EMISSION PROCESSES OF HIGH ENERGY GAMMA RAYS FROM GAMMA-RAY BURSTS

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Abstract
Synchrotron self-Compton (SSC) process in the reverse shocks of gamma-ray bursts is suggested to be responsible for the observed prompt high-energy gamma-ray emissions from several gamma-ray bursts. We find that the SSC emission from the reverse shocks dominates over other emission processes in energy bands from tens of MeV to tens of GeV, for a wide range of shock parameters. This model is favorable for escape of energetic photons from the emitting regions due to a lower internal pair-production optical depth, as the characteristic size of the reverse shock region is much larger than that of internal shocks. We predict that, in this model, the prompt high-energy emissions are correlated with the prompt optical flashes, which can be test in the forthcoming GLAST era.

Keywords: gamma rays: bursts—radiation mechanisms: non-thermal

1. Introduction

EGRET has detected prompt emission above 30MeV from several bright GRBs triggered by BATSE (Catelli et al. 1998), among which GeV photons have been detected from GRB930131 (Sommer et al. 1994; Ryan et al. 1994) and GRB940217 (Hurley et al. 1994). GRB940217 even exhibits delayed GeV emission 90 minutes after the trigger. Two classes of models have been proposed to explain the delayed and prompt GeV emissions.

One is related to "Hadron processes". It is widely assumed that GRB shocks (internal and/or external) can accelerate protons to very high energies, a proposed mechanism for the production of ultra-high energy cosmic rays (Waxman 1995; Vietri 1995). The photo-meson processes (Waxman & Bahcall 1997; Böttcher & Dermer 1998) or synchrotron radiations of the protons (Vietri 1997; Totani 1998a,b) have been suggested
to be responsible for the GeV emissions. Katz (1994) even suggested that the impact of the fireball on a dense clouds could produce high-energy gamma-ray emission via $\pi^0$ decay process.

Another class is related to the inverse Compton processes in GRB shocks, including internal shocks and external shocks. In the standard picture of GRBs, sub-MeV gamma-rays are formed in internal shocks. When the relativistic ejecta encounters the external medium, a relativistic forward shock expands into the external medium and a reverse shock moves into and heats the fireball ejecta. The forward shock continuously heats fresh gas and accelerates electrons, producing long-term afterglows through the synchrotron emission (e.g. van Paradijs et al. 2000). A strong prompt optical flash (Akerlof et al. 1999) and late time radio flare behavior (Kulkarni et al. 1999), accompanying GRB990123, have been attributed to the synchrotron emissions from the reverse shock (Sari & Piran 1999; Mészáros & Rees 1999). Papathanassiou & Meszaros (1994) proposed that electron IC processes in internal shocks produce GeV emissions, while Meszaros, Rees & Papathanassiou (1994), Dermer et al. (2000) and Zhang & Meszaros (2001) suggest that electron IC processes in forward shocks may be responsible for the prompt and delayed GeV emissions.

We here suggest an alternative mechanism, that is the SSC emissions from reverse shocks. As shown below, the SSC emission from the reverse shocks dominates over other emission processes in energy bands from tens of MeV to tens of GeV, for a wide range of shock parameters (Wang, Dai & Lu 2001a,b). Moreover, it involves a much larger emitting size, hence a lower internal pair-production optical depth than models related to internal shocks.

In section 2, we consider the attenuation effects of high energy photons in internal and external shocks. We analytically study (section 3) the high energy $\gamma$-ray emission from the SSC process in reverse shocks and in section 4 numerically calculate the SSC radiation components in the reverse shocks and compare it with the SSC emission from forward shocks and another two combined-IC processes (Mészáros, Rees & Papathanassiou 1994), i.e. scatterings of reverse shock photons on the forward shocked electrons and forward shock photons on the reversely shocked electrons.

2. Attenuation of high energy photons in internal and external shocks

It has been suggested that high energy photons are produced in internal shock regions (e.g. Papathanassiou & Meszaros 1994; Waxman &
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Bahcall 1997). However, as we show below, energetic GeV photons may suffer strong attenuation by other photons produced in internal shocks. The observed photon spectra of GRBs can be approximated as power law, with a high-energy part of the form $dn/d\varepsilon \propto \varepsilon^{-\beta}$ for $\varepsilon > \varepsilon_b$, where $\varepsilon = h\nu/m_e c^2$ is the photon energy in units of the electron’s rest energy and $\varepsilon_b \sim 1$ is the break energy above which $\beta \sim 2 - 3$. As a photon with energy $\varepsilon$ will annihilate any photon with energy above $\varepsilon_c = \eta^2/\varepsilon$ (where $\eta$ is the Lorentz factor of GRB fireball), its optical depth is given by

$$\tau_{\gamma\gamma} = \frac{11}{180} \frac{\sigma_T N_c}{4\pi R_{\text{in}}^2}$$

in (Lithwick & Sari 2001), where $N_c \equiv \int_{\varepsilon_c}^{\infty} dn/d\varepsilon d\varepsilon$ and $R_{\text{in}} = 2\eta^2 c \delta t$ is the radius of internal shocks, with $\delta t$ being the rapid variability timescale in GRB light curves. Setting $\tau_{\gamma\gamma}(\varepsilon_c) = 1$, we derive the cut-off energy

$$h\nu_c = 0.5\text{GeV} \delta t^{-1} E_{\gamma,53}^{-1} \varepsilon_b^{-\frac{\beta-2}{\beta+1}} \eta_{300}^{\frac{2\beta+2}{\beta+1}}$$  \hspace{1cm} (1)

where $E_{\gamma} \equiv 10^{53}\text{erg} E_{\gamma,53} = \int \varepsilon n_e c^2 d\varepsilon$ is the burst energy in gamma-rays, $\delta t \equiv 10^{-1}\text{s} \delta t_{-1}$, $\eta \equiv 300 \eta_{300}$ and the numerical coefficient on the right hand side corresponds to $\beta = 2.2$.

However, this problem will find a natural solution if the high-energy photons are formed in external shocks because the size of the latter is 2-3 orders of magnitude larger than that of internal shocks.

3. The analytic estimate

The synchrotron emission spectrum at the deceleration time ($t_{\text{dec}}$) can be described by two break frequencies and the peak flux (for redshift $z = 1$):

$$\nu_{r_m} = \frac{\Gamma(\gamma_{r_m})^2 eB'}{2\pi m_e c} = 6.4 \times 10^{15} \text{Hz} \xi_{0.6}^{-1/2} B_{-2}^{-2} \eta_{300} n_0^{1/2}$$  \hspace{1cm} (2)

$$\nu_{r_c} \approx 10^{17} \text{Hz} \left(\frac{Y_{r_c} + 1}{Y_{r_s} + 1}\right)^{3/2} \xi_{-2}^{-3/2} B_{-2}^{-2} \eta_{300} n_0^{-3/2} \left(\frac{t_{\text{dec}}}{10\text{s}}\right)^{-2}$$  \hspace{1cm} (3)

$$f_{r_m} \approx 1.5 \text{Jy} h_{65}^2 \xi_{0.6}^{1/2} B_{-2}^{-1/4} \eta_{300}^{-1/4} E_{53}^{5/4} \left(\frac{t_{\text{dec}}}{10\text{s}}\right)^{-3/4}$$  \hspace{1cm} (4)

where $E = 10^{53} E_{53}\text{erg}$ is the shock isotropic energy, $n = 1n_0\text{cm}^{-3}$ is the number density of the interstellar medium, $z$ is the redshift of the GRB source, $B' = 12G \xi_{0.01}^{1/2} \eta_{300} n_0^{1/2}$, is the magnetic field in the comoving frame, $\xi_e \equiv 0.6\xi_{0.6}$ and $\xi_B \equiv 0.01\xi_{-2}$ are the equipartition values of electron and magnetic energies respectively, and a flat universe with zero cosmological constant and $H_0 = 65h_{65}\text{Km s}^{-1}\text{Mpc}^{-1}$ is assumed. The Compton parameter $Y$, expressing the cooling rate of electrons due to
inverse Compton effect, is defined as $Y = \frac{4}{3} \tau_e \int \gamma^2 \tilde{N}_e(\gamma) d\gamma$, where $\tilde{N}_e(\gamma)$ is the normalized electron distribution and $\tau_e$ is the optical thickness to electron scattering.

Then we derive the SSC spectrum of the reverse shocks:

$$
\nu_{rs,IC}^m = 2(\gamma_{rs}^m)^2 \nu_{rs}^m = 1.0 \times 10^{21} \text{Hz} \varepsilon_{0.6}^{1/2} \xi e^{-13/6} \eta_{300}^{1/2} \gamma_{rs}^m, \quad (5)
$$

$$
\nu_{c,IC}^m = 2(\gamma_c^m)^2 \nu_c^m = 2.1 \times 10^{22} \text{Hz} \varepsilon_{0.6}^{-7/2} \xi e^{-13/6} \eta_{300}^{1/2} E_{53}^{4/3}, \quad (6)
$$

$$
f_{\text{max}}^m = \frac{\gamma_{rs}^m \nu_{rs}^m}{\gamma_c^m} = 2.6 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} h_{50}^{3/2} E_{53}^{4/3} \eta_{300}^{1/2} \eta_{1000}^{1/2}. \quad (7)
$$

For typical parameters $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.5$ and $n = 1$, we give the flux of the inverse Compton component at two representative frequencies:

$$
f_{rs,IC}^m(\varepsilon = 100 \text{MeV}) = 1.0 \times 10^{-9} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}^{4/3};
$$

$$
f_{rs,IC}^m(\varepsilon = 1 \text{GeV}) = 1.5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}^{2/3}. \quad (8)
$$

As a comparison, the derived high energy flux of the synchrotron and SSC emissions from forward shocks are, respectively,

$$
f_{fs}^m(\varepsilon = 100 \text{MeV}) = 1.0 \times 10^{-9} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53};
$$

$$
f_{fs}^m(\varepsilon = 1 \text{GeV}) = 0.5 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}, \quad (9)
$$

$$
f_{m,IC}^m = 3 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}. \quad (10)
$$

Therefore, we conclude that for the typical parameter values of the shock and the surrounding medium, the synchrotron self-Compton emission from the reverse shock dominates over the synchrotron and synchrotron self-Compton emissions from the forward shock at high energy gamma-ray bands. Our result is different from that of Dermer et al. (2000), who argue that the synchrotron self-Compton emission from the forward shock may be responsible for the prompt and delayed high energy gamma-ray emission. The key point of the difference is that they considered a rather dense circumburst medium with number density $n \sim 100 \text{cm}^{-3}$, while we consider a typical interstellar medium with $n \sim 1 \text{cm}^{-3}$.

As an example, we try to fit the high-energy emissions from GRB930131. The photon spectrum of GRB990131 can be described by $dn/d\varepsilon \sim 7.4 \times 10^{-6} \text{photons (cm s MeV)}^{-1} (\varepsilon/147 \text{MeV})^{-2.07 \pm 0.36}$ (Sommer et al. 1994), while our model prediction for $\varepsilon > h\nu_{rs,IC}^e$ is $dn/d\varepsilon \sim 2.2 \times 10^{-6} \text{photons (cm s MeV)}^{-1} (\varepsilon/147 \text{MeV})^{-2.25} E_{53}^{2/3}$. Thus, if the fireball shock energy $E \sim 4 \times 10^{53} \text{erg}$ and other parameters such as $\xi_e, \xi_B, \eta,$
z and the number density \( n \) of the surrounding medium take the above representative values, then both the flux level and the spectrum agree well with the observations.

4. Numerical Result

Four IC processes, including the synchrotron self-Compton (SSC) processes in GRB forward and reverse shocks, and two combined-IC processes (i.e. scattering of reverse shock photons on the electrons in forward shocks and forward shock photons on the electrons in reverse shocks), are considered now (Wang, Dai & Lu 2001b).

For single scattering, the IC volume emissivity in the comoving frame for a distribution \( N(\gamma) \) of scattering electrons is given by (Rybicki & Lightman 1979; Sari & Esin 2001)

\[
j_{\nu}^{\gamma IC} = 3\sigma_T \int_{\gamma_{min}}^{\gamma_{max}} d\gamma N(\gamma) \int_0^1 dx g(x) f_{\nu s}'(x),
\]

where \( x \equiv \nu' / 4\gamma^2 \nu_s' \), \( f_{\nu s}' \) is the incident specific flux at the shock front in the comoving frame, and \( g(x) = 1 + x + 2x\ln(x) - x^2 \) reflects the angular dependence of the scattering cross section for \( \gamma_e \gg 1 \) (Blumenthal & Gould 1970). Noting that \( f_{\nu}^{\gamma IC} = j_{\nu}^{\gamma IC} 4\pi r^2 \Delta r'/4\pi D^2 \) and the synchrotron flux \( f_{\nu s}' = f_{\nu s}' 4\pi r^2 / 4\pi D^2 \), where \( \Delta r' \) is the comoving width of the shocked shell or ISM medium and \( D \) is source distance, we obtain the IC flux in the observer frame

\[
f_{\nu}^{\gamma IC} = 3\Delta r'\sigma_T \int_{\gamma_{min}}^{\gamma_{max}} d\gamma N(\gamma) \int_0^1 dx g(x) f_{\nu}(x)
\]

by transforming Eq.(11) into the observer frame.

Apart from the SSC scattering processes in the reverse and forward shocks, another two combined-IC scattering processes are also present. Because approximately one-half of the photons arised in one shock region will diffuse into the another shock region from the point of view of the comoving frame, the IC flux Eq.(12) for the combined-IC scatterings should be divided by a factor of two. Though the scattered photons move isotropically in the comoving frame, the beaming effect makes these photons moving along the direction to the observer.

Our main calculation results are as follows:

i) The IC spectral flux from a relativistic shell expanding into an ISM at the deceleration time are shown in Fig. 1. Typical shock parameters are used: \( E = 10^{53} \text{erg}, \ \xi_e = 0.6, \ \xi_B = 0.01, \ p = 2.5 \) and \( n = 1 \). It can be clearly seen that the SSC from the reverse shock dominates over the other three IC components at gamma-ray bands less than a few tens of GeV with a peak around a few MeV.
The spectra of the IC emissions at the reverse shock peak time for typical shock parameters. The solid and dotted curves represent the SSC emissions from the reverse shock and forward shock, respectively. Also plotted are the IC emissions of scatterings of reverse shock photons on the forward shock electrons (dash-dotted curve) and forward shock photons on the reversely shocked electrons (dashed curve).

ii) In Fig. 2, we present the energy spectra ($\nu f^{IC}_\nu$) of the IC emissions with various shock parameters. We find that a) for a wide range of shock parameters, the SSC component from reverse shocks is the most important at energy bands from tens of MeV to tens of GeV, to which EGRET is sensitive. b) For small value of $p$ (e.g. $p = 2.2$), the SSC emission from the reverse shock dominates over the synchrotron and IC processes even in the TeV energy bands (see Fig. 2(d)). Fig. 2 also suggest that strong TeV emission should also be emitted from the two combined-IC and forward shock SSC processes for most GRBs. For a moderate steep distribution of the shocked electrons (e.g. $p = 2.5$), the combined-IC and/or forward shock SSC become increasing dominated at TeV bands. However, it would only be detected from nearby, low-redshift bursts for which the attenuation due to intergalactic infrared emission is small.

iii) We here compute the slope of the photon spectrum at high energy bands and plot it in Fig. 3. We can see that at energy bands from tens of MeV to tens of GeV, the photon spectrum index $\alpha$ (the photon number $dn(h\nu)/d\nu \propto \nu^\alpha$) ranges from 1.7 to 2.15, which is consistent with the observed high energy gamma-ray photon spectrum by EGRET from some bright GRBs (e.g. Sommer et al. 1994).
Figure 2. The energy spectra of synchrotron and IC emissions at the reverse shock peak time for the ISM circumburst environment case with various shock parameters: a) $E = 10^{53}$ erg, $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.5$ and $n_1 = 1$; b) $E = 10^{52}$ erg, $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.5$ and $n_1 = 1$; c) $E = 10^{53}$ erg, $\xi_e = 0.6$, $\xi_B = 10^{-4}$, $p = 2.5$ and $n_1 = 1$; d) $E = 10^{53}$ erg, $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.2$ and $n_1 = 1$. The thin dash-dotted and dashed curves represent the synchrotron spectra of the reverse shock and forward shock, respectively. The four IC spectra are shown by the curves in the same way as in Fig. 1.

Figure 3. The high energy gamma-ray photon spectrum index $\alpha$ of the SSC emission from the reverse shock with shock parameters as used in Fig.1.
5. Conclusions and Discussions

If optical flashes and GeV emissions are, respectively, resulted from synchrotron and SSC emissions from reverse shocks, they should show correlations in both their light curves and spectra. Below we will give the decaying light curve of the synchrotron self-Compton component of the reverse shock after it has passed through the ejecta ($t_{\text{obs}} > t_{\text{dec}}$). Since $f_{\text{rs}} \propto t_{\text{obs}}^{-47/48}$ and $\tau_{\text{rs}} \propto t_{\text{obs}}^{-1/2}$, the peak flux of the inverse Compton spectral component $f_{\text{rs,IC}} = f_{\text{rs}} \tau_{\text{rs}} \propto t_{\text{obs}}^{-3/2}$. If the observed frequency locates between the two break frequencies ($\nu_{\text{rs,IC}} < \nu < \nu_{\text{rs,IC}}$), then $f_{\nu}^{\text{rs,IC}} = f_{\nu}^{\text{rs}} \left( \frac{\nu}{\nu_{\text{rs,IC}}} \right)^{-(p-1)/2}$. According to Sari & Piran (1999), $\gamma_{\text{m}} \propto t_{\text{obs}}^{-13/48}$ and $\nu_{\text{rs}} \propto t_{\text{obs}}^{-73/48}$, so $\nu_{\text{rs,IC}} = 2\gamma_{\text{m}}^{2/5} \propto t_{\text{obs}}^{-33/16} \sim t_{\text{obs}}^{-2}$, thus $f_{\nu}^{\text{rs,IC}} \propto t_{\text{obs}}^{-1/2-p} \propto t_{\text{obs}}^{-3}$ for $p = 2.5$. On the other hand, if the observed frequency is above $\nu_{\text{rs,IC}}$, the flux drops exponentially with time since all the electrons above the corresponding energy cool and no fresh electrons are accelerated once the reverse shock has crossed the ejecta shell. Therefore, in general, we expect to see a rapidly decaying high energy flux from the reverse shock, which constitutes a unique characteristic distinguished from other models suggested for the observed high energy gamma-ray emission from some GRBs. Measurements of the time dependence of the high energy gamma-ray flux and the spectra with the planned Gamma-ray Large Area Space Telescope (GLAST) mission will test this synchrotron self-Compton scenario.

In summary, we showed that SSC process in the reverse shocks of gamma-ray bursts is a plausible model for the observed prompt high-energy gamma-ray emissions from several bursts. It is found that the SSC emission from the reverse shocks dominates over other emission processes in energy bands from tens of MeV to tens of GeV, for a wide range of shock parameters. This model is more favorable for energetic photons than those related to internal shocks, since it involves a much lower internal pair-production optical depth due to a much larger emitting size. We predict that, in this model, the prompt high-energy emissions are correlated with the prompt optical flashes, which can be test in the forthcoming GLAST era.

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