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Numerical study of relativistic shock breakout in circumstellar medium

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Supernova shock breakout is known as the very fast emergence of a high energy thermal radiation from the shocked medium. When breakout occurs in a relativistic situation, a large amount of X-rays or γ-rays are expected to be produced, and they must contain some pieces of information of the radiative envelope directly after the explosion. So it will be interesting if we see some dependences of the light curves or the spectral evolution of shock breakout on the energy supplying rate from the central engine. We perform a radiative transfer Monte Carlo calculation of ultra-relativistic shock breakout occurring in the dense circumstellar medium. We obtain hydrodynamical profiles in spherical symmetry by using a self-similar solution, which assumes a power law dependence on time of the shock Lorentz factor with index $-m/2$. The results indicate that breakout radiation produced by the decelerating shock ($m > 0$) have some distinguishable features from the accelerating ($m < 0$) or the constant velocity shock ($m = 0$), both in the light curves and the temporal evolution of the spectral shape.

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1. Introduction

Stars more massive than $8M_\odot$ turn into core collapse supernovae (CCSNe) at the end of their lives, and their entire envelopes will be blown away immediately after catastrophic explosions. At that moment, a strong shock propagating from the boundary of the central core appears from the surface as a luminous X-ray or UV transient. This is so-called shock breakout. The transient is visible only during the light crossing time of the progenitor, typically less than several hours. Although the breakout radiation can be a information source of the radiative envelope at early stage of the stellar explosion, they have not been directly detected for a long time, except for some fortunate detections; e.g. GRB 060218/SN 2006aj and XRO 080109/SN 2008D [1, 2].

From theoretical points of view, it is intriguing to explore similar phenomena in highly relativistic situations such as relativistic jets formed in CCSNe. Relativistic jets are believed to be indispensable to explain the presence of long gamma-ray bursts (lGRBs), but actually not so much is known about its physics. Even the exact mechanism of the central engine is an unsolved riddle. Many authors have argued the issue mainly by studying lGRBs. A popular theory of GRB attributes the prompt γ-ray emission to the photospheric emission in the jet outflow [3, 4].The photospheric model is suitable for the high fraction of the prompt emission relative to the afterglow. A difficulty of this scenario is that it is necessary to consider some additional interactions between particles to explain nonthermal spectral features, represented by the Band function. Inverse Compton scattering is likely to produce the tail of the Band function. At least one former study indicates that the scattering must play an important role also in the spectrum of XRO 080109 [5].

Emission from ultra-relativistic shock breakout from the surface of the star was already investigated using a self-similar solution to describe the hydrodynamics [6]. Since the self-similar solution does not contain any information of the central engine, the emission is determined solely by the structure of the stellar envelope and energetics. If we consider ultra-relativistic shock breakout in the circumstellar matter (CSM) using another self-similar solution by Blandford and McKee [7], it will be possible to extract information on the central engine from the emission. Here we performed a series of calculations of radiative transfer of the relativistic shock breakout in the CSM by using the self-similar solutions. In Section 3, we show the calculation results. Section 4 is the conclusions.

2. Methods

In order to investigate relations between the central engine and the breakout features, it is convenient to use the Blandford and McKee self-similar solution, which enables us to estimate effect of the engine activity on the shock driven. We assume a pure oxygen, fully ionized atmosphere. The second assumption may considerably overestimate absorption probability of low energy photons (below 1 keV) at low electron density.

2.1 Hydrodynamics

In Section 2.1.1 we describe the Blandford and McKee solution applied for the shocked region outside the contact discontinuity. To express the inside of the discontinuity, we use a different, very simplified model described in Section 2.1.2.

2.1.1 Shocked circumstellar matter

We assume that the matter density distribution follows $\rho \propto r^{-2}$, where r is the radius, and the shock propagates with the Lorentz factor Γ described by

$$\Gamma^2 = At^{-m}, \tag{2.1}$$

where t is the time. Determination of the constant value m depends on the rate of energy supply L from the central engine; which derived as the following function; $L \propto t^q$. Here, the index m equals to $q/(2+q)$. Combination of the basic equations in relativistic limit yields the following equations;

$$\frac{d}{dt}\left(p\gamma^4\right) = \gamma^2 \frac{\partial p}{\partial t}, \tag{2.2}$$

$$\frac{d}{dt}\ln\left(p^3\gamma^4\right) = \frac{-4}{r^2}\frac{\partial}{\partial r}(r^2\beta), \tag{2.3}$$

$$\frac{\partial n'}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 n'\beta\right) = 0, \tag{2.4}$$

where β is the velocity in unit of c, γ the Lorentz factor, n' the number density in the fixed frame, p the pressure. The boundary condition is given by the Rankine-Hugoniot relation;

$$p_1 = \frac{1}{3}e_1 = \frac{2}{3}\Gamma^2 w_0, \tag{2.5}$$

$$n'_1 = 2\Gamma^2 n_0, \tag{2.6}$$

$$\gamma_1^2 = \frac{1}{2}\Gamma^2, \tag{2.7}$$

where e is the energy density. The subscript 0 and 1 denotes the unshocked and the shocked gas. Since there is a requirement that the gas pressure reaches the minimum at the contact discontinuity, we should select the value of m so that it falls in the range larger than -1 and smaller than 1. In this study we investigate breakout in the case of $m =$-2/3, -1/3, 0, 1/2, and 2/3. These values of m correspond to $q =$-4/5, -1/2, 0, 2, and 4.

2.1.2 Uniform ejecta

In the region behind the contact discontinuity, we use a simple model by assuming that the ejecta expand with the same velocity of the contact discontinuity, and the density has a uniform distribution, 10^4 times greater than that on the shock front. Of course, it is a very rough approximation. Nevertheless, photons can not travel long distances in the dense ejecta. Thus, the approximation will not be too bad in the narrow region near the contact discontinuity.

2.2 Monte Carlo method

Using a Monte Carlo code, we calculate radiative transfer process through the matter in the shocked ejecta, the shocked CSM, and the unshocked CSM. Since the ultra-relativistic shock propagates at almost the same pace as photons, they are likely to stay in the thick circumstance for long time. Therefore, most photons have chances to be scattered more than once even immediately before the wind disappears. Construction of the code is almost the same with our previous code, which investigates breakout at the stellar surface [6]. In this section, we describe only the different points from that.

We take into account free-free absorption and inverse Compton scattering. We determine the position of the photosphere so that half of the photons emitted as blackbody radiation end up being absorbed, and the other half being escaped far away. Since the observation of XRO 080109 suggests that the burst was likely to occur at radius of $R_{\rm i} = 10^{12}$ cm from the stellar center, we start the calculation at the moment shock reaches this position. We stop the calculation when the shock expands to the radius of $R_{\rm f} = 10^{15}$ cm. In the following, we define the start time as $t_{\rm i} = R_{\rm i}/c$ and the termination time as $t_{\rm f} = R_{\rm f}/c$.

3. Results

3.1 Light curves

Figure 1 shows the resultant light curves for 10 parameter sets of $(m, \Gamma_{\rm i})$, where $\Gamma_{\rm i}$ is the shock Lorentz factor at $t = t_{\rm i}$. The vertical line indicates the time at which 50% of photons have escaped from the outflow (, hereafter T_{50}). We find that the durations roughly correspond to $R/(c\Gamma^2)$ at $t = t_{\rm f}$. (If $m = 2/3$ the duration is much shorter than expected. It might mean that the actual terminate time is much longer than $t_{\rm f}$.) There is a transition between $m \leq 0$ and $m > 0$, that a positive value of m results in the very early peak, while otherwise in the peak later than T_{50}. As is well known, photons are collimated into a cone with an opening angle of $1/\Gamma$ due to the beaming effect. Arrival of photons from the edge of the cone delay compared to those from the center. If $m \leq 0$, since the cone angle becomes smaller, a large numbers of photons emitted at $t = t_{\rm i}$ and at $t = t_{\rm f}$ arrive together. Therefore, the luminosity increases slowly. On the other hand, if $m > 0$, photons emitted at $t_{\rm i}$ can escape quickly from the outflow. Thus, the peak occurs immediately after the onset of the outburst.

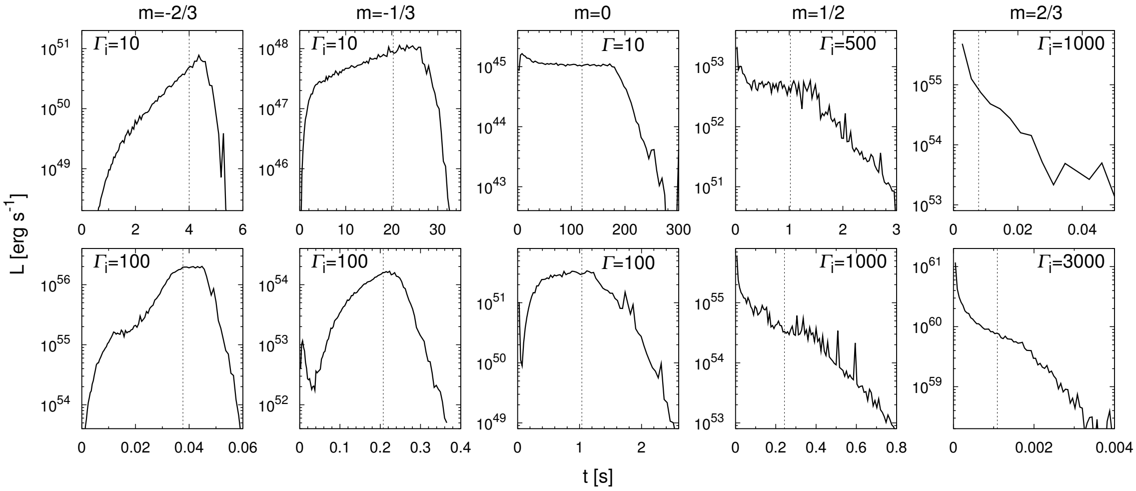

Figure 1: Light curves. The vertical lines indicates T_{50}.

3.2 Spectral evolution

Figure 2 shows the time integrated spectra (solid lines) and the time resolved spectra (open and filled triangles). The blue dotted lines indicate the initial photons (before scattering) and the red solid lines the scattered photons. The open and filled triangles display the scattered photons reaching the observer before and after T_{50}. Overall spectral shapes are similar for any parameter set we choose. Each spectrum composed by scattered photons has at least one peak or cut-off break corresponding to the cut-off of the initial photon distribution. The break energy (hereafter, we call E_{b}) corresponds to $\Gamma k_{\mathrm{B}} T$, where k_{B} is the Boltzmann constant and T the shock temperature, at the photosphere at $t = t_{\mathrm{f}}$. We fit a broken power law form to the spectrum. Table 3.2 summarize the three fitting parameters; the break energy E_{b}, the spectral index on the lower energy side α_{b}, and on the higher energy side β_{b}. The index β_{b} for any positive value of m is significantly larger than that for negative m. There is a different behavior also in the spectral time evolution. In the case of $m \leq 0$, both the spectra before and after T_{50} have the same shape; however in the case of $m > 0$, the flux above E_{b} before T_{50} significantly exceeds that after T_{50}. The above difference can be explained by the argument about angular distribution referred in Section 3.1. If $m > 0$, the radiation appeared before T_{50} consists of only photons emitted in the normal direction to the shock front at around the time of t_{i}. These photons are highly boosted, therefore expected to contribute the very high energy component.

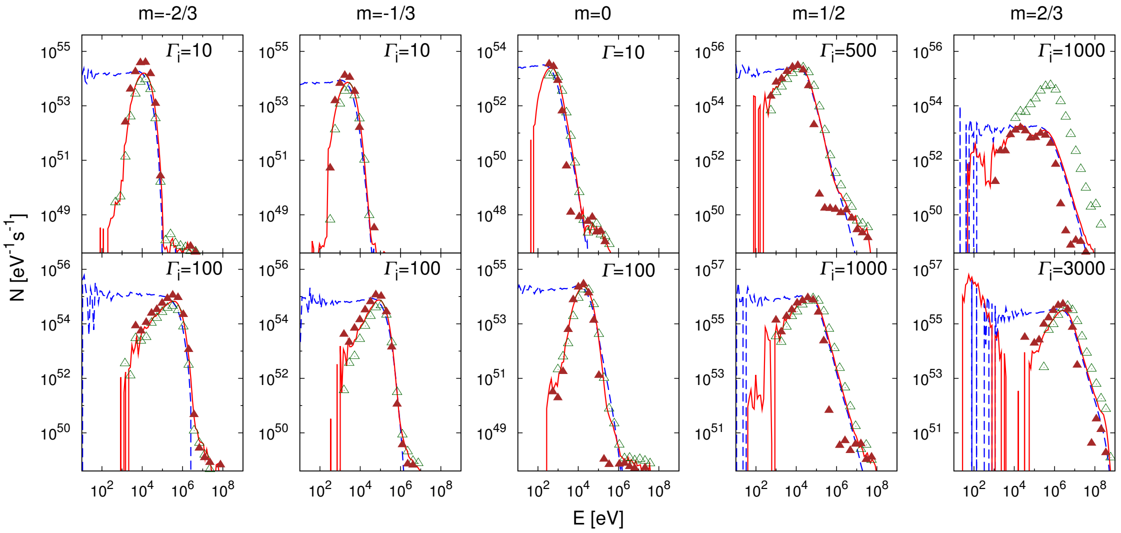

Figure 2: Count-rate spectra of the initial photons (blue dotted line) and the scattered photons (red solid line). The triangles display the spectral changes before (unfilled mark) and after (filled mark) T_{50}.

4. Conclusions

The results of calculations imply that the properties of shock breakout radiation from the CSM depend mainly on two factors; the shock Lorentz factor and the maximum radius of the photosphere before it disappears. There are some different properties between whether the central engine lasts long ($m \leq 0$) or not ($m > 0$), as follows;

m	Γ_i	E_b [keV]	α_b	β_b
-2/3	10	11	0.8	-4.2
	100	420	0.8	-4.2
-1/3	10	2.3	3.0	-4.5
	100	80	1.3	-4.5
0	10	0.3	1.3	-4.2
	100	12	1.4	-4.2
1/2	500	11	0.8	-2.9
	1000	48	0.8	-2.9
2/3	1000	320	-0.2	-2.3
	3000	2700	1.0	-2.4

Table 1: Properties of the time integrated spectra; the break energy E_b and the power law fitting indexes α_b and β_b for the lower and higher energy sides of E_b.

1. The rise time is longer than the decay time if $m \leq 0$, while it is much shorter if $m > 0$.
2. The power law spectral index of photons with energies higher than the break energy is smaller than -4 if $m \leq 0$, while it is larger than -3 if $m > 0$.
3. The spectral shape does not change with time if $m \leq 0$, while the flux of photons above the break energy quickly decays if $m > 0$.

Accordingly, it seems possible to obtain some information on the central engine by looking into the light curve and/or the temporal change of the spectrum.

References

[1] E. Waxman, P. Mészáros, and S. Campana, *GRB 060218: A Relativistic Supernova Shock Breakout*, *ApJ*, **667** (2007) pp. 351-357.

[2] A. M. Soderberg, E. Berger, K. L. Page et al., *An extremely luminous X-ray outburst at the birth of a supernova*, *Nature*, **453** (2008) 469.

[3] P. Mészáros and M. J. Rees, *Steep Slopes and Preferred Breaks in Gamma-Ray Burst Spectra: The Role of Photospheres and Comptonization*, *ApJ*, **530** (2000) pp. 292-298.

[4] F. Ryde, C.-I. Björnsson, Y. Kaneko, P. Mészáros, R. Preece, and M. Battelino, *Gamma-Ray Burst Spectral Correlations: Photospheric and Injection Effects*, *ApJ*, **652** (2006) pp. 1400-1415.

[5] A. Suzuki and T. Shigeyama *Non-thermal Photon Production via Bulk Comptonization at Supernova Shock Breakout*, *ApJ*, **719** (2010) pp. 881-889.

[6] Y. Ohtani, A. Suzuki, and T. Shigeyama, *Generation of High-energy Photons at Ultra-relativistic Shock Breakout in Supernovae*, *ApJ*, **777** (2013) 113.

[7] R. D. Blandford and C. F. McKee, *Fluid dynamics of relativistic blast waves*, *Physics of Fluids*, **19** (1976) 1130.