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Magnetic Energy Dissipation through Multiple Collisions of Jets and Winds

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We demonstrate the efficient internal shock dissipation through the multiple interactions between magnetized relativistic jets with weakly magnetized winds by our implemented spherically symmetrical one-dimensional special relativistic magneto-hydrodynamic simulation. We estimated an energy dissipation efficiency through multiple interactions with alternately injected magnetized jets and weakly magnetized winds. Our numerical results show the magnetic energy of the jet is converted into the kinetic energy of the shocked external medium by the magnetic pressure, then dissipated into the internal energy by the shock waves. Multiple magnetic energy conversion processes can produce kinetically dominated relativistic outflows with almost 10% average dissipation efficiency. Such outflows are relevant for observed non-thermal emissions in blazars or gamma-ray bursts.

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1. Introduction

Relativistic jets with more than 99% of the light speed emerge in pulsar wind nebulae, gamma-ray bursts (GRBs), and active galactic nuclei (AGNs), which are thought to be launched through magnetic processes [1]. The theory implies magnetically dominated outflows of $\sigma \gg 1$, where σ is the magnetization parameter defined as the ratio of the Poynting flux to the enthalpy flux. Dissipation of the energy by interaction with interstellar mediums (ISM) or stellar winds leads to multi-wavelength radiation, which is called the external shock model explaining GRB afterglows [2, 3]. The energy dissipation of jets can also occur inside themselves, which is called the internal shock model explaining the prompt emission of GRBs and blazar flares [4, 5].

Shock waves are important in the radiation from jets. Shock waves can dissipate the kinetic energy of jets, a part of which will be converted to the energy of non-thermal particles through diffusive shock acceleration [6, 7]. However, the dissipation efficiency of the shocks at $\sigma \gg 1$ outflows is quite low [8] compared to the observed radiative efficiency of GRBs and Blazars [9]. In addition, the diffusive shock acceleration is inefficient for $\sigma > 10^{-3}$ [10, 11]. Therefore, conventional internal shock models are not suitable for the explanation of particle acceleration and energy dissipation for high-σ jets.

Magnetic reconnection is an alternative particle acceleration process in high-σ plasma [10, 12, 13]. Magnetic reconnection can dissipate magnetic energy efficiently [14] and lead to ultra-fast variability of radiation [15], which can explain the observed short timescale variability of Blazar gamma-ray [16]. However, gamma-ray emission sites of some BL Lac objects are considered to be $\sigma \ll 1$ [17], which is inconsistent with magnetic reconnection models [14]. In addition, the Imaging X-ray Polarimetry Explorer observations of X-ray polarization imply the existence of shock acceleration at the emission site [18, 19].

The energy of the magnetized jet is efficiently transferred to the external medium in the external shock models. Thus, the dynamical energy dissipation by inducing shock waves in a low-σ medium is the prior method to convert the magnetic energy into radiation. Even in the internal shock models, the intermittency of jets may be one of the possible ideas for realizing the energy dissipation of high-σ outflows. The strongly variable radiation in blazers and GRBs is due to the variable activity of the central engine. Also, some numerical studies find a short timescale for intermittent ejection of jets [20, 21]. Assuming intermittent ejections, we can imagine that low-σ mediums can invade between intermittent jets. The interaction of the high-σ outflow and low-σ medium results in the conversion of the magnetic energy into low-σ regions [22, 23]. Possible mediums in the internal shock models are winds from accretion disks.

In this research, we estimate how much the magnetic energy of high-σ jets is converted into thermal energy in low-σ plasma by performing one-dimensional (1D) special relativistic magneto-hydrodynamical (SRMHD) simulations. In our 1D fluid systems, the kinetic or magnetic energy is dissipated into the thermal energy, which may implicitly include the energy of non-thermal particles produced via stochastic shock acceleration, or turbulence energy. Such turbulence is also responsible for the production of non-thermal particles [24]. A part of the dissipated energy in our simulations can radiate away from such particles accelerated by shocks or turbulence [25].

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2. Method

We consider high-σ relativistic jets launched from a central engine. To evaluate the energy dissipation of high-σ jets via interaction with external medium or non-relativistic winds, we perform 1D SRMHD simulations assuming spherically symmetric geometry. In the spherical coordinate, we consider only the radial component for the fluid velocity $\boldsymbol{v} = (v, 0, 0)$ with a magnetic field perpendicular to the direction of the velocity, say θ-component $\boldsymbol{B} = (0, B, 0)$, both are measured at the rest frame of the external medium. Whereas, the mass density ρ, the gas pressure p, and the energy density ϵ are measured at the fluid rest frame. The equation of state is

$$\epsilon = \frac{p}{\hat{\gamma} - 1} + \rho c^2, \tag{1}$$

where $\hat{\gamma}$ is the adiabatic index, which can be approximated as [26]

$$\hat{\gamma} = 1 + \frac{\epsilon + \rho c^2}{3\epsilon}. \tag{2}$$

The mass, energy, momentum conservation laws, and the induction equation are described as

$$\frac{1}{c}\frac{\partial \rho \Gamma}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \rho \Gamma \beta\right) = 0, \tag{3}$$

$$\frac{1}{c}\frac{\partial}{\partial t}\left[(\epsilon + p + \frac{B^2}{4\pi\Gamma^2}\right)\Gamma^2 - p - \frac{B^2}{8\pi\Gamma^2}\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\left(\epsilon + p + \frac{B^2}{4\pi\Gamma^2}\right)\Gamma^2\beta\right]\right) = 0, \tag{4}$$

$$\frac{1}{c}\frac{\partial}{\partial t}\left[\left(\epsilon + p + \frac{B^2}{4\pi\Gamma^2}\right)\Gamma^2\beta\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\left[\left(\epsilon + p + \frac{B^2}{4\pi\Gamma^2}\right)\Gamma^2\beta^2 + p + \frac{B^2}{8\pi\Gamma^2}\right]\right) = \frac{2p}{r}, \tag{5}$$

$$\frac{1}{c}\frac{\partial B}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\beta B) = 0, \tag{6}$$

respectively, where $\beta = v/c$ is the fluid velocity normalized by the speed of light, and $\Gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor of the fluid. We define the magnetization parameter σ as

$$\sigma \equiv \frac{B^2}{4\pi(\epsilon + p)\Gamma^2}. \tag{7}$$

For spatial interpolation, we use the 2nd-order MUSCL scheme [27]. For time interpolations, we adopt the 2nd-order Runge-Kutta method and set the CFL number about 0.1. We choose the minmod function as a flux limiter [28] and compute numerical flux by approximate Riemann solver, the CENTRAL scheme [29]. For the primitive recovery, we use the Newton-Rhapson method. Relativistic ($\Gamma \gg 1$) flows with a high $\sigma > 1$ produce strong shock structures in our simulations. To resolve such shocks and suppress numerical dissipation, an ultra-high resolution is required [30]. Thus, we implement the adaptive mesh refinement [31] to obtain a higher resolution around all discontinuities of magnetic pressure. We have confirmed that the numerical dissipation is negligible for our purpose by resolution studies for the energy dissipation efficiency.

3. Results

We demonstrate the energy dissipation of multiple high-σ relativistic jets interacting with low-σ winds as shown in Figure 1. We assume that the jets are collimated by the ram pressure of the winds. At inner radii, the centrifugal forces may prevent the winds from invading between the jets. But at outer radii, the surrounding materials confine the winds so that the winds may go in low-pressure regions between the jets. We carry out 1D spherically symmetrical SRMHD simulations. We inject jets and winds into the simulation box randomly and alternately as shown in the right-side panel of Figure 1.

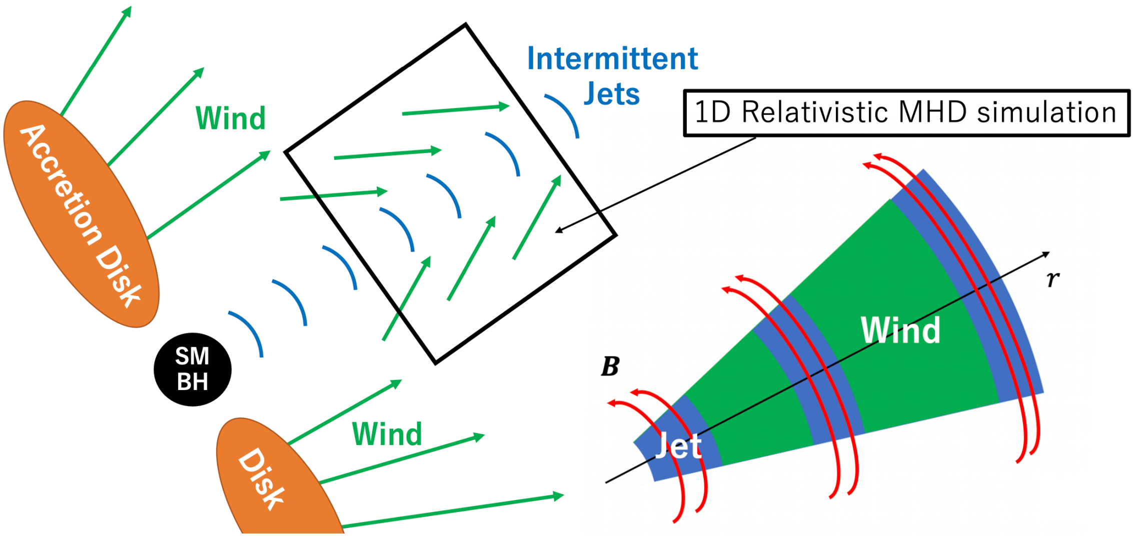

Figure 1: A schematic picture of the simulation. The animations of the our simulations are available at https://www.youtube.com/playlist?list=PLgnUM4yGp9oLxqXlcKcc8ftJne9kTpHEs

The simulation box size is $[R_0, 20R_0]$, where $R_0 = 10^{16}$ cm. The inner boundary is set to be an injection boundary. The outer boundary is set to be an open boundary. The number of static cells is 2×10^5, effectively 3.2×10^6 via the adaptive mesh refinement procedure. For the initial condition, wind fills the simulation box with the density profile of $\rho \propto r^{-2}$.

We inject jets and winds alternately from the inner boundary. The Lorentz factor of the jets $\Gamma_{\rm jet}$ are randomly following a cutoff-Gaussian probability distribution: a Gaussian with maximum and minimum cutoffs. The typical Lorentz factor of ejecta is around 10 for Blazars [32]. Thus, we choose the mean value of $\Gamma_{\rm jet}$ is 10 and its dispersion is 5. The cutoffs are at 10 ± 5. We define the minimum injection duration of the jets as

$$t_0 = \frac{R_0}{\Gamma_{\rm jet}^2 c}. \tag{8}$$

The injecting duration of the jets $t_{\rm jet}$ is randomly determined with a cutoff-Gaussian probability distribution with the mean value of $3t_0$, the dispersion of $2t_0$, and the cutoffs at $3t_0 \pm 2t_0$. The initial magnetization and temperature of the jets are fixed as $\sigma_{\rm jet} = 10$ and 100 MeV, respectively. The total luminosity of the jets is fixed as $L_{\rm jet} = 10^{45}$ erg s^{-1}, which means that the density changes according to changing $\Gamma_{\rm jet}$.

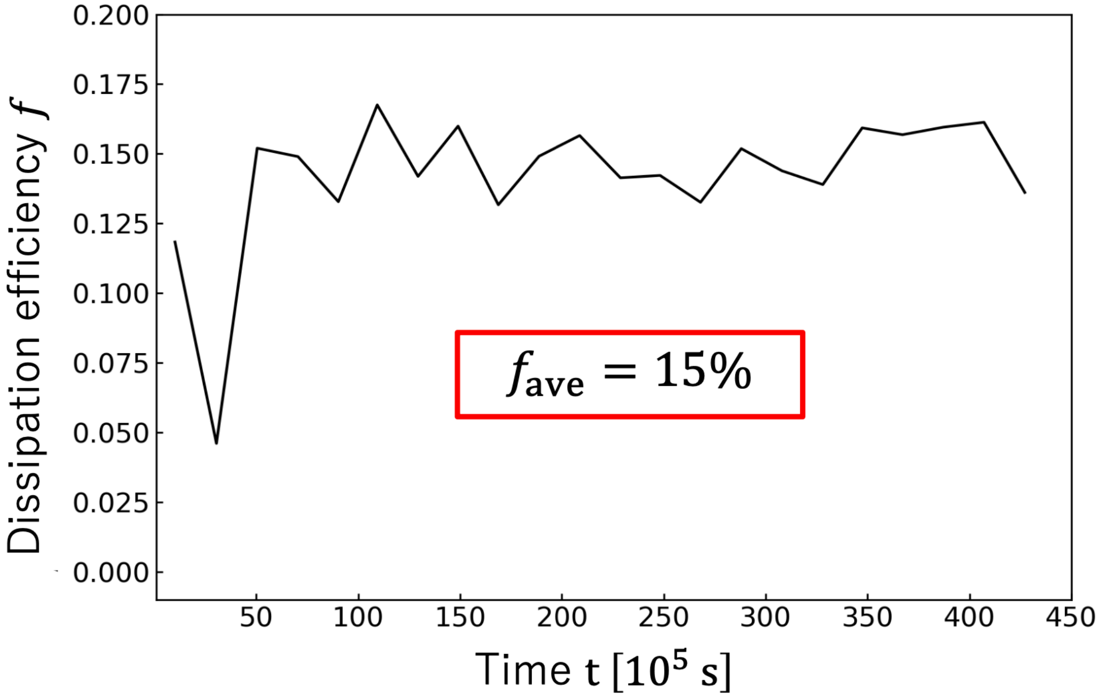

Figure 2: The time-dependent dissipation efficiency f at 5×10^{16} cm as a function of time.

For winds, the velocity, magnetization, and temperature are fixed as $0.1c$, $\sigma_{\rm wind} = 10^{-10}$, and 100 MeV, respectively. To reduce the computational cost due to adaptive mesh refinement procedures, we assume the mean injection duration of winds t_w is significantly longer than t_0. The injecting duration of the winds $t_{\rm wind}$ is determined by a cutoff-Gaussian probability distribution with the mean value of $t_w = R_0/c$, the dispersion of $0.1t_w$, and cutoffs at $t_w \pm 0.1t_w$. The total luminosity of the winds is fixed as $L_{\rm wind} = 10^{-4}L_{\rm jet} = 10^{41}$ erg s^{-1}.

We calculate the thermal luminosity of outflows passing some radius R as

$$L_{\rm th} = 4\pi R^2 \left[(\epsilon + p_g - \rho c^2)\Gamma^2 c\beta\right]. \tag{9}$$

Because our interest is the thermal energy of the low-σ relativistic outflows, we estimate the thermal energy for only outflows with $\sigma < 1$ and $\Gamma > 5$. Then, we estimate the time-dependent dissipation efficiency at $R = 5 \times 10^{16}$ cm using the following equation

$$f(t) = \frac{\int_t^{t+\delta t} dt' L_{\rm th}(R,\ t';\ \sigma < 1,\ \Gamma > 5)}{L_{\rm in}\delta t}, \tag{10}$$

where δt is set to be long as 2×10^6s$\sim 10^3 t_0$ to produce a smoothed shape of f. $L_{\rm in}$ is the time-averaged total injection luminosity of the outflow. The results are plotted in Figure 2. After reaching the quasi-steady state ($\sim 10^7$ s), the time-dependent dissipation efficiency is almost stationary ($f_{\rm ave} \sim 15\%$). Irrespective of the high σ values at injection, significantly high efficiencies are successfully obtained in our simulations.

4. Conclusion

We demonstrate the energy dissipation of the magnetic field in relativistic outflows by 1D ideal MHD simulations. We conducted numerical experiments on the magnetic energy dissipation of multiple jets launched intermittently. Between the high-σ relativistic jets, we inject non-relativistic winds without a magnetic field. Low-σ relativistic outflows with a significantly high temperature can be produced by interactions between high-σ relativistic jets with low-σ winds or rarefaction tails of other ejecta. We found that the energy dissipation efficiency into hot, low-σ, and relativistic outflows is about 10 %. Such outflows are relevant for observed non-thermal emissions in blazars or gamma-ray bursts.

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