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Synergetic Growth of the Rayleigh–Taylor and Richtmyer–Meshkov Instabilities in the Relativistic Jet

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Abstract. We investigate the growth of the Rayleigh–Taylor and Richtmyer–Meshkov instabilities at the interface of the relativistic jet using three-dimensional hydrodynamic simulations. The propagation of the relativistic jet that is continuously injected from the boundary of the calculation domain into a uniform ambient medium is solved. We find that the interface of the jet is deformed by a synergetic growth of the Rayleigh–Taylor and Richtmyer–Meshkov instabilities regardless of the launching condition, such as the specific enthalpy of the jet or the effective inertia ratio between the jet and ambient medium. The material mixing between the jet and external medium due to these instabilities causes the deceleration of the jet.

Keywords. galaxies: jets, shock waves, instabilities, methods: numerical

1. Introduction

The relativistic jet is ubiquitous phenomenon among astrophysical systems consisting of a black hole surrounded by an accretion disk, e.g., active galactic nuclei, microquasars, and the central engine of gamma-ray bursts. The dynamics and stability of the relativistic jet is important in order to understand the emission properties of the jet.

The radially oscillating motion of the jet is naturally excited due to the pressure mismatch between the jet and surrounding medium, that is, cocoon when the jet propagates through an ambient medium and is confined by the pressure of the cocoon (Daly & Marscher 1988; Matsumoto *et al.* 2012). In the rest frame of the decelerating jet interface that expands radially, an effective inertia force acts on the interface and is directed outward. Therefore the jet medium is on top of the cocoon medium in the effective gravity in this frame and the Rayleigh–Taylor instability (RTI) is expected to grow at the jet interface (Matsumoto & Masada 2013).

Since the pressure mismatch can not be alleviated immediately without some damping processes, it repeatedly excites the reconfinement shock inside the jet. The convergence of the reconfinement shock produces an outward propagating shock at the center of the jet. The collision of the outward propagating shock with the jet interface is the origin of the Richtmyer–Meshkov instability (RMI) and thus it is expected to be quasi-periodically excited whenever this type of collision occurs (Matsumoto & Masada 2013).

We investigate the growth of the RTI and RMI at the interface of the jet using three-dimensional (3D) hydrodynamic simulations in the cylindrical coordinate system. The propagation of the relativistic jet that is continuously injected from the boundary of the calculation domain ($z = 0$ and $r < r_{jet}$) into a uniform ambient medium is solved considering launching conditions. A small-amplitude (1%) random pressure perturbation is introduced to the injected relativistic flow in order to break the symmetry of the jet.

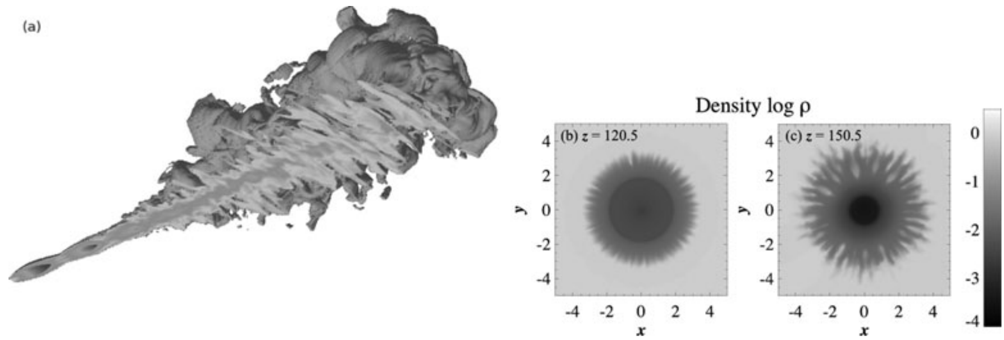

Figure 1. 3D structure of the jet in the large inertia and hot model when the relativistic jet reaches the boundary of the calculation domain ($z = 1000$). Panel (a) shows the density map of the jet in the half simulation box. Panel (b) and (c) show 2D cuts of the density distribution in the x-y (r-ϕ) plane where $z = 120.5$ and $z = 150.5$, respectively.

2. Results

Four-types of models are simulated with focusing on two parameters: One is the effective inertia ratio of the jet to the ambient medium (large or low inertia model), which controls the morphology and dynamics of the propagating jet (Marti *et al.* 1997), and the other is the relativistic hotness of the jet (hot or cold case). Fig. 1 shows the 3D structure of the jet in the large inertia and hot model when the relativistic jet reaches the boundary of the calculation domain ($z = 1000$). The jet–cocoon medium interface becomes unstable for the RTI. The amplitude of the corrugated interface of the jet at $z = 150.5$ is large compared to the interface at $z = 120.5$ due to the RTI. Unlike the RTI, the RMI grows impulsively when the outward propagating shock collides with the jet interface. The material mixing due to the deformation of the interface between the jet and cocoon medium leads to the deceleration of the jet. The flow velocity of the jet in the region where $z \sim 900$ is roughly $0.7c$ although that of the injected relativistic flow at the lower boundary is $0.99c$.

The propagation velocity of the jet head is slow and the jet is surrounded by a thick cocoon in the low inertia model compared to the large inertia model. On the other hand, the pressure of the cocoon is higher in the cold jet case than the hot jet case because the large kinetic energy of the cold jet is converted into the thermal energy of the cocoon at the jet head. Although the relativistic jet shows a rich variety of the propagation dynamics depending on its launching condition, the interface of the relativistic jet is deformed by a synergetic growth of the oscillation–induced RTI and secondary RMI for all models.

Acknowledgements

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