THERMAL RADIATION FROM GAMMA-RAY BURST JETS

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ABSTRACT

In this study, the light curves and spectrum of the photospheric thermal radiation from ultrarelativistic gamma-ray burst (GRB) jets are calculated using two-dimensional relativistic hydrodynamic simulations of jets from a collapsar. As the jet advances, the density around the head of the jet decreases, and its Lorentz factor reaches as high as 200 at the photosphere and 400 inside the photosphere. For an on-axis observer, the photosphere appears concave due to the low density and high beaming factor of the jet. The luminosity varies because of the abrupt change in the position of the photosphere due to the internal structure of the jet. Comparing our results with GRB 090902B, the flux level of the thermal-like component is similar to our model, although the peak energy appears slightly higher (but still within a factor of two). From the comparison, we estimate that the bulk Lorentz factor of GRB 090902B is $\Gamma \sim 2.4 \times 10^2 (r/10^{12}\text{ cm})$, where $r$ is the radius of the photosphere. The spectrum for an on-axis observer is harder than that for an off-axis observer. There is a time lag of a few seconds for high energy bands in the light curve. This may be the reason for the delayed onset of GeV emission seen in GRB 080916C. The spectrum below the peak energy is a power law and the index is $2.3$–$2.6$, which is softer than that of a single temperature Planck distribution but still harder than that of the typical value of the observed spectrum.

Key words: gamma-ray burst; individual (GRB 090902B, GRB 080916C) – hydrodynamics – methods: numerical – radiation mechanisms: thermal

Online-only material: color figures

1. INTRODUCTION

Gamma-ray bursts (GRBs), the most energetic explosions in the universe, show a non-thermal spectrum, implying that GRBs originate from an optically thin region (e.g., Piran 1999, and references therein). On the other hand, some long GRBs are associated with a supernova (SN) explosion (e.g., Soderberg et al. 2008; Woosley 1993; MacFadyen & Woosley 1999; and Woosley & Bloom 2006, and references therein). Are GRBs already optically thin when they break out of their progenitors? The answer is obviously no, since the jet density should be high and the Lorentz factor should be low. Thus, we can expect to observe the thermal radiation from the photosphere prior to GRBs. Even in the prompt phase, there may be a thermal radiation component coming from the photosphere.

About 25 years ago, it was suggested GRBs should show thermal spectra unless they are coming from relativistically moving objects (Goodman 1986). With a motivation similar to ours, the thermal radiation from the photosphere of GRBs was analytically discussed in several papers (Blinnikov et al. 1999; Ryde 2005; Pe’er et al. 2007; Li 2007; Pe’er 2008). In the photospheric model of Lazzati et al. (2009), thermal radiation is scattered by relativistic electrons producing non-thermal photons of GRBs (e.g., Rees & Mészáros 2005; Ioka et al. 2007; Toma et al. 2009, 2010). The effects of magnetic fields, for example, the reconnection, on the emission, have also been discussed in several papers (Giannios 2006 and Zhang & Pe’er 2009).

Thermal components have been observed in some GRBs from the data obtained from the BATSE and/or BeppoSAX catalogs (Ghirlanda et al. 2007, Ryde & Pe’er 2009). A thermal component has been reported for GRB 060218 associated with SN2006aj (Campana et al. 2006; Liang et al. 2006). Recently, the Fermi Gamma-ray Space Telescope observed GRB 090902B, showing a clear spectrum consisting of two components (Ryde et al. 2010; Zhang et al. 2011), with one appearing to be a thermal component.

In this study, we investigate the thermal radiation from the photosphere of GRBs through numerical simulations. Some studies have been carried out on the jet propagation of GRBs (e.g., Mizuta & Aloy 2009, and references therein); however, with the exception of Lazzati et al. (2009), these studies did not determine the photosphere’s location and the number of thermal photons radiated from GRBs. In this study, we determine the location and shape of the photosphere of GRBs as a function of time and estimate the light curve and spectrum of the thermal radiation. We present thermal spectra and light curves for different viewing angles and light curves for several energy bins corresponding to Fermi and Swift data. We also discuss the unique spectrum of GRB 090902B and show the delayed onset of hard photons possibly related to that seen in GRB 080916C (Abdo et al. 2009).

2. NUMERICAL SETUP

This section describes the progenitor model and the numerical conditions of the hydrodynamic calculations. Although the structure of the progenitor at the pre-SN stage is not known, realistic calculations of the stellar evolution of massive stars have recently been done by Woosley & Heger (2006), Yoon & Langer (2005), and Yoon et al. (2006). We choose one of the models in Woosley & Heger (2006). The model is named 16TI, whose core has a relatively high spin at the pre-SN stage; this progenitor model is also used by Morsony et al. (2007, 2010) and Lazzati et al. (2009). At zero age, the progenitor is assumed...
to have a mass of 16 solar masses and low metallicity (0.01 $Z_{\odot}$). At the pre-SN stage, the total mass is 13.95 solar masses and the progenitor radius ($r_{\text{p}}$) is $4 \times 10^{10}$ cm.

The two-dimensional spherical coordinate system ($r \times \theta$) is used for hydrodynamic calculation, assuming axisymmetry and equatorial plane symmetry. The computational domain covers the region of $10^9$ cm $\leq r \leq 3 \times 10^{12}$ cm and $0^\circ \leq \theta \leq 90^\circ$. We remap the density profile from the progenitor model into the computational domain ($r_{\text{min}} \leq r \leq r_{\text{p}}$), assuming spherical symmetry. The reflective boundary condition is applied at the polar axis and the equatorial plane. Since the stellar wind theory is not well known so far and a weak wind is expected due to very low metallicity, we assume the gas outside the progenitor is dilute and the power-law distribution $\rho = 1.8 \times 10^{-14} (r/r_{\text{p}})^2$ g cm$^{-3}$. Since this weak wind does not affect the jet dynamics and the opacity, the model corresponds to the most luminous case.

The radial grid consists of $N_r = 2640$ points, uniformly spaced in log $r$, extending from $r_{\text{min}} = 10^9$ cm to $r_{\text{max}} = 3 \times 10^{12}$ cm. The smallest radial grid spacing, at $r_{\text{min}}$, is $\Delta r_{\text{min}} = 10^7$ cm, while the largest one, at $r_{\text{max}}$, is $\Delta r_{\text{max}} = 7.6 \times 10^9$ cm. The 120 uniform polar grids are spaced between $0^\circ \leq \theta \leq 30^\circ$, i.e., $\Delta \theta = 0.25$. The 60 uniform logarithmic grids are spaced in the range of $30^\circ \leq \theta \leq 90^\circ$.

The mechanism of the jet formation near the central black hole is still under debate (but see, e.g., Nagataki et al. 2007; Nagataki 2009). A very hot, relativistic, and temporary constant jet is injected from the innermost grid, i.e., $r = r_{\text{min}}$ with a half-opening angle $10^\circ$. The velocity vector is parallel to the radial unit vector. The luminosity of the injected jet is $5.5 \times 10^{39}$ erg s$^{-1}$. The Lorentz factor ($\Gamma_0$) is 5 and the specific internal energy ($\epsilon_0/c^2$) is 80, where $c$ is the speed of light. This jet has the potential to be accelerated to a Lorentz factor of more than 500, applying the relativistic Bernoulli’s principle; $h\Gamma = \text{const}$, along a stream line ($h_0\Gamma_0 = 538$ in our case), where $h$ is specific enthalpy, if all thermal energy is converted to kinetic energy without dissipation. We follow the jet propagation until the head of the jet reaches $r = 3 \times 10^{12}$ cm.

A special relativistic hydrodynamic code developed by one of the authors (Mizuta et al. 2004, 2006) is used for hydrodynamic simulations. The version with second-order accuracy both in time and space is used, including some dissipation to prevent numerical oscillation at strong shocks.

3. RESULTS

3.1. Hydrodynamics

In the early phase of the evolution, the jet drills through the progenitor envelope, keeping good collimation, as shown in previous numerical simulations by Aloy et al. (2000), Zhang et al. (2003, 2004), Mizuta et al. (2006), Morsony et al. (2007), Mizuta & Aloy (2009), and Lazzati et al. (2009). The forward shock drives the envelopes to high pressure and high temperature. A cocoon originates from the jet material because of the reverse shock at the head of the jet and surrounds the jet. Since the density of the jet is considerably lower than that of the stellar envelopes, a fast backflow and some vortices appear in the cocoon (Mizuta et al. 2010). Internal shocks in the jet appear due to interaction between the jet and the high-pressure cocoon and backflows (Komissarov & Falle 1997, 1998; Morsony et al. 2007). The jet reaches the progenitor surface at about $t_{\text{lab}} = 7$ s.

When the shock breaks out of the progenitor surface, the components near the head of the jet start expanding, resulting in a high Lorentz factor component ($\Gamma \sim 200$; top two panels of Figure 1); density and Lorentz factor contours at $t_{\text{lab}} = 30$ s). The shocked envelopes are also expanding into circumstellar matter. Since most of the components of the jet are still surrounded by the expanding cocoon and high-density progenitor envelopes, the jet remains collimated. The pressure in the cocoon and envelope decreases as they expand. The components injected from the computational boundary ($r = r_{\text{min}}$) at a later phase can easily propagate in a radial direction without dissipation (bottom four panels of Figure 1). The blue regions in density contours and the red and purple regions in Lorentz factor contours are free expanding regions. The Lorentz factor exceeds 400. This free expansion ends at the internal shock. On the other hand, since the velocity of the expanding cocoon and stellar envelopes is less than its sound speed (~0.5c), it is delayed with the head of the jet. As a result, the head of the jet is quite relaxed, resulting in a high Lorentz factor component ($\Gamma \sim 200$). The internal structures imprinted in the jet before the shock break still remain near the head of the jet. Such discontinuities can also be seen in a one-dimensional radial plot (Figure 2; Lazzati et al. 2009), but the structure is different from our simulations. This may be caused by the different code and resolution for the hydrodynamic calculations.

3.2. Thermal Radiation from Photosphere

The thermal radiation from the photosphere is derived in post-processing, from data taken every 1.0 s of the laboratory frame.
In each snapshot of the hydrodynamic simulations, we find the photosphere at unity optical depth for the Thomson scattering. The optical depth ($\tau$) is defined as follows:

$$\tau = \int_{x_{ph}}^{\infty} \sigma_T \Gamma(1 - \beta \cos \theta) n d l,$$

where $\sigma_T$ is the Thomson scattering cross section, $\Gamma \equiv (1 - \beta^2)^{-1/2}$ is the Lorentz factor, $\beta$ is the absolute value of the velocity normalized by the speed of light, $\theta$ is the angle between the velocity vector ($\vec{v}$) and the line of sight (LOS), and $n$ is the proper number density of the electron, $n \equiv 2 \rho / m_{\text{He}}$, where $m_{\text{He}}$ is the mass of helium atom. Though the progenitor includes many elements except hydrogen, we assume that all materials consist of fully ionized helium for simplicity. The expression in the integral includes the inverse of the beaming factor ($\delta$), i.e., $\Gamma(1 - \beta \cos \theta)(\equiv \delta^{-1}(\theta))$, to include the relativistic effect (Abramowicz et al. 1991). Here, we study the effect of the viewing angles, for an on-axis observer $\theta_{\text{v}} = 0$ and for off-axis observers, i.e., the angle between the jet axis and LOS, $\theta_{\text{v}} = 1^\circ$ and $2^\circ$.

Assuming an observer located at infinity, the isotropic luminosity of thermal radiation from the photosphere is evaluated as

$$L_{\text{iso}}(\theta_{\text{v}}) = a c \int \delta(\theta)^4 \tau^4 \cos \theta_{ph} d S,$$

where $a$ is the radiation constant, and $\theta_{ph}$ is the angle between the LOS and the normal vector of the emission surface (Pe' er et al. 2007). The isotropic luminosity on the left-hand side is considered by the observer time ($t_{\text{obs}}$) which is related to the laboratory time ($t_{\text{lab}}$) as $t_{\text{obs}} = t_{\text{lab}} + d/c$, where $d$ is the distance between each photosphere and the observer. The local temperature at the photosphere is evaluated as $T = (3 p/a)^{1/4}$, where $p$ is the thermal pressure of the fluid. The photosphere for $\theta_{\text{v}} = 0^\circ$ on the plane of the jet axis and the observer is shown by the solid lines in Figure 1. Though we also plot the cases for $\theta_{\text{v}} = 5^\circ$ and $10^\circ$, we do not show the light curves and spectra for these cases due to too short a duration at the observer frame (see Section 3.3). The photospheres for each observer almost overlap at $t_{\text{lab}} = 30$ s. As the jet advances, its density decreases. As a result, the photosphere shifts further inside the jet (bottom four panels in Figure 1 at $t_{\text{lab}} = 65$ and 90 s). On an off-axis observer, the photosphere in particular appears highly concave.

### 3.3. Light Curves

Hereafter, we assume that the burst occurs at the redshift of $z = 1$. Figure 2 shows the light curves for the observer at different viewing angles as a function of the observer time. The observer detects the radiation at different observer times, even if the radiation comes from the same laboratory time, due to the curved photosphere. We set $t_{\text{obs}} = 0$ as the burst trigger for each viewing angle. Though we integrate thermal radiation only for the whole computational laboratory time ($0 < t_{\text{lab}} < 100$ s) due to limited CPU time, the radiation will continue for some cases, especially the off-axis case. Thus, we should stress that the light curves shown here are not completed yet, though the early phase of the light curve is valid. We need to follow longer timescales at laboratory time in the future.

The light curves exhibit time variability, i.e., for the observers $\theta_{\text{v}} = 0^\circ$ and $1^\circ$ the second ($10 < t_{\text{lab}} < 22$ s) and third ($t_{\text{lab}} > 22$ s) phase after the constant luminosity phase in the beginning.

Figure 2. Light curves for the observer at different viewing angles, i.e., $\theta_{\text{v}} = 0^\circ$ (solid), $1^\circ$ (dashed), and $2^\circ$ (dotted). It is assumed that the burst occurs at the redshift of $z = 1$. The duration of the radiation is longer for the on-axis observers. The light curve for an on-axis observer is bright and has time variability. We stress that the light curves still continue and the last part of the light curves for each viewing angle is not completed.

The features of the light curves are consistent with Lazzati et al. (2009) in which the case of $\theta = 0^\circ$ is shown. Since the observer sees the skin of the jet at the beginning, the photosphere moves almost at the speed of light. The duration for the observer is about $1/\gamma$ times as long as that for the laboratory frame, where $\gamma$ is the Lorentz factor of the motion for the photosphere ($\gamma \sim 10$). The arrival time of the radiation concentrates within a few seconds for the observer which causes a quick rise. As time passes, the density near the head of the jet decreases due to the expansion of the jet. The beaming factor for the on-axis observer is very large, since the velocity vector is almost parallel to the jet axis. So, the distance between the forward shock and photosphere increases, i.e., Equation (1). The observer can see the region very deep inside the jet. The photosphere for the off-axis observer is concave, as shown in the bottom four panels of Figure 1. Because of discontinuities in the Lorentz factor and density in the jet, the photosphere suddenly moves deeper inside the jet. The second phase caused by the detection of the internal shock ($\Gamma \sim 200$) and beaming factor at the photosphere is more than 400. The third phase is caused by the radiation from a much deeper side. The Lorentz factor at the photosphere is smaller than that in the second phase.

Figure 3 shows the photon number flux for an observer in the four energy bands that are usually used in Swift analysis. Figure 4 is the same as Figure 3, but with different energy bands, such as are usually used in Fermi analysis. For $\theta_{\text{v}} = 0^\circ$, only soft photons ($E \lesssim 100$ keV) appear in the beginning ($t_{\text{lab}} < \text{a couple of seconds}$) since the Lorentz factor of the photosphere is still small. Then, high-energy photons follow. A few seconds time lag for high-energy photons can be clearly seen in Figure 4 for both the on-axis ($\theta_{\text{v}} = 0^\circ$) and off-axis observers ($\theta_{\text{v}} = 1^\circ$ and $2^\circ$).

### 3.4. Spectrum

Figure 5 shows the $\nu F_{\nu}$ plot for an observer ($\theta_{\text{v}} = 0^\circ$, $1^\circ$, and $2^\circ$). The spectrum is the superposition of Planckian at local rest frame and each Planck distribution is boosted by the beaming factor. The interval of the whole observer time is integrated (top panel). The distribution is a power law both below and above the peak energy. For $\theta_{\text{v}} = 0^\circ$, the spectrum has the peak energy at...
Figure 3. Photon number flux as a function of observer time for each energy band (from top to bottom, 15 keV < E < 25 keV, 25 keV < E < 50 keV, 50 keV < E < 100 keV, 100 keV < E < 350 keV). It is assumed that the burst occurs at the redshift of z = 1. The cases of three different viewing angles, θv = 0°, 1°, and 2°, are shown.

Figure 4. Same as in Figure 3, but for different energy bands: 8 keV < E < 250 keV (top) and 250 keV < E < 50 MeV (bottom).

Figure 5. νFν plot for different viewing angles θv = 0°, 1°, and 2°. Total time-averaged spectra are shown (top), and time-averaged plots for two intervals for the on-axis observer are shown (middle and bottom). It is assumed that the GRB occurs at the redshift of z = 1. Thin dashed lines shown in the middle and bottom panels are single temperature Planckian distributions (peak energy and absolute value are fitted). The power-law indices below the peak energy are 2.3–2.6.
As for GRB 090902B, the flux level of the thermal-like component reaches as high as 10^{-5} keV cm^{-2} s^{-1} at high peak energy ($E_{pk}$) (≈300 ± 100 keV) even though it is a distant GRB with $z = 1.822$ (Ryde et al. 2010). If we put our simulated GRB at $z = 1.822$, the flux level would also be about 10^{4} keV cm^{-2} s^{-1} but with lower peak energy $E_{pk} \sim$ 190 keV. To explain the discrepancy between the peak energy of GRB 090902B and our model by $\delta(\Gamma)T$ (Equation (2)), this factor should be greater by a factor of 1.57. On the other hand, since the flux level is comparable between GRB 090902B and our model, it is suggested that the value for $\delta(\Gamma)T$ is comparable (Equation (2)). Thus, we can deduce that ($\Gamma^{-4}T^{-4}$)GRB/($\Gamma^{-4}T^{-4}$)Model will be of the order of unity. Here, $\Gamma$ is the bulk Lorentz factor of the photosphere and $r$ is the radius of the photosphere. This is because $\delta(\Gamma)T$ can be rewritten as $2\pi\delta(\Gamma)T^{-4}r^{-3}$ (beaming factor), and $\delta(\Gamma) \sim \Gamma$ for a face-on observer. Since $r \sim 2 \times 10^{12} \text{cm}$ and $\Gamma \sim 2 \times 10^{2}$ in our model, we can constrain the value of $(r/\Gamma)$ for GRB 090902B as 4.1 × 10^{4}. This can be written as $\Gamma \sim 2.4 \times 10^{4}(r/10^{12} \text{cm})$ in GRB 090902B. It is noted that the radius of the photosphere depends on many factors in a complicated way such as the power, initial Lorentz factor, and mass loading of the jet. In this analysis, the radius of the photosphere of GRB 090902B is assumed to be of the order of 10^{12} cm like the simulation in this study.

There are many explanations for many GRBs not showing a clear thermal spectrum. The power-law component probably dominates the thermal component; see, e.g., Pe`er & Ryde (2010). For all viewing angles, the derived spectrum below the peak energy is a power law with the indices 2.3 - 2.6. Maybe this thermal component changes to a non-thermal one. The time delay of hard photons shown in Figures 3 and 4 is of interest, because it may be related to the delayed onset observed in some bursts (e.g., GRB 080916C; Abdo et al. 2009). It should be noted that very high energy emission may not always correlate with lower energy emission, depending on how it is created (Pe`er et al. 2006; Giannios 2008; Lazzati & Begelman 2010).

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