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Particle-Based Analysis of Relativistic Jet

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Relativistic jets are among the most energetic and enigmatic phenomena in the universe. They are observed in active galactic nuclei (AGN) and gamma-ray bursts (GRBs). A central open question in high-energy astrophysics concerns how these jets are accelerated to ultra-relativistic speeds, achieving bulk Lorentz factors of 10–100 or higher. Although several mechanisms have been suggested, such as magnetohydrodynamic processes [1] and radiation pressure acceleration [2], the potential of purely hydrodynamic expansion from high-temperature sources into low-density environments remains an intriguing yet under-explored possibility.

When a stationary, high-temperature gas is allowed to expand into a vacuum, a rarefaction wave propagates through the gas, converting its internal energy into bulk kinetic energy. In theory, to achieve Lorentz factors comparable to those inferred in GRBs, the density of the ambient medium must be less than 10^{-13} times that of the high-temperature gas—effectively approximating a vacuum (Fig. 1). However, such an extreme density contrast poses significant numerical challenges, particularly for conventional grid-based methods, which struggle to maintain stability and accuracy in low-density regimes.

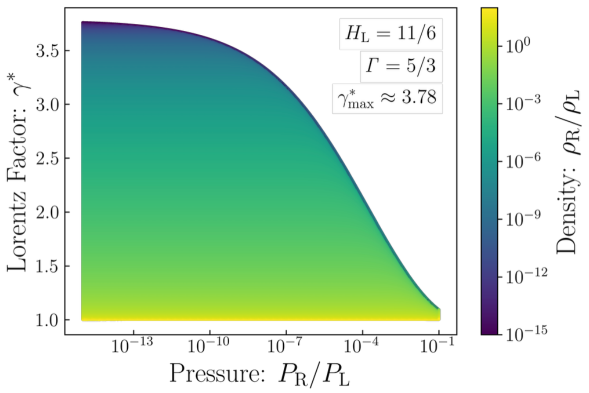

Fig. 1. Lorentz factor attained by the expansion wave as a function of ambient vacuum level in a relativistic shock tube problem. A high-temperature gas with initial specific enthalpy $H_L = 11/6$ is placed on the left side of a partition, while the ambient density on the right side is varied. The adiabatic index is fixed at $\Gamma = 5/3$. In the limiting case of a perfect vacuum, the maximum Lorentz factor is $\gamma^*_{max} \approx 3.78$. The result shows that an ambient density below 10^{-13} is required to reach the theoretical maximum acceleration.

To address these difficulties, we have developed the Special Relativistic Godunov Smoothed Particle Hydrodynamics (SRGSPH) method, a Lagrangian particle-based scheme tailored for accurately capturing relativistic shock waves and rarefaction dynamics without relying on a fixed computational mesh [3]. This method is particularly well-suited for problems involving steep gradients and large enthalpy contrasts, and it naturally handles fluid–vacuum interfaces by simply omitting particles in vacuum regions.

In this study, we simulate the acceleration of a hot, initially stationary gas as it expands into a surrounding vacuum, using SRGSPH to resolve the detailed dynamics of the rarefaction-driven jet. The specific enthalpy of the gas is treated as a free parameter, allowing us to systematically investigate its influence on the terminal Lorentz factor and jet structure. Our results demonstrate that, under ideal conditions, the maximum acceleration predicted by relativistic hydrodynamics can be closely approached even in the presence of discretization noise and finite particle resolution.

This presentation will detail the numerical setup, validation of the method against analytic benchmarks, and physical insights into the energy conversion process during rarefaction-driven acceleration. Our findings contribute to a deeper understanding of hydrodynamic jet formation and provide a robust framework for modeling high-enthalpy outflows in relativistic astrophysical systems.

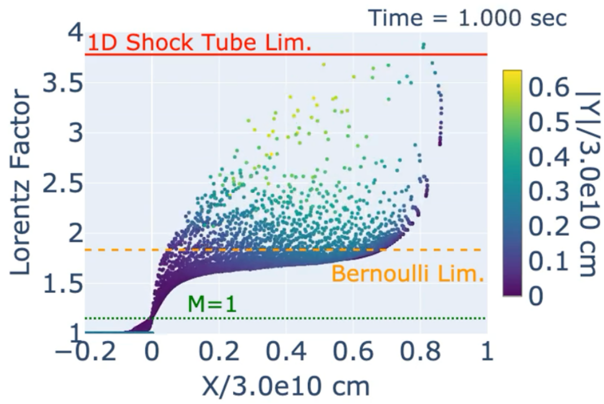

Fig. 2. Spatial profile of the Lorentz factor for a high-temperature gas initially in thermal equilibrium ($x < 0$) and expanding into vacuum ($x > 0$). The horizontal axis represents the spatial coordinate, while the vertical axis shows the Lorentz factor of the gas. The color gradient indicates the transverse distance of each SPH particle from the jet axis. The plot demonstrates that the gas asymptotically approaches the theoretically predicted terminal Lorentz factor through rarefaction-driven acceleration.

References

[1] Blandford, R. D., & Znajek, R. L., 1977, MNRAS, 179, 433

[2] Ohsuga, K., et al., 2005, ApJ, 628, 368

[3] Kitajima, K., et al, 2025, JCP, Revised