GeV emission from neutron-rich internal shocks of some long γ-ray bursts

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ABSTRACT

In the neutron-rich internal shocks model for γ-ray bursts (GRBs), the Lorentz factors (LFs) of ion shells are variable, and so are the LFs of accompanying neutron shells. For slow neutron shells with a typical LF of approximate tens, the typical β-decay radius is \( \sim 10^{14} \text{–} 10^{15} \) cm. As GRBs last long enough \( [T_{90} > 14(1 + z) \text{ s}] \), one earlier but slower ejected neutron shell will be swept successively by later ejected ion shells in the range \( \sim 10^{13} \text{–} 10^{15} \) cm, where slow neutrons have decayed significantly. Part of the thermal energy released in the interaction will be given to the electrons. These accelerated electrons will mainly be cooled by the prompt soft γ-rays and give rise to GeV emission. This kind of GeV emission is particularly important for some very long GRBs and is detectable for the upcoming satellite Gamma-Ray Large Area Space Telescope (GLAST).

Key words: radiation mechanisms: non-thermal – ISM: jets and outflows – gamma rays: bursts.

1 INTRODUCTION

As realized firstly by Derishev, Kocharovsky & Kocharovsky (1999a), the fireball of γ-ray bursts (GRBs) may contain a significant neutron component in several progenitor scenarios. For the neutron-rich fireball, the acceleration will be modified (Bahcall & Mészáros 2000, hereafter BM00) and there could be many novel observational signatures. (i) If the neutron abundance is comparable to that of proton, the inelastic collision between differentially streaming protons and neutrons in the fireball will provide us observable 5–10 GeV neutrinos/photons (Derishev et al. 1999a; BM00; Mészáros & Rees 2000; Koers & Giannios 2007); (ii) the very early afterglow emission of GRBs would be modified significantly because of the β-decay \( n \rightarrow p + e^- + \nu_e \) of the ‘fast’ neutrons carried in the outflow (Derishev, Kocharovsky & Kocharovsky 1999b; Pruet & Dalal 2002; Beloborodov 2003; Fan, Zhang & Wei 2005b); (iii) in the neutron-rich internal shock model, for GRBs with a duration \( > 20(1 + z) \) s, the β-decay products of the earlier ‘slow’ neutrons with a typical Lorentz factor (LF) approximately tens will interact with the ion shell ejected at later times and give rise to detectable ultraviolet/optical (UV/optical) flashes (Fan & Wei 2004; Fan, Zhang & Wei 2005a); (iv) as shown in Vlahakis, Peng & Königl (2003), for a magnetized neutron-rich outflow, the neutrons can decouple from the protons at a LF \( \Gamma \) in the tens, while protons, which are collimated to a narrower angle by the electromagnetic force, continue to be accelerated to a value of \( \Gamma \) in the hundreds. As a result, a two-component jet might be formed (Vlahakis et al. 2003; Peng et al. 2005). (v) Jin et al. (2007) claimed that the X-ray flat segment of short GRB 051221 was attributed to such a scenario. (v) Razzake & Mészáros (2006) calculated the synchrotron radiation of the electrons resulting in the β-decay and found unique temporal and spectral signature.

In this work, we show that in the neutron-rich (unmagnetized) internal shock model, besides the possible UV/optical flashes predicted in Fan & Wei (2004), there could be a strong GeV emission. This high-energy radiation component is a result of the inverse-Compton cooling of the electrons due to the space–time overlapping between the prompt soft γ-ray photon flow and the interaction region between the proton shell and decay products of the neutron shell. Such a cooling process, suppressing the UV/optical emission significantly, has been taken into account by Fan et al. (2005a). These authors, however, did not calculate the possible GeV emission.

1 In this case, the protons and neutrons are separated in the narrow and wide jet components, respectively. The decay products of the neutrons have no interaction with the protons collimated in the narrow core. If this is true, the discussion in this work is invalid.

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2 GEV EMISSION FROM NEUTRON-RICH INTERNAL SHOCKS

2.1 Neutron-rich internal shocks

In the standard baryonic fireball model, the prompt emission of long GRBs is likely to be powered by the violent collision of shells with different LFs (Paczynski & Xu 1994; Rees & Mészáros 1994). Until now, the practical LF distribution of shells in neutron-free internal shocks model is unknown, let alone the case of neutron-rich. To reach a high efficiency of radiation, significant difference of LFs between two shells with approximately the same mass (M) is favoured (Piran 1999).

The unmagnetized outflow is controlled by the dimensionless entropy $\eta = L/(Mc^2)$ at $r_0$, where $L$ being the total luminosity of the ejecta and $r_0$ being the radius of the central engine. The decoupling of protons and neutrons in a fireball occurs in the coasting or accelerating regime, depending on whether $\eta$ is below or above the critical value $\eta_c \approx 2.2 \times 10^8 L_{51}^{0.75} n_0^{-0.5} (1 + x)/2 -1.4 \times 10^7 \xi$ being the ratio of number density of neutrons to protons (BM00). The convention $Q_s = Q/10^8$ has been adopted in this paper, in units of cgs. If a slow shell is concerned with $\eta_s < \eta_z$, neutrons are coupled with protons until the end of the acceleration epoch. However, for a fast shell, $\eta_f > \eta_z$, neutrons decouple from protons, keeping the velocity at that time, while protons can be accelerated to higher velocity. As a result, $\Gamma_{n,s} = \Gamma_{s}$ for slow shells and $\Gamma_{n,f} > \Gamma_{s}$ for fast shells, where the subscripts $p$, $n$ represent the proton/neutron component; $s$, $f$ represent the fast/slow shells, respectively (BM00). So far we have four kinds of shells, i.e. slow neutron/ion shells and fast neutron/ion shells.

Similar to the standard neutron-free fireball, the fast ion shell will catch up with the slower but earlier one and forms a new one moving with a LF $\Gamma_m \sim \sim$ a few hundred at a radius $R_{\text{int}} \sim 10^{15}$ cm, suppose that the ejection time-lag between these two shells is about 0.01 s (hereafter the formed ‘new’ shell is named as the ‘i-shell’). The $\beta$-decay radius of a neutron shell (hereafter, the ‘n-shell’) reads as

$$R_\beta \sim 2.6 \times 10^{13} \Gamma_{n,s} \text{ cm}. \quad (1)$$

For $\Gamma_n \sim \text{tenshundreds}, R_\beta \gg R_{\text{int}}$, so the $\beta$-decay of these fast neutrons would not influence the physical process taking place at $R_{\text{int}}$ significantly.

However, the much later ejected i-shell will catch up the earlier slow n-shell at a radius $R_{\text{int}} \sim 2 \Gamma_{n,s}^2 cS(1 + z)$, where $\delta T$ being the ejection time-lag between the earlier slow n-shell and the later i-shell and $z$ being the redshift of GRB. As long as $R_{\text{int}}$ is comparable with $R_{\beta,n}$, i.e.

$$\delta T \geq 14(1 + z)(\Gamma_{n,s}/30)^{-1} \text{ s}, \quad (2)$$

the decay product of earlier ejected but slower neutron shells will be swept orderly by the later ejected ion shells in a range $\sim R_{\text{int}} - R_{\beta,n}$ and interesting UV/optical and GeV emission are produced.

In this paper, following Fan & Wei (2004), we assume: (i) the LF of shells has bimodal distribution, $\Gamma_{ej} = \eta_l$ or $\Gamma_{ej} = \eta_s$ with equal probability, which is favoured by its relatively high efficiency of energy conversion and high peak energy of the internal shock emission (Guetta, Spada & Waxman 2001). (ii) $\xi = 1$. As a result, the ratios between the mass of the fast neutrons, slow neutrons and i-shells are $\sim 1 : 1 : 2$. (iii) Proton and neutron shells move with LF $\Gamma_{p,s} \sim 1000$, $\Gamma_{n,s} \sim 200$ for fast shells and $\Gamma_{p,s} = \Gamma_{n,s} \sim 30$ for slow shells. After the merger of a pair of fast/slow ion shells, the resulting i-shell moves with (Piran 1999)

$$\Gamma_i \approx \sqrt{\frac{M_{p,i} \Gamma_{p,i} + M_{n,i} \Gamma_{n,i}}{M_{p,i} \Gamma_{p,i} + M_{n,i} \Gamma_{n,i}}} \approx 200,$$

(iv) The ejecta expands into low-density interstellar medium (ISM), as mostly found in afterglow modelling (Panaitescu & Kumar 2002). The ISM has been swept by the early and fast ions as well as the decayed products of fast neutrons, so the decay products of slow neutrons move freely.

Note that in front of the i-shells ejected at a time $\geq 14(1 + z)$ ($\Gamma_{n,s}/30)^{-1}$ s, there are hundreds of decaying n-shells. With assumptions made before, the whole process of each i-shell interacting with these decaying n-shells is rather similar. For convenience, in our following treatment, the discrete interaction of each i-shell with these decaying n-shells has been simplified as the situation of an i-shell sweeping a moving proton trail (the LF of which is $\Gamma_{n,a}$) with a number density (Fan & Wei 2004):

$$n \approx \frac{\Gamma_{n,a} M_{n,a}}{2\pi R_{\text{int}}^2 m_p R_{\text{f}}}, \quad (3)$$

continually, where $m_p$ is the rest mass of protons and $M_{n,a} \propto \exp (-R/R_{\text{f}}) \equiv \text{the mass of the decaying/slow neutron shell}.

2.2 dynamics

The dynamical evolution of the i-shell is governed by the energy conservation of the system and can be estimated as (Fan & Wei 2004)

$$\frac{d\gamma_{rel}}{dm} = -\frac{\gamma_{rel} - \Gamma_{n,a}}{M_{i} + m + (1 - \epsilon)} U', \quad (4)$$

where $\gamma$ represents the Lorentz factor of the decreasing i-shell and $\gamma_{rel} \approx \Gamma_{n,a} + \gamma/\Gamma_{n,a}/2$ indicates the LF of the i-shell relative to the n-shell. In the adiabatic situation, the radiation efficiency factor $\epsilon$ is assumed as zero. $U = (\gamma_{rel} - 1)m c^2$ is the thermal energy in the comoving frame. The swept mass satisfies $dm = 4\pi m m_p R_{\text{f}} R_{\text{int}}^2 (\beta_{i} - \beta_{\text{rel}}) dR$. $\beta_{i}$ and $\beta_{\text{rel}}$ are the corresponding velocity of $\gamma$ and $\Gamma_{n,a}$.

In the numerical calculation, we take the following parameters: the mass of i-shell and n-shell $M_i = 2M_n \approx 5.6 \times 10^{57}$ g, the initial LF of i-shell $\Gamma_{i} \approx 200$, the LF of n-shell $\Gamma_{n,a} \approx 30$ and the width of n-shell is taken to be $\sim 3 \times 10^{19}$ cm. $\epsilon_{c}$ and $\epsilon_{B}$, the fraction of shock energy given to the electrons and magnetic field, are taken as 0.3 and 0.01, respectively. The minimum LF of the shocked electrons is estimated as

$$\gamma_{m} \approx \frac{1}{p - \frac{2}{p - 1} m_e} (\Gamma_{rel} - 1) + 1, \quad (5)$$

where $m_e$ being the rest mass of electrons and $p$ being the power-law index of the distribution of accelerated electrons. Our numerical results are shown in Fig. 1.

The electrons lose their energy via synchrotron radiation and inverse-Compton scattering on the soft $\gamma$-ray photons with a luminosity $L_{\gamma} \sim 10^{51}$ erg s$^{-1}$. The inverse-Compton is usually in the Thompson regime because $\gamma_{m} E_{\gamma}/\gamma_{m} \sim E_{\gamma} < m_c c^2$, where $E_{\gamma} \sim 200$ keV is the typical peak energy of GRBs (Preece et al. 2000). So, the inverse-Compton parameter can be estimated by

$$\gamma_{E_{\gamma}} \approx \frac{U_{\gamma}}{U_B}, \quad (6)$$

where $U_{\gamma}$ and $U_B$ are the radiation and magnetic energy density.
The thick solid line represents the evolution of the external γσ = Y - which are moving E(7) ≫ 2 GeV (Γ1 ≥ 1 for(1 + Γ1t)Y 389, + is the comoving downstream magnetic field (9) γ10L ∼ (11) is the observer’s time-scale, R1. Here, the same parameters are + β ∼ Γ - decay products of a series of neutron shells is 100) 1) ∼ 108 4 of the electrons can be estimated ∼ 4E × 20 per cent (Guetta, Spada & Waxman 2001). We thus draw the 4E ≈ (10) ≈ E ≈ γYR R ∼ 1) ∼ 108 4 + (1 + Y EIC)2 + 4εe/εb,
which gives (see also Fan & Piran 2006)
\[ Y_{EIC} \approx \begin{cases} \frac{\epsilon_e}{1 + Y_{EIC}} + \sqrt{\frac{1 + Y_{EIC}}{4\epsilon_e/\epsilon_b}} & \text{for } (1 + Y_{EIC})^2 \gg 4\epsilon_e/\epsilon_b, \\
\frac{4\epsilon_e/\epsilon_b}{1 + Y_{EIC}} - \sqrt{4\epsilon_e/\epsilon_b} & \text{for } (1 + Y_{EIC})^2 \ll 4\epsilon_e/\epsilon_b. 
\end{cases} \]
(8) From Fig. 1, we see that (1 + Y_{EIC})^2 \gg 4\epsilon_e/\epsilon_b in most of the cases, so the EIC emission always dominates the SSC emission.

The cooling Lorentz factor γc of the electrons can be estimated as (Piran 1999)
\[ \gamma_c \approx \frac{6\pi m_e c (1 + z)}{(1 + Y_{EIC}) \sigma_T B^2 t}. \]
(9) where t is the observer’s time-scale, σT is the Thomson cross-section and B is the comoving downstream magnetic field B ∼ 32πεeγγc(Y_0 - 1)m_e c^2. As shown in Fig. 1, γc ≪ γ_m. The electrons are in the fast cooling regime.

2.3 GeV emission

The electrons accelerated in the interaction between i-shell and the decay product of n-shells will subsequently Compton scatter the prompt soft γ-ray photons, and boost them to an energy
\[ h\nu_{EIC} \sim \gamma_m^2 E_p \sim 2 \text{ GeV}(\gamma_m/100)^2(E_p/200 \text{ keV}). \]
(10) The total energy of the GeV emission can be estimated as follows. Note that in our simplest model, the energy released in an i-shell interacting with the β-decay products of a series of neutron shells is equivalent to that of the interaction between an ion shell and all the decay products of a neutron shell. So the GeV emission is largely the same as that resulting in the internal shocks at R_{i,n} powered by two ion shells. Following Piran (1999), we consider a collision between these two shells with mass M_i and M_n, which are moving with different LFs: Γ_i ≫ Γ_{i,n} ≫ 1. Here, the same parameters are taken as in Section 2.2. The resulting bulk LF Γ_m in an elastic collision is
\[ \Gamma_m = \sqrt{\frac{M_i \Gamma_i + M_n \Gamma_{i,n}}{M_i \Gamma_i + M_n \Gamma_{i,n}}} = 108. \]
(11) The total internal energy (the difference of the kinetic energies before and after the collision) is
\[ E_{\text{in}} = \Gamma_i M_i c^2 + \Gamma_{i,n} M_n c^2 - \Gamma_m (M_i + M_n) c^2 = 3.1 \times 10^{56} \text{erg}. \]
(12) Then, the total energy given to electrons:
\[ E_e = \epsilon_e E_{\text{in}} = 9.3 \times 10^{49} \text{erg} (\frac{\epsilon_e}{0.3}). \]
(13) Since the electrons are in the fast cooling regime, the GeV radiation efficiency can be estimated as (for Y_{EIC} ≥ 1)
\[ \eta_{\text{GeV}} = \frac{Y_{EIC}}{1 + Y_{EIC}} \frac{E_e}{E_{\text{in}}} \approx E_c \frac{E_e}{\Gamma_i M_i c^2 + \Gamma_{i,n} M_n c^2}. \]
(14) With the typical parameters adopted in this work, we get \eta_{\text{GeV}} ≈ 8.5 per cent. This is comparable to the typical GRB efficiency η ≈ 20 per cent (Guetta, Spada & Waxman 2001). We thus draw the conclusion that the total energy of our GeV radiation component is comparable to the total energy of the soft γ-ray photons in some very long GRBs.

The EIC photons may be absorbed due to pair production by photons with energy above E_e ≈ (γmc^2)^2/(h\nu_{EIC}) ≈ 1 MeVγ^2/(h\nu_{EIC}/5 GeV). And the corresponding optical depth can be estimated as (e.g. Svensson 1987)
\[ \tau_{\gamma\gamma} \approx \frac{11\pi T N_{\gamma_{-e}}}{720\nu R^2} \sim 0.2 \frac{R^2}{L_{\gamma\gamma} \Delta T} \left( \frac{E_p}{200 \text{ keV}} \right) \frac{h\nu_{EIC}}{5 \text{ GeV}} \frac{N_{\gamma_{-e}}}{E_{\gamma e}} \frac{1}{\beta_y}, \]
where \( N_{\gamma_{-e}} \) = \( \frac{\beta_y - 1}{\beta_y} \left( \frac{E_{\gamma e}}{E_p} \right) \left( \frac{F_{\gamma e}}{F_{\gamma e}} \right) \) is the total number of photons of the prompt emission satisfying h\nu > E_{\gamma e}, i.e. T ∼ R_{i,n}/(2γ^2 c) is the time-scale of the late prompt emission overlapping with EIC emission and its power-law index β_y ≈ 1.2 has been used to get the analytical coefficient. The ultimate optical depth is ≈ 0.2 and the spectrum around 5 GeV would not suffer a significant absorption.

Now we estimate the detectability of this GeV component by the upcoming satellite Gamma-Ray Large Area Space Telescope (GLAST). The Large Area Telescope (LAT) on board covers the energy range from 20 MeV to 300 GeV. The effective area around 1 GeV is S_{eff} ≈ 10 cm^2. So the expected number of the GeV photons is
\[ N_{\text{det}} \approx \frac{\eta_{\text{GeV}} E_{\gamma e}}{\pi D_l^2 \nu h\nu_{EIC}} S_{\text{eff}} \sim 5 \frac{E_{\gamma e}}{10^8 \text{ erg}} \left( \frac{h\nu_{EIC}}{1 \text{ GeV}} \right)^{-1}. \]
(15)
Usually at least five high-energy photos are needed to claim a detection (e.g. Zhang & Mészaros 2001), so we conclude that this component is detectable for some bright long GRBs. Please see Fig. 2 for a numerical example, which shows $vF_\nu \propto \nu^{1/2}$ below the peak as a result of the scattering electrons in the fast cooling phase.

3 DISCUSSION AND CONCLUSION

The physical composition of GRB outflows is not clear yet. The outflows, in principle, could be Poynting-flux dominated or neutron-rich. People found some evidences for either model. For example, the modelling of optical flashes in some GRBs suggested the magnetization of the reverse shock regions and favoured the hypothesis that these GRB outflows were at least weakly magnetized, while the delayed/prompt optical flares detected in GRB 041219a and some other afterglow modelling got some indication evidences for neutron-rich outflows (see Zhang 2007 for a review). The physical composition of GRB outflows may not be universal and more effects are needed to get some ‘unique’ signatures of the Poynting-flux dominated or neutron-rich ejecta. In this work, we calculate the possible GeV emission signature of the unmagnetized neutron-rich internal shocks. This high-energy component, only emerging in some very long GRBs, is accompanying some UV/optical flares (Fan & Wei 2004) and is expected to be correlated with the prompt $\gamma$-ray emission but to have a $\sim 10(1+z)$ s lag. This is very different from Li & Waxman (2008), in which the UV/optical/GeV flares are powered by a series of weaker and weaker internal shocks at a distance $\sim 10^{15}$ cm and are almost simultaneous with the prompt $\gamma$-rays without an obvious lag. The time delay of the EIC emission, caused by the anisotropic emission of the scattered photons in the rest frame of the shocked medium (see Fan & Piran 2008 for a recent review), $\sim (1+z)R_{z,1}/(2\gamma^2c)$, is also ignorable in the case we consider.

In some very long bright GRBs, the delayed GeV emission discussed in this work is energetic enough to be detectable for the upcoming GLAST satellite (see Section 2.3 for details). It, however, might be outshined by the SSC radiation of the regular internal shocks at a radius $R_{\gamma} \sim 10^{13}$ cm. So only for the regular internal shocks having $\epsilon_\gamma \sim \epsilon_e$, the delayed GeV emission may be the dominant signal. As shown in Fig. 1, for $\epsilon_e \sim \epsilon_\gamma$, $Y_{\text{EIC}} \gg 1$ at $t \sim R_{\gamma,1}$, $(1+z)/2\gamma^2c > 1$. So most of the energy generated at a radius $\sim R_{\gamma,1}$ is lost into the EIC GeV emission. For Gamma-ray Burst Monitor (GBM; <20 MeV) onboard GLAST, the field of view is all sky not occulted by the earth and that of the LAT (30 MeV ~ 300 GeV) is ~2.5 sr. So ~1/5 GRBs will be detected by GBM and LAT simultaneously. With a good quality of keV–GeV spectrum, we may be able to check our model.

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