Investigating AGN Jet Recollimation Shocks: Findings from 2D and 3D RMHD Simulations

Abstract

Understanding the structure of active galactic nucleus (AGN) jets is still an open question. Relativistic magnetohydrodynamical (RMHD) simulations help study these jets' dynamics and emission. Recent research focuses on instabilities downstream of recollimation shocks, using 3D simulations to show their complex dynamics and effects on jet structures. Turbulence and shocks in these regions can accelerate particles to high energies, which may explain extreme behaviors in high-energy peaked blazars. However, intense magnetic fields can suppress these instabilities, which are still being studied. This work looks at different instabilities downstream of recollimation shocks in AGN jets and how they impact particle acceleration and emission in various jet regions. We use high-resolution 2D and 3D simulations to set the stage for detailed RMHD simulations with the PLUTO code. Our results aim to enhance understanding of the spectral energy distribution, intensity, and polarization of non-thermal emissions, providing new insights into AGN jet dynamics.

Motivation

Electrons can be accelerated in a series of oblique shocks induced by the recollimation of relativistic jets [1, 2, 3, 4].

New 3D simulations of recollimated, weakly magnetized jets (post-first recollimation shock) show:

- Rapidly growing instability in the flow
- Development of high turbulence
- Flow deceleration
- Inhibition of multiple shock structure formation as seen in 2D simulations

Research Question: *Can electrons be accelerated at the recollimation shock and further energized through stochastic acceleration in the turbulent downstream?*

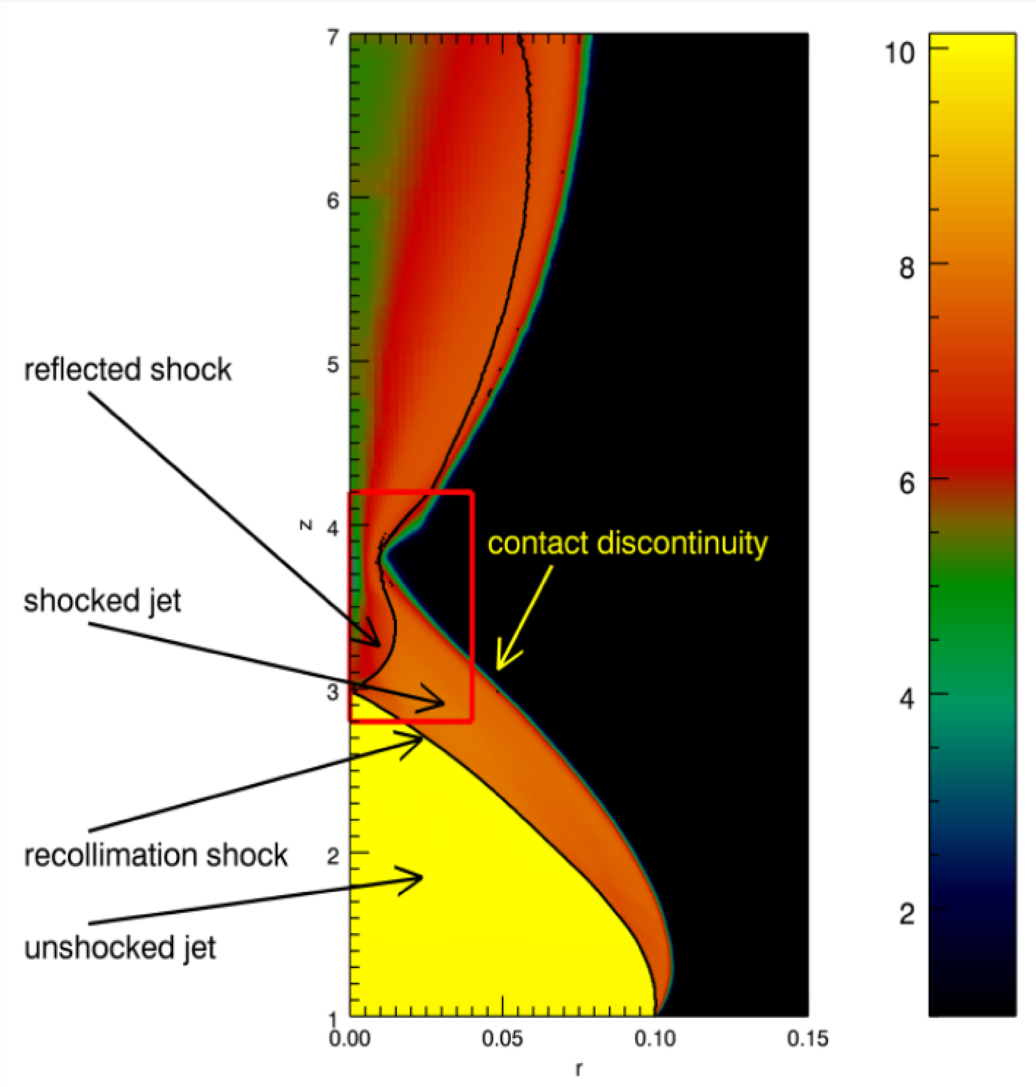

Figure: The distribution of the Lorentz factor, highlighting the key features of the steady-state solutions. Adapted from [2].

Numerical Approach

Using the RMHD module of the MHD code PLUTO [5], we conduct both 2D and 3D simulations:

2D Simulations: Performed in cylindrical coordinates (r, z) within the domain $[0, 6] \times [1, 30]$, where distances are normalized to z_0, the distance from the jet's launching site. The jet is injected into a non-equilibrium state, with simulations tracking its equilibration.

3D Simulations: Transition from 2D cylindrical to 3D Cartesian coordinates. The 2D simulations provide a nearly equilibrium initial state for the 3D simulations. High resolution is crucial to capture and trigger instabilities accurately. Additional numerical functions used include: `InputDataInterpolate` and `StaggeredRemap`.

References

[1] S. S. Komissarov and S. A. E. G. Falle. Simulations of Superluminal Radio Sources. , 288(4):833–848, July 1997.

[2] G. Bodo and F. Tavecchio. Recollimation shocks and radiative losses in extragalactic relativistic jets. , 609:A122, February 2018.

[3] Konstantinos N. Gourgouliatos and Serguei S. Komissarov. Reconfinement and loss of stability in jets from active galactic nuclei. *Nature Astronomy*, 2:167–171, December 2018.

[4] A. Costa, G. Bodo, F. Tavecchio, P. Rossi, A. Capetti, S. Massaglia, A. Sciaccaluga, R. D. Baldi, and G. Giovannini. FR0 jets and recollimation-induced instabilities. , 682:L19, February 2024.

[5] A. Mignone, G. Bodo, S. Massaglia, T. Matsakos, O. Tesileanu, C. Zanni, and A. Ferrari. PLUTO: A Numerical Code for Computational Astrophysics. , 170(1):228–242, May 2007.

Parameters

We consider a jet with an initial opening angle $\theta_j = 0.1$ and Lorentz factor $\Gamma = 10$. The density ratio of the jet to the ambient medium is $\nu = \frac{\rho_j}{\rho_{ext}} = 10^{-5}, 10^{-4}$. The pressure ratio is $P_{\rm ratio} = \frac{P_j}{P_{ext}} = 10^{-3}, 10^{0}, 10^{1}$. The source magnetization ranges from 0 (unmagnetized) to 0.1, defined as $\sigma_r = \frac{B_p^2 + B_\phi^2/\Gamma^2}{h}$, where $h = \frac{5}{2}T + \sqrt{\frac{9}{4}T^2 + 1}$ and $T = \frac{P}{\rho c^2}$. All profiles are smoothed.

Results

Magnetization Impact: Increased magnetization decreases the position of the first recollimation point due to poloidal pressure and toroidal tension.

Pressure Ratio: Higher pressure ratios allow freer jet expansion and larger recollimation distances, preserving jet structure.

Cold, High Magnetization Jets: Almost absent recollimation shocks due to poloidal dominance.

Jet Acceleration: Less expansion results in less acceleration.

Heavy Jets: Recollimation at larger distances.

3D Simulation Insights:

HD cases show strong instabilities and rapid jet deceleration.

Low magnetization (σ_r = 0.01) stabilizes jets by suppressing instabilities.

Moderate magnetization (σ_r=0.03) allows instabilities like Kelvin-Helmholtz and Kink modes post-rec. shock.

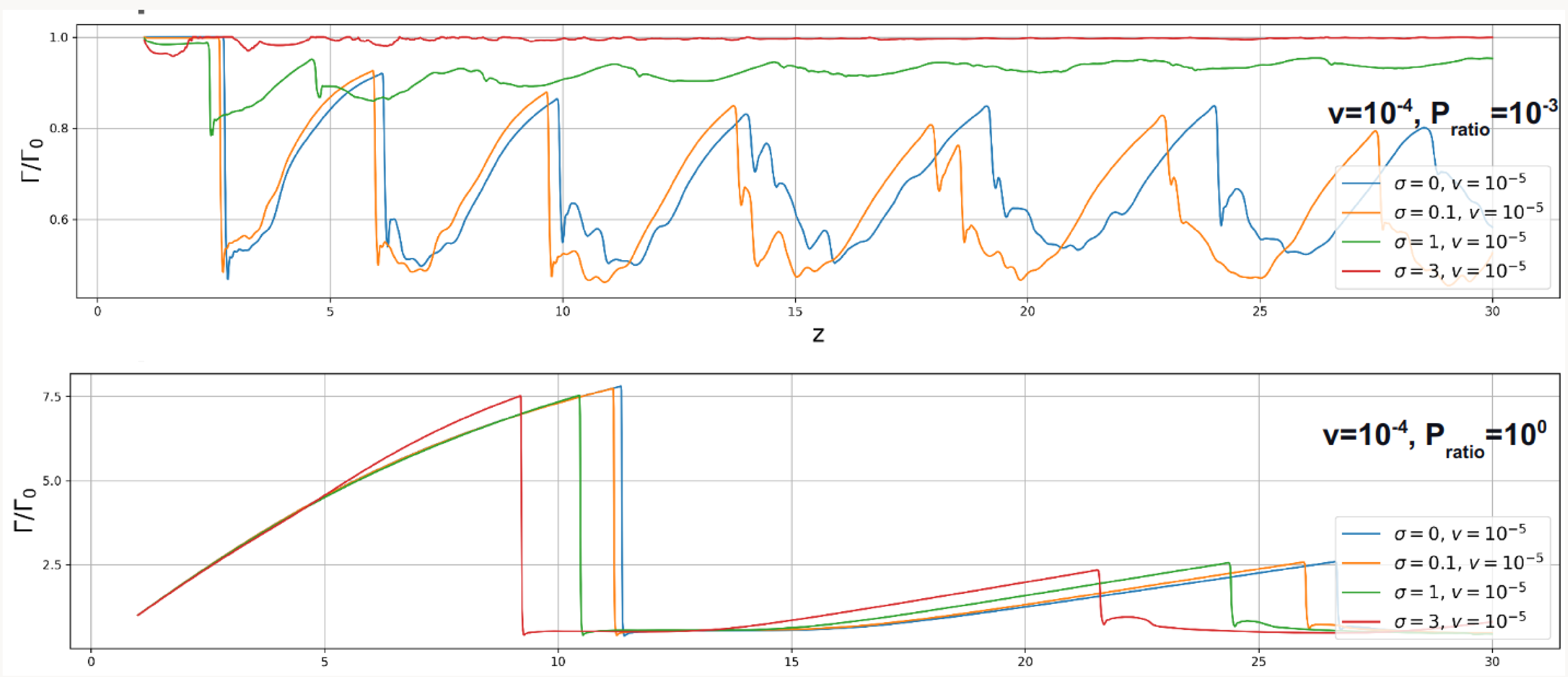

Figure: A comparison of Lorentz factor profiles along the z-axis in 2D simulations, varying the magnetization (with σ values measured in the jet's frame).

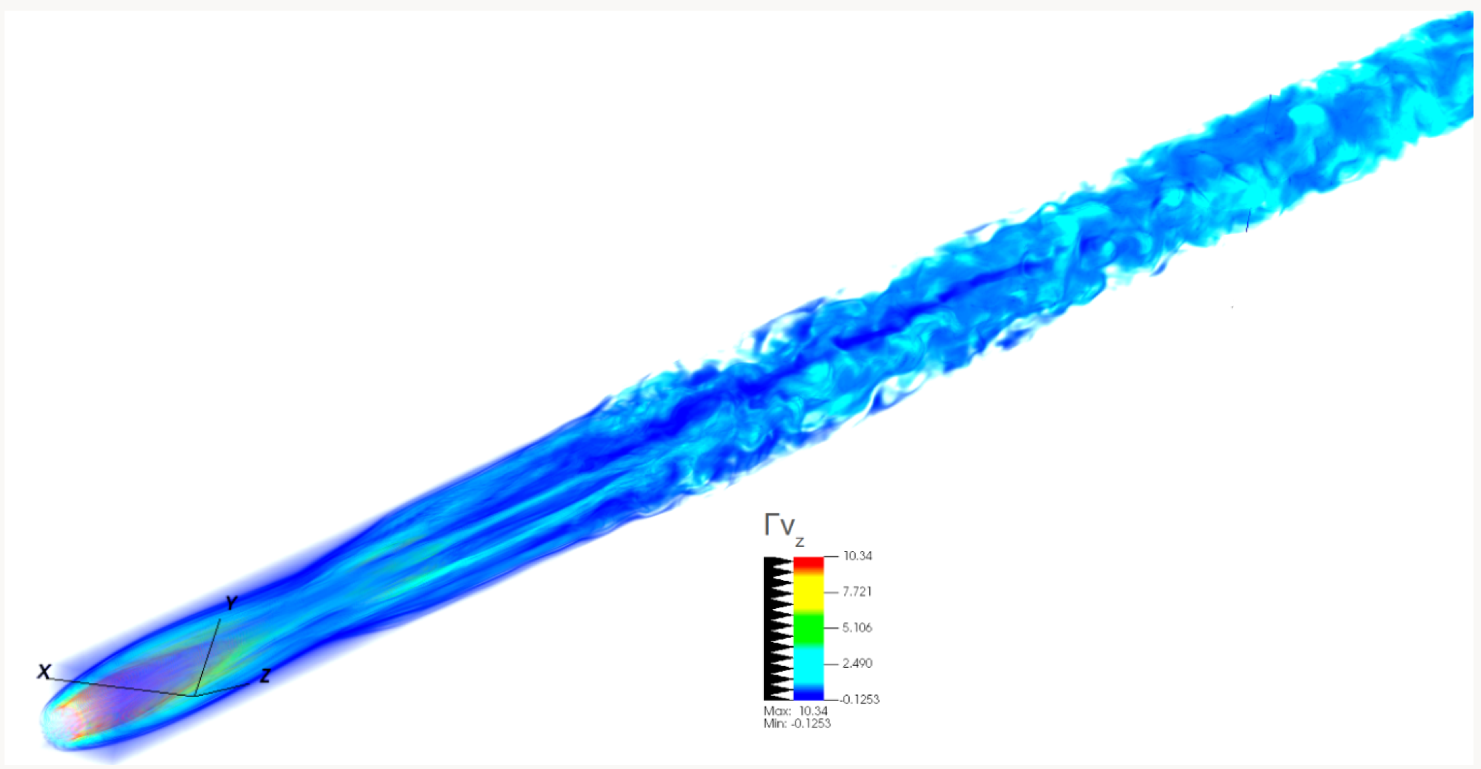

Figure: 3D volume rendering of the z component of the jet four-velocity in the case of σ_r=0.03.

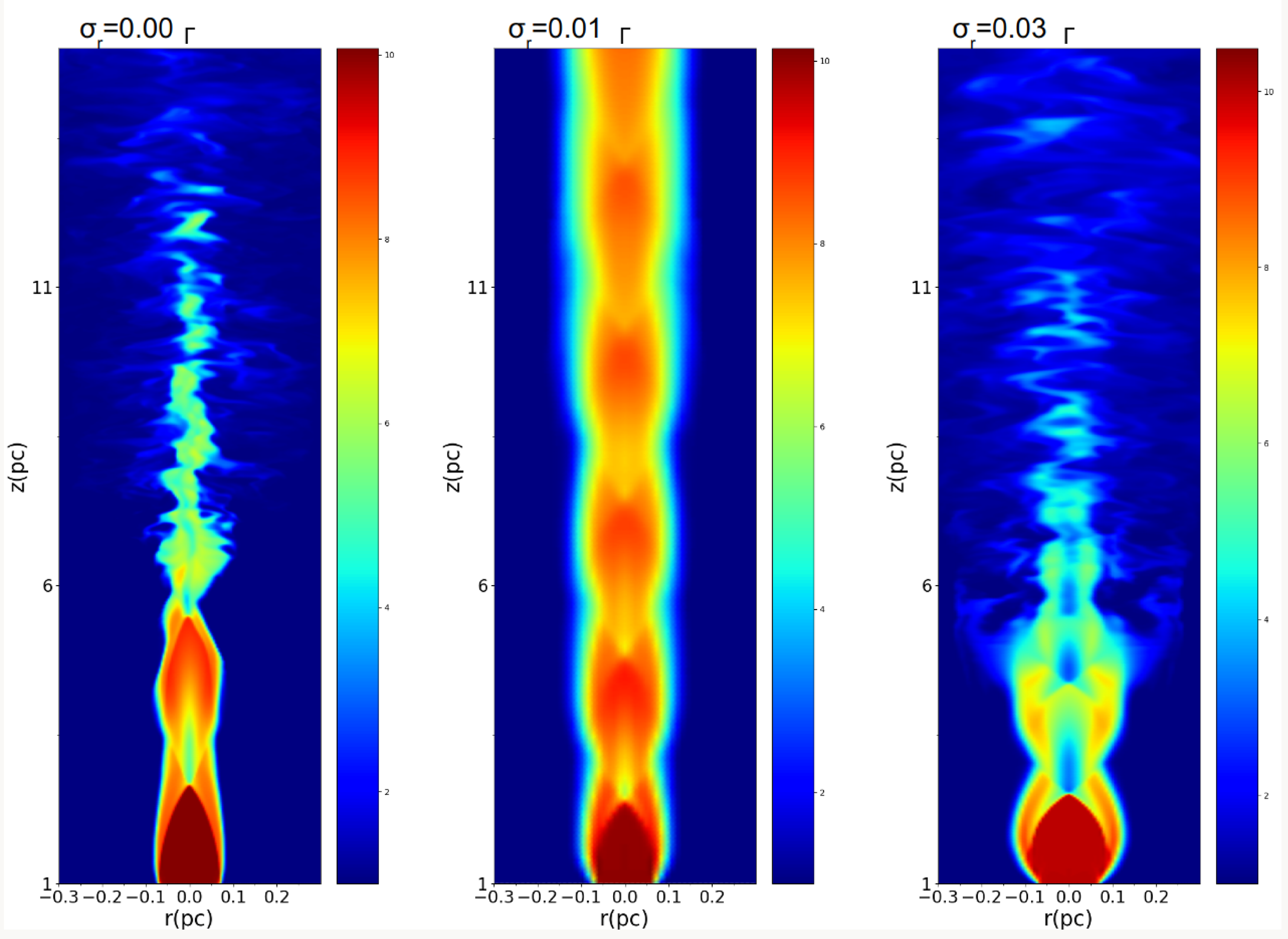

Figure: Comparison of jet stability under different magnetization conditions. X-Z plane slices from 3D simulations with $\nu = 10^{-4}$ and $P_{\rm ratio} = 10^{-3}$.

Stella S. Boula, Fabrizio Tavecchio, Gianluigi Bodo
styliani.boula@inaf.it
INAF-Osservatorio di Brera

Finanziato dall'Unione europea NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani
INAF