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Identical algorithm of radiative transfer across ultrarelativistic shock in different inertial frames

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ABSTRACT

Some high-energy photons are thought to be produced by the inverse Compton scattering process in ultrarelativistic flows, and the high-energy component of spectra in gamma-ray bursts can be interpreted by the process. To examine numerically the trajectory of photons traveling in relativistic jets in detail, a coupled computation method of radiative transport with relativistic hydrodynamics is required. We have developed a three-dimensional code of radiative transport on a background with a relativistic flow using Monte Carlo method. Radiative transfer simulations have been implemented in different inertial frames which are described as a shock rest frame or shock moving frames, and obtained results are compared in the shock rest frame to identify a consistent transformation among different frames. Optical depth τ for every directions agrees among each frame if a time duration of the computation is small enough to resolve photon path close to a shock front with almost the speed of light. Although the obtained results of the direction distribution and the spectrum of the escaped photons from the computational domain in each frame show discrepancies due to different flow velocities, they are identical after Lorentz transforming to the shock rest frame. We found the second peak of energy in the high-energy side of the spectra if the simulation condition is determined to allow the scattering process in the upstream side of the shock, and this peak is formed by the inverse Compton scattering process.

1. Introduction

Gamma-ray bursts (GRBs) are highly energetic phenomena which eject extremely large amount of energy for a few seconds to minutes. In particular, long GRBs whose duration exceeds ~2 s are possibly thought to occur in association with relativistic jets that are formed around collapsing massive stars and have highly collimated configuration. Although the prompt emission of GRBs has been interpreted by synchrotron emission at internal shocks in jets [1,2], the internal shock model has insufficient radiation efficiency for the GRBs, and the spectrum is too hard in the low-energy side compared to the observations. Recently, the energy spectra of GRBs have been explained by the photospheric emission model which has high radiation efficiency [3,4]. The structure of relativistic jets has been studied by multi-dimensional relativistic hydrodynamical simulations in the context of GRBs [5–8]. Some light curves and spectra were obtained by such simulations [5,9,10]. Although the observed spectra are characterized by a broken power-law shape [11], these properties have not been reproduced accurately in the numerical works of the relativistic hydrodynamics. Analytical and numerical solutions for the equation of radiative transfer in relativistic flows can be obtained by various methods [12,13]; in particular, some authors have developed the method to solve the problem statistically by Monte Carlo (MC) technique [14,15], which has been adopted for the problem in the context of radiative transport in supernova explosions [16,17]. Since some observations indicate spectra with a thermal component [18], radiative transport for thermal photons produced by photospheric emission is regarded as the feasible model, and the feature of the spectra in GRBs

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was interpreted by overlapping thermal spectra for some components of various angles of photons escaped from the photosphere due to different observed time [19]. The structure of the ultra-relativistic shock wave in the fluid moving self-similarly has also been examined numerically [20], and the high-energy component of spectra of GRBs might be explained by the bulk Compton scattering [21,22], which occurs when photons traveling across relativistic shocks are scattered by relativistic electrons and gain energies. To obtain the high-energy spectra, the bulk Comptonization appeared under the situation where photons travel in the relativistic jet with the discontinuity of the flow velocity was also investigated [23,24]. Although some radiative transfer simulations have been performed on the background in steady-state which models the relativistic jet at a certain moment, there is no simulation on a time-dependent relativistic flowfield in spite of the fact that it may not be negligible for the detailed analysis of radiative transport in relativistic flows. We numerically constructed a radiative transfer technique in an ultrarelativistic flowfield with consistent transformation between comoving frame (CMF) and observer frame (OBF), in preparation for the coupling computation of radiative transport with relativistic hydrodynamics.

The remainder of this paper is as follows. We present the numerical method in Sec. 2 and explain about the physical setting of a background flowfield in Sec. 3. After showing simulation results in Sec. 4, we summarize this paper in Sec. 5.

2. Numerical method

We have numerically investigated the radiative transport in the relativistic flowfield using the MC method. The radiative transfer equation with scatterings is described by

$$\left(\frac{1}{c}\frac{\partial}{\partial t}+\boldsymbol{\Omega}\cdot\nabla\right)I(\boldsymbol{r},\boldsymbol{\Omega},\nu,t)=j(\nu,T)+\frac{\rho(\boldsymbol{r},t)}{4\pi}\int\int\sigma(\nu)I(\boldsymbol{r},\boldsymbol{\Omega}',\nu',t)\varphi(\boldsymbol{\Omega}',\boldsymbol{\Omega},\nu',\nu)\mathrm{d}\nu'\mathrm{d}\boldsymbol{\Omega}'-[k(\nu)+\sigma(\nu)]\rho(\boldsymbol{r},t)I(\boldsymbol{r},\boldsymbol{\Omega},\nu,t), \quad (1)$$

where $I(\boldsymbol{r},\boldsymbol{\Omega},\nu,t)$ is the specific intensity which is a function of a position vector $\boldsymbol{r}$, a traveling direction vector $\boldsymbol{\Omega}$, a photon frequency ν, and time t. The quantities c, ρ, k, and σ are the speed of light, density, an absorption cross-section, and a scattering cross-section, respectively. j denotes the emissivity which depends on a matter temperature T. $\phi(\boldsymbol{\Omega}',\boldsymbol{\Omega},\nu',\nu)$ is the scattering kernel, defined by an incident direction $\boldsymbol{\Omega}'$, an incident frequency ν', a scattered direction $\boldsymbol{\Omega}$, and a scattered frequency ν.

A lot of photons are assumed to be emitted through the bremsstrahlung process and collide with thermal electrons with Thomson scattering. We adopt the same MC technique to solve the radiative transfer as the previous work [14].

We construct a numerical code of radiative transport in a relativistic flow in preparation for the coupling computation of radiative transfer with relativistic hydrodynamics. To obtain simulation results in different inertial frames in which the flow includes ultrarelativistic regime, we carried out radiation transfer simulations in a shock rest frame and in shock moving frames. In so doing, we examined our numerical treatment including the Lorentz transformation between the CMF and OBF. Here, the photon cross-section is estimated for collision with electrons in the CMF, and the photon free path is calculated for free traveling in the OBF. Comparing the results in the different frames, we identify the validation of our simulation and determine the appropriate computational condition for obtaining the reliable solutions.

3. Background flowfield

3.1. Simulation condition

We prepared the relativistic flowfield with shock waves as a background field of radiative transport. The cylindrical system was adopted with one cell in the r-direction and two cells in the z-direction, as shown in Fig. 1. The cell interface in the z-direction was set to be the shock wave front. Physical quantities (ρ_2, p_2, v_2) were set into the cell in the upstream side of the shock; similarly physical quantities (ρ_1, p_1, v_1) were set into the cell in the downstream side, where ρ, p, and v are density, pressure, and flow velocity, respectively. These quantities were determined as satisfying the Rankine–Hugoniot (R–H) relations between the upstream and downstream of the shock. The width of the cell in the z-direction, Δz, was fixed by an optical depth τ measured from the upstream side of the computational domain along the z-axis:

$$\tau = n_e\sigma_0\Gamma_f\left(1-\frac{v_f}{c}\right)\Delta z, \quad (2)$$

so as to be $\tau = 0.001$ and $\tau = 10$ in the upstream and downstream, respectively. Here electron density n_e and a scattering cross-section σ_0 are the values in the CMF, and Γ_f is the Lorentz factor of the flow velocity v_f in the shock rest frame. The width of the computational cells in the shock rest frame is determined by Eq. (2), and those in the shock moving frame can be calculated by Lorentz contraction. The width of the computational cell in the r-direction is equivalent to the total width of the two cells in the z-direction in the shock rest frame. Every photons are emitted at the same timing at one point

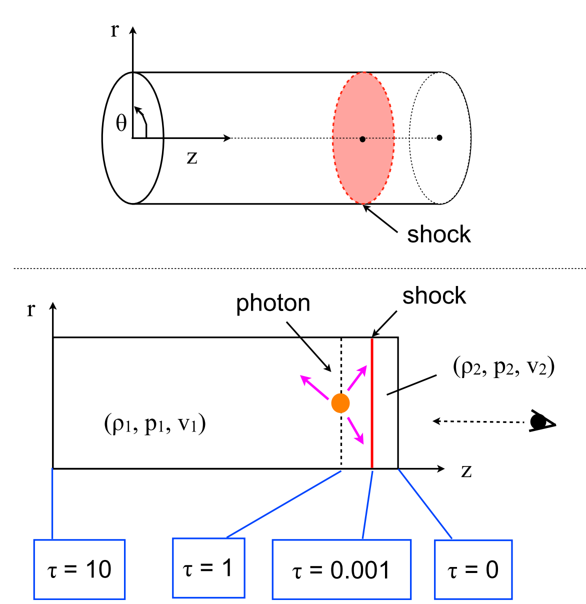

Fig. 1. Cylindrical coordinate system (top) and setting of one-dimensional shock wave (bottom).