Effect of Interacting Rarefaction Waves on Relativistic Jets

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1 Introduction

Relativistic jets are collimated bipolar outflows that have a velocity almost equal to light speed. They are ubiquitous among astrophysical systems consisting of a compact object surrounded by an accretion disk, e.g., active galactic nuclei [2], microquasars [4] and the central engine of gamma-ray bursts [5, 3]. Although there are a lot of works that try to determine the mechanism by which relativistic jets are accelerated and collimated, it is still not understood.

Aloy & Rezzolla (2006) recently reported that relativistic jets can be powerfully boosted along the interface between the jet and ambient medium, if the jet has sufficiently large velocity and specific enthalpy, and is overpressured. A rarefaction wave excited at the interface converts the relativistic thermal energy of the plasma into kinetic energy and yields an amplification of the Lorentz factor in the jet-ambient medium interface. This type of boost, which we label rarefaction acceleration, is not possible in Newtonian dynamics, but is an inherent process in relativistic hydrodynamics.

In this paper, we study in detail how the rarefaction acceleration affects the propagation dynamics of relativistically hot jets through one-dimensional (1D) and two-dimensional (2D) relativistic hydrodynamic simulations. The nonlinear interaction of rarefaction waves excited at the interface between the jet and ambient medium is especially focused upon because it might have a potential impact on the boosting process and even alter the dynamics and structure of the jet.

2 Numerical Models and Setup

In order to investigate the interaction of rarefaction waves excited at the jet-ambient medium interface, we initially set a relativistically hot jet surround by ambient gas in the calculation domain. The initial density and pressure in the jet are chosen as $\rho_{\rm jet,0} = 0.1$ and $P_{\rm jet,0} = 1$, respectively. Those of the ambient medium are $\rho_{\rm amb,0} = 1$ and $P_{\rm amb,0} = 0.1$. In addition, the jet velocity to the z-direction is relativistic $v_{\rm jet,0} = 0.99c$, with a Lorentz factor of $\gamma_{\rm jet,0} \sim 7$. The ambient medium does not move and the radial velocity v_r is set to be zero initially in the calculation domain. In the 1D model, we calculate the evolution of the jet only in the radial direction. On the other hand, in the 2D model, axisymmetric simulations of the jet propagation are carried out in cylindrical coordinates.

The normalization units in length, velocity, time, and energy density are chosen as the initial jet width $W_{\rm jet,0}$, light speed c, light crossing time over the initial jet width $W_{\rm jet,0}/c$, and rest mass energy density in the ambient medium $\rho_{\rm amb,0}c^2$. The computational domain spans $0 < r < 2$. A uniform grid with a grid size $\Delta r = 10^{-3}$ is adopted for our calculations. We use a reflecting boundary condition on the axis $r = 0$. The outer boundary of the grid uses the outflow (zero gradient) boundary condition.

3 Results

3.1 1D calculation

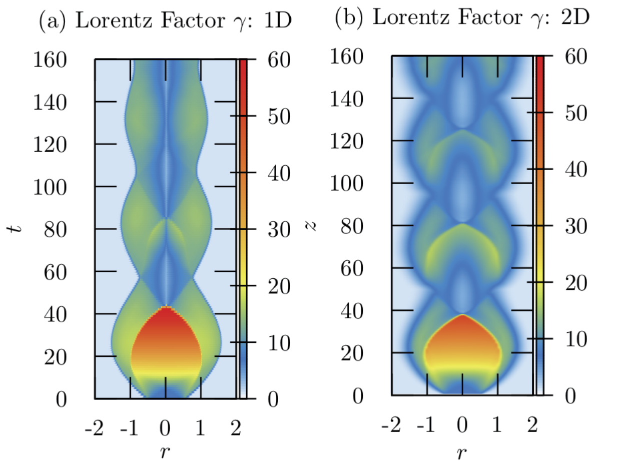

Fig. 1. Panel (a): Temporal evolution of the Lorentz factor in 1D model. Panel (b): Spatial distribution of the Lorentz factor in 2D model.

Figure 1(a) shows the temporal evolution of our jet-ambient medium system. The color contour represents the spatial distribution of the Lorentz factor. In the early evolutionary stage ($0 < t < 5$), the single rarefaction acceleration of the gas is observed in the jet-ambient medium interface. Subsequently at $t \sim 5$ the rarefaction waves converge on the central region of the jet, bringing a substantial change in the dynamics. The gas pressure in the interacting region of rarefaction waves is then further reduced and becomes lower than that of the ambient gas. Since the thermal energy is converted to the bulk kinetic energy of the gas, the gas in the interacting region is further boosted. The peak Lorentz factor of the gas inside the rarefaction region reaches ~ 60 at $t \sim 40$, which is a factor ~ 5 higher than that due to the single rarefaction acceleration.

The interaction of rarefaction waves generates a strong inward pressure gradient behind the jet-ambient medium interface which acts to decelerate the radial expansion of the jet, turning expansion of the jet into contraction at around time $t = 25$. The contraction of the contact discontinuity results in converging flows inside the jet.

When $t = 43$, the converging flows collide with each other at the center of the jet and excite shock waves that propagate outward. The gas bounded by the shock is compressed and heated. Since a time-increasing pressure decelerates the tangential velocity of the jet, the Lorentz factor of the jet reduces.

When the shock wave encounters the contact discontinuity at around $t = 58$, the system has almost returned to its initial state. The jet still has sufficiently larger tangential velocity and specific enthalpy than the ambient medium. Since the system is restored to a condition that is almost the same as the initial conditions, the three types of hydrodynamic wave, an outward propagating shock wave, a contact discontinuity (the edge of the jet), and a converging rarefaction wave, appear at the jet-ambient medium interface. Therefore the contracting radial motion of the jet becomes an expanding motion.

After returning to conditions similar to the initial conditions, the radial motion of the jet changes between expansion and contraction until the pressure of the jet becomes equal to that of the ambient gas. Using the energy conservation, we can give the scaling law for the oscillation time

$$\tau = \sqrt{3}\gamma_{\mathrm{jet},0}\left(\frac{W_{\mathrm{jet},0}}{c}\right)\left(\frac{P_{\mathrm{jet},0}}{P_{\mathrm{amb},0}}\right)^{1/2}. \qquad (1)$$

In Figure 2, we plot the oscillation time averaged over ten cycles for numerical runs with different initial pressure ratios. The solid line represents the analytic scaling we derived. This indicates that our numerical results are well captured by our simple scaling law shown in Equation (1).

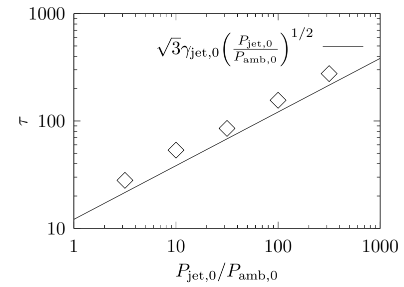

Fig. 2. Relation between the oscillation time scale of the system and initial pressure ratio of the jet to the ambient gas. Diamonds denote the oscillation time averaged over ten cycles for each parameter.

3.2 2D calculation

We investigate how the oscillating motion found in the 1D model affects the propagation dynamics and the structure of the jet in a more realistic two dimensional axisymmetric system. Our axisymmetric simulation of the jet propagation has been carried out in cylindrical coordinates (r, z), where the z-axis coincides with the symmetric axis. Relativistically hot flow is continuously injected into an uniform ambient medium from the lower boundary of the computational domain. Hydrodynamic parameters in 2D model are the same as the 1D model.

The spatial distribution of the Lorentz factor near the jet injection point is shown in Figure 1(b) when the jet is injected into the uniform ambient medium. The size of the cusp-shaped rarefaction region in both 1D and 2D cases seems to be almost the same, although the vertical axis is the time in Figure 1(a). This suggests that the typical size of the region where the Lorentz factor of the jet is powerfully boosted is essentially determined by the modulation caused by the interaction of rarefaction waves which propagate toward the center of the jet.

4 Conclusion

The nonlinear evolution of the interacting rarefaction waves excited at the cylindrical jet-ambient medium interface is studied through one-dimensional relativistic hydrodynamic simulations. It is found that an enhanced decrease in the relativistic pressure due to the interaction of rarefaction waves transiently yields a more powerful boost of the Lorentz factor of the bulk jet than that expected from a single rarefaction wave. The cyclic in-situ energy conversion between thermal energy and bulk kinetic energy is a natural relativistic outcome of the jet scenario studied and responsible for the radial oscillating motion of the jet. The oscillation timescale is characterized by the initial pressure ratio of the jet to the ambient medium, and follows a simple scaling relation $\tau_{\mathrm{oscillation}} \propto (P_{\mathrm{jet},0}/P_{\mathrm{amb},0})^{1/2}$.

It is confirmed from extended two-dimensional simulations that repeated excitation and convergence of rarefaction waves result in the alignment of the interacting regions of rarefaction waves, confined by oblique shocks, along the propagation direction of the jet when a relativistically hot jet propagates through an ambient medium. The typical size of the reconfinement region inside the jet is essentially determined by the modulation caused by the interaction of rarefaction waves.

References

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