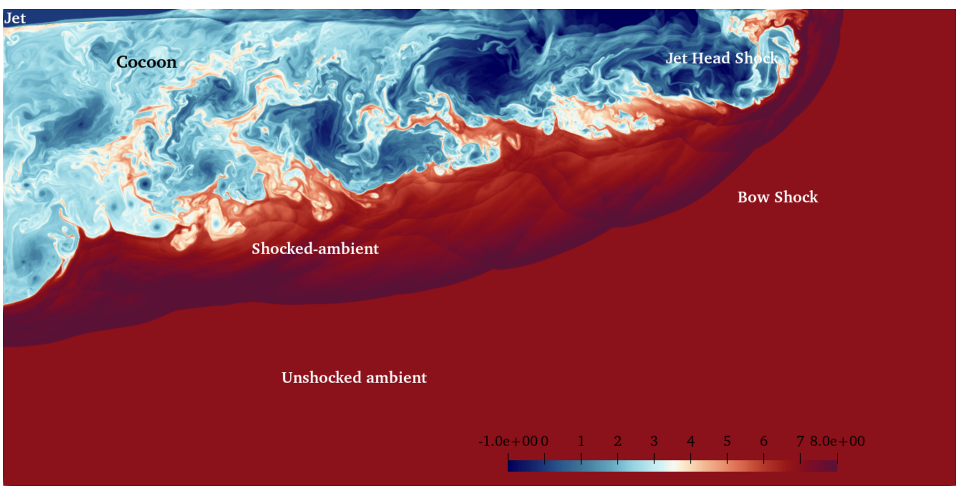


Figure 3. logarithmic density distribution of relativistic jet at $t = 200 \sim 0.6524$MYr for $\Gamma_j = 15.0$

Compressible non-relativistic jet has been numerically explored by both Thaker et al.[Thaker, Mathew, and Ghosh 2023] and Rahatgaonkar et al.[Rahatgaonkar, Pradhan, and Ghosh 2025], where they have investigated the basic flow features and associated it's shock turbulence interaction. But there is a significant difference between non-relativistic compressible jet & compressible underdense relativistic astrophysical jet associated with flow physics and it's propagation.

Norman et al.[Norman et al. 1982] carried out the first numerical simulation of relativistic hydrodynamic jet propagation and described the complex flow features during jet and ambient interaction. The interaction between relativistic hydrodynamic jet & ambient can be described in a few sequential stages, (a) formation of contact discontinuity at the interface between jet and ambient due to huge density difference, (b) formation of jet head shock (reverse shock) at the frontal portion of the jet, which is used to propagate against the core jet flow, (c) formation of bow shock at the ambient, which causes the acceleration of fluid at the unshocked ambient, (d) deceleration of shocked jet fluid due to the presence of jet head shock, (e) jet head shock forcefully pushes back the decelerated shocked jet in the backward direction and at last the shocked jet inflates into a cocoon structure & (f) formation of compression waves, shock waves inside the shocked ambient medium; the medium is in between the cocoon and unshocked ambient medium. Now the relativistic magnetohydrodynamic jet issuing from a blackhole is characterized by narrow beam of hot plasma, which interacts with cold interstellar medium during it's propagation. Also the interstellar medium can be uniform or non-uniform in nature, but in the present numerical study the medium is a uniform interstellar medium. The complex flow features associated relativistic magnetohydrodynamic astrophysical jet propagation issuing from a supermassive blackhole can be described by the logarithmic density distribution shown in Figure3. At t = 200 $\sim$ 0.6524 Myr, the contact discontinuity forms due to huge density difference between jet and ambient, as the relativistic jet just interacts with the cold ambient. Both the jet head shock and the bow shock (BS) form at the frontal portion of relativistic jet at t = 200 as shown in Figure3 (here blue color represents the jet material and red color represents the ambient material), which is known as dual shock formation. The jet head shock continuously pushes the shocked jet towards the backward direction and inflates into a cocoon structure. Also, the bow shock (BS) continuously accelerates the fluid elements present inside the unshocked ambient medium as time evolves. When the jet head shock continuously sweeps out the shocked core jet towards the backward direction, the bulk kinetic energy of jet transferred to thermal energy and stored inside the cocoon during inflation.

Conclusion

In this study, we simulated the propagation of relativistic astrophysical jets through a uniform interstellar medium (ISM) by solving the relativistic magneto-hydrodynamic (RMHD) equations using a high-order finite volume method in an astrophysical CFD solver [Mignone et al. 2007].These jets, which primarily originate from the poles of supermassive black holes in active galactic nuclei (AGN), are modeled to capture the intricate flow physics involved.

Our comprehensive analysis elucidates the complex dynamics governing jet propagation through the ISM, offering detailed insights that not only reinforce current theoretical frameworks but also pave the way for future advances in high-energy astrophysics.

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Conflicts of Research Interest

Authors declare that there is no conflict of research interest.

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