GeV AND HIGHER ENERGY PHOTON INTERACTIONS IN GAMMA-RAY BURST FIREBALLS AND SURROUNDINGS

SOEBUR RAZZAQUE,1 PETER MÉSZÁROS,1,2,3 AND BING ZHANG1,4

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ABSTRACT

We have calculated the opacities and secondary production mechanisms of high-energy photons arising in gamma-ray burst internal shocks, using exact cross sections for the relevant processes. We find that for reasonable choices of parameters, photons in the range of tens to hundreds of GeV may be emitted in the prompt phase. Photons above this range are subject to electron-positron pair production with fireball photons and would be absent from the spectrum escaping the gamma-ray burst. We find that, in such cases, the fireball becomes optically thin again at ultrahigh energies (\(\gtrsim\) PeV). On the other hand, for sufficiently large fireball bulk Lorentz factors, the fireball is optically thin at all energies. Both for \(\gamma\gamma\) self-absorbed and optically thin cases, the escaping high-energy photons can interact with infrared and microwave background photons to produce delayed secondary photons in the GeV–TeV range. These may be observable with GLAST or at low redshifts with ground-based air Cerenkov telescopes. Detection of the primary prompt spectrum constrains the bulk Lorentz factor, while detection of delayed secondary gamma rays would provide a consistency check for the primary spectrum and the bulk Lorentz factor, as well as constraints on the intergalactic magnetic field strength.

Subject headings: gamma rays: bursts — gamma rays: theory — radiation mechanisms: nonthermal

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1. INTRODUCTION

GeV photons have been detected from a number of gamma-ray bursts (GRBs) (Dingus 2003; Fishman & Meegan 1995) with the EGRET detector on the Compton Gamma Ray Observatory. Photons at energies in this range and higher can make pairs via \(\gamma\gamma \rightarrow e^+e^-\) interactions in the GRB fireball, the optical depth being dependent on the bulk Lorentz factor \(\Gamma_b\), so spectral observations at this energy can provide useful constraints (Baring & Harding 1997; Lithwick & Sari 2001) on this key ingredient of GRB models. In addition, high-energy photons that escape \(\gamma\gamma\) absorption in the source can still suffer such interactions far from the source but before reaching the observer, against cosmic infrared background (CIB) and/or cosmic microwave background (CMB) photons. The electron-positron pairs thus produced can inverse-Compton scatter again on the most numerous CMB photons, giving rise to a delayed secondary spectrum (Plaga 1995; Dai & Lu 2002), which ranges typically up to hundreds of GeV.

In this paper we investigate, using the exact cross sections, the high-energy interactions of photons produced in a simple GRB internal shock model, as a function of the luminosity, the typical variability timescale, and the bulk Lorentz factor. We approximate the original GRB spectrum through an observable motivated Band function (Band et al. 1993) and calculate the emerging spectrum as a function of the burst parameters. This spectrum is then subjected to interactions with the CIB and CMB, and the shape of the secondary spectrum and its time delay is calculated assuming typical cosmological distances \(z \sim 1\) and various values for the intergalactic magnetic field strength. The pair-production cutoff of the primary spectrum and the delayed secondary spectrum fall, for typical GRB parameters, in the GLAST (Gehrels & Michelson 1999) energy range, and for a range of intergalactic magnetic field strengths the latter should be detectable by GLAST, as well as by the newer generation of air Cerenkov telescopes (Weekes 2000).

2. GRB INTERNAL SHOCK MODEL

We denote with \(U\) the GRB fireball total energy density. After the initial expansion phase the kinetic energy is carried by the baryons, since \(m_p \gg m_e\) (where \(m_p\) and \(m_e\) are baryon and lepton masses, respectively). Thus, \(U \sim U_p \sim 4n_b^2 p^2 \Gamma_b^2\), where \(n_b\) is the total baryon number density in the comoving fireball frame and \(\Gamma_b\) is the bulk Lorentz factor of the fireball in the observer’s frame. Later on, a significant fraction of the fireball’s kinetic energy is transferred to leptons, in internal shocks that randomize the relative bulk motion between different portions of the expanding fireball, as well as external shocks when the fireball is decelerated by the external medium. Here we concentrate on the internal shocks, which are thought to be responsible for the usual prompt MeV emission. The fraction of energy transferred to the leptons is given by a parameter \(\varepsilon_e = U_e/U \gg m_e/m_p\). Charged particles, \(p\) and \(e^+e^-\), are accelerated in the shocks by interaction with magnetic fields within the GRB fireball. High-energy protons and electrons cool mostly as a result of synchrotron radiation, but the proton cooling time is much longer than that of the electrons, and the prompt \(\gamma\)-ray emission is most likely due to electron synchrotron emission, whose cooling time in the prompt phase (tens of seconds after the trigger) is generally shorter than the dynamical or expansion time.

1 Astronomy and Astrophysics Department, Pennsylvania State University, University Park, PA 16802.
2 Physics Department, Pennsylvania State University, University Park, PA 16802.
3 Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540.
4 Current address: Department of Physics, University of Nevada, Las Vegas, NV 89154.

5 We use primed variables in the comoving frame and unprimed variables in the laboratory or observer’s frame.
In this so-called fast cooling case, valid in the internal shocks, most of the electron energy is converted into γ-rays: \( U_e \approx U_{\gamma, \text{iso}} / (4 \pi r_s^2 c) \). Here \( r_s = 2 c b t \Gamma_e^2 \) is the shock radius, \( b t \) is the observed variability timescale, and \( L_{\gamma, \text{iso}} \) is the isotropic-equivalent γ-ray luminosity in the observer’s frame during the prompt γ-ray emission phase. Neglecting e⁺ pair formation in the shocks, the total volume number density of leptons and baryons in the fireball (which are the same because of charge neutrality) can be calculated, assuming \( U_p \approx U_e / \varepsilon_e \), as

\[
n'_e \approx n'_p = \frac{L_{\gamma, \text{iso}} / \varepsilon_e}{4 \pi r_s^2 \Gamma_e^2 b^2 m_p c^3}
\]

in the comoving frame. Here \( \Gamma_0 \approx 1 \) is the comoving random Lorentz factor acquired by protons in the internal shocks. The magnetic field energy density \( U_B = B^2 / 8 \pi \) can be estimated as

\[
B' = \sqrt{\frac{2 \varepsilon_B L_{\gamma, \text{iso}}}{\varepsilon_e r_s^2 \Gamma_e^2 b}}
\]

so in the comoving frame \( \varepsilon_B = U_B / U \) is the fraction of the shocked fireball energy that goes into magnetic energy.

The process of Fermi acceleration in the shocks leads to a differential electron and proton volume number density distribution that is a power law in energy,

\[
\frac{dN_{e,p}}{d\gamma_{e,p}} = \frac{(p-1) \gamma_{e,p}}{\gamma_{e,p}^{p+1} \gamma_{e,p,\text{min}}^{-p}} ; \quad \gamma_{e,p} > \gamma_{e,p,\text{min}}^{-p} ;
\]

where

\[
\gamma_{e,p,\text{min}} \approx \frac{m_p}{m_e} \varepsilon_e \gamma_{e,p,\text{min}}^{-p} ; \quad \gamma_{e,p,\text{min}} \approx 1
\]

are the minimum Lorentz factors for electrons and protons, respectively, in the comoving frame. The maximum Lorentz factors are obtained by equating the acceleration time \( t_{\text{acc}} = A_0 / \varepsilon_e \) of a particle \( j \) to the shorter of the synchrotron cooling time

\[
t_{\text{syn}} = \frac{6 \pi m_j^3}{\sigma_{\text{Th}} \gamma_j^2 m_e B'^2}
\]

and the dynamic time (\( \delta t_{\Gamma_0} \)) in the comoving frame. Electrons cool faster, by synchrotron radiation, than the dynamic time, and the maximum electron Lorentz factor is

\[
\gamma_{e,\text{max}}' = \sqrt{\frac{6 \pi e}{A_0 \sigma_{\text{Th}} B'}}
\approx 2.2 \times 10^8 (A_1^{-1/2} L_{\gamma, 52}^{-1/4} \varepsilon_e^{-1/4} \varepsilon_B^{-1/2} \delta t_{\text{acc}} B_{2.5}^{-1/2})
\]

in the comoving frame. Here we have chosen \( L_{\gamma, \text{iso}} = 10^{52} \) ergs s⁻¹, \( \varepsilon_e = 10^{-1} \), \( \varepsilon_B = 10^{-1} \), \( \varepsilon_B = 10^{-2} \), \( \delta t = 10^{-2} \delta t_{\text{acc}} \), \( A = 10 A_1 \), and \( \Gamma_0 = 10^{5} \). Note that the inverse Compton (IC) cooling time of the electrons is proportional to the synchrotron cooling time in equation (5) and the proportionality constant in the fast cooling case is given by \( Y = [-1 + (1 + 4 \varepsilon_e / \varepsilon_B)^{1/2}] / 2 \) (Sari & Esin 2001). For the present choice of parameters, \( Y \approx 0.6 \), and we have ignored the IC cooling of the electrons compared to the synchrotron cooling while calculating \( \gamma_{e,\text{max}}' \). Our choice of the value of \( \varepsilon_B \) is motivated by the assumption that the observed peak γ-ray energy is due to electron synchrotron radiation and only a small fraction of the total γ-ray power is radiated by the IC process at small internal shock radii (Daigne & Mochkovitch 1998; Derishev et al. 2001; Baring & Braby 2004). A recent study by Zhang et al. (2003) also suggests that the fireball value of \( \varepsilon_B \) should be 10–100 times larger than the afterglow fit of 0.01–0.001.

The observed γ-ray spectrum from the GRB prompt emission can be approximated by the phenomenological Band function in the high-energy range as \( \sim \varepsilon_c^{-\alpha} \) above the synchrotron peak energy \( \varepsilon_{\gamma, \text{pk}} \), which is typically a few hundred keV. For observed cases of \( \alpha > 2 \), most of the γ-ray energy is concentrated near \( \varepsilon_{\gamma, \text{pk}} \) and one can roughly estimate the peak volume number density of photons in the fireball as

\[
n'_{\gamma} = \frac{L_{\gamma, \text{iso}}}{4 \pi r_s^2 \Gamma_e b \varepsilon_{\gamma, \text{pk}}}
\]

in the comoving frame. Below the synchrotron peak energy the Band spectrum is \( \sim \varepsilon_c^{-\alpha} \) and the total number density of photons in equation (7) increases only logarithmically.

Low-energy photons are expected to be absorbed by fireball electrons in the presence of a magnetic field by the synchrotron self-absorption mechanism below a photon energy of

\[
\varepsilon_{\gamma, \text{ssa}} = \Gamma_0 b \left[ \frac{\pi(1-1/4) \Gamma_0 (p+1/4)}{2} \varepsilon_{\gamma, \text{pk}} \right]^{2/(p+4)}
\]

in the observer’s frame. Here we have estimated \( \varepsilon_{\gamma, \text{ssa}} \) for power-law indices in equation (3) of \( p = 2, 2.5, \) and 3 (top to bottom in eq. [8]). Observed GRB spectra, fitted by a Band function, do not correspond in a straightforward manner to a theoretical synchrotron spectrum from a one-zone region with some power-law index \( p \), especially in the fast-cooling regime. However, the usual Band function values can arise as a result of the superposition of many shocks, each giving rise to a power-law energy distribution with index \( 2 \leq p \leq 3 \). In our calculation, we assume the nominal Band fit values for the resulting photon spectrum, and we use a nominal reference value for the absorption energy of \( \varepsilon_{\gamma, \text{ssa}} = 10 \varepsilon_{\gamma, \text{pk}} \), which is more than an order of magnitude below the observed synchrotron peak energy of \( \varepsilon_{\gamma, \text{pk}} = 500 \varepsilon_{\gamma, \text{pk}} \).

3. HIGH-ENERGY PHOTON INTERACTIONS AND INTERNAL ATTENUATION

Observation of high-energy photons from the GRB fireball is mainly limited by the opacity of two-photon annihilation into an electron-positron pair \( (e^+ e^-) \). The cross sections for \( \gamma \gamma \rightarrow e^+ e^- \) in the nonrelativistic (NR) and extremely relativistic (ER) cases are given by Jauch & Rohrlich (1955) as

\[
\sigma_{\gamma \gamma}^{\text{NR}}(\omega) = \frac{3}{8} \sigma_{\text{Th}} \frac{m_e^2 c^4}{\omega^2},
\sigma_{\gamma \gamma}^{\text{ER}}(\omega) = \frac{3}{8} \sigma_{\text{Th}} \frac{m_e^2 c^4}{\omega^2} \left( \ln \frac{2 \omega}{m_e c^2} - 1 \right),
\]

where

\[
\sigma_{\text{Th}}(\omega) = \frac{3}{4 \pi} \frac{m_e^2 c^4}{\omega^2}
\]
where $\omega$ is the photon energy in the center of mass frame. The observed photon energy ($E_\gamma$) above the threshold for pair production with photons at an energy $\epsilon_\gamma$ must satisfy the condition $\omega > m_e c^2$ or $E_\gamma \gtrsim E_{\gamma, \text{th}} = \frac{m_e^2 c^4}{2 \epsilon_\gamma}$. Observation of photons of a maximum energy $\epsilon_{\gamma, \text{max}} > E_{\gamma, \text{th}}$ may therefore be used to put a limit on $\Gamma_\gamma$, if the corresponding optical depth is unity. Photons below $E_{\gamma, \text{th}}$ may escape from the fireball (provided no other interaction becomes important) even though they might interact with photons from the high-energy tail of the Band function, but the relevant optical depth is less than unity because of a much lower photon density at that energy than in equation (7).

For a given $\Gamma_\gamma$ and $\delta t$, the lower limit threshold of the $\gamma\gamma$ absorption energy range within the source can be found from the pair-production threshold energy with peak synchrotron photons of energy $\epsilon_{\gamma, \text{pk}}$ as

$$E_{\gamma, \text{th}} = \frac{m_e^2 c^4}{2 \epsilon_{\gamma, \text{pk}}} \approx 26 \Gamma_0^2 \delta t c \Gamma_{\gamma, \text{th}}^{-1} \text{ GeV}$$

in the observer’s frame, for the present choice of parameters. The total volume number density of photons and hence the $\gamma\gamma$ optical depth in the fireball increases slowly as the photon energy decreases from $\epsilon_{\gamma, \text{pk}}$ to $\epsilon_{\gamma, \text{ssa}}$. High-energy photons in the energy range capable of producing pairs with fireball photons in the energy range $\epsilon_{\gamma, \text{pk}} - \epsilon_{\gamma, \text{ssa}}$ are absent in the spectrum escaping from the source. Ultrahigh-energy photons, however, may escape the GRB fireball as the pair production cross section, in the ER limit in equation (9), decreases with increasing photon energy and so does the optical depth. Ultrahigh-energy primary photons will again appear above this “thinning” energy. This energy can be found, roughly, from the optical depth corresponding to the $\gamma\gamma$ cross section with photons at the self-absorption energy ($\epsilon_{\gamma, \text{ssa}}$) in the ER limit in equation (9) as

$$E_{\gamma, \text{th}} \approx 2 \times 10^9 \frac{\Delta L_{\gamma, \text{iso}} \sigma_{\gamma\gamma} m_e^2 c^2}{\Gamma_\gamma \delta t \epsilon_{\gamma, \text{th}}^2} \approx 2 \times 10^9 \frac{\Delta L_{\gamma, \text{iso}} \sigma_{\gamma\gamma} m_e^2 c^2}{\Gamma_\gamma \delta t \epsilon_{\gamma, \text{th}}^2} \text{ GeV},$$

where $\Delta = \ln \left[ 2 (\epsilon_{\gamma, \text{ssa}} E_{\gamma, \text{th}})^{1/2} / m_e \Gamma_{\gamma, \text{th}} \right] - 1 \approx 3 \Delta_3$, for the same parameters used in equation (11).

We calculate the high-energy photon interactions with other fireball photons and electrons using the exact cross-section formulae (Jauch & Rohrlich 1955). In Figure 1 we plot the opacities of high-energy photons as functions of observed energy ($E_\gamma$), due to electron Compton scattering, $e^\pm$ pair production with electrons ($\gamma e \rightarrow e^\pm$), and $\gamma\gamma$ interactions, dominantly, with fireball photons in the energy range $\epsilon_{\gamma, \text{ssa}} - \epsilon_{\gamma, \text{pk}}$. The cross section for the $\gamma e \rightarrow e^\pm$ process is given by Jauch & Rohrlich (1955) as

$$\sigma_{\gamma e}^{\text{NR}} (E_\gamma) = 2.25 \times 10^{-3} \frac{\alpha}{\pi} \sigma_{\text{Th}} \left( \frac{E_\gamma}{m_e c^2} - 4 \right),$$

$$\sigma_{\gamma e}^{\text{ER}} (E_\gamma) = \frac{3 \alpha}{8 \pi} \sigma_{\text{Th}} \left( 28 \ln \frac{2 E_\gamma}{m_e c^2} - \frac{218}{27} \right)$$

in the nonrelativistic and extreme relativistic limits, respectively. Here $E_\gamma$ is the photon energy in the comoving frame. The flat region in Figure 1, for the $\gamma\gamma$ pair creation curves above $E_{\gamma, \text{pk, th}}$, corresponds to a change in the target photon energy from $\epsilon_{\gamma, \text{pk}}$ to $\epsilon_{\gamma, \text{ssa}}$ and a slow increase of the total target photon number density $n'_{\gamma}$ (in eq. [7]), accordingly.

We plot the boundaries of the optically thin and thick regions for high-energy photon emission from GRB internal shocks in Figure 2, for different choice of parameters $L_{\gamma, \text{iso}}$, $\epsilon_{\gamma, \text{pk}}$, and $\delta t$. Note that for certain parameter values, e.g., $L_{\gamma, \text{iso}} = 10^{53}$ ergs s$^{-1}$, $\delta t = 0.1$ s, and $\epsilon_{\gamma, \text{pk}} = 0.5$ MeV or $L_{\gamma, \text{iso}} = 10^{52}$ ergs s$^{-1}$, $\delta t = 1$ s, and $\epsilon_{\gamma, \text{pk}} = 1$ MeV, the GRB fireball is optically thin to photons of all energies above $\Gamma_\gamma \approx 775$ or 676, respectively.

Extra complications can arise because of increased $e^\pm$ pairs produced in the fireball by $\gamma\gamma$ interactions by high-energy photons (Totani 1999; Mészáros et al. 2001), which can affect the photon opacities plotted in Figure 1. This is a complex problem, requiring a numerical treatment (Pe’er & Waxman 2004). Here we use an approximate treatment, using a pair formation rate in the comoving frame of $\epsilon_{\gamma e} (\epsilon') dN'/d\epsilon'$ to estimate the total number of $e^\pm$ pairs created by an incident (denoted by $i$) high-energy photon. The differential volume number density of incident high-energy photons capable of producing pairs, as a function of energy, can be estimated using the Band spectrum and equation (7) as

$$\frac{dN'_{\gamma, i}}{d\epsilon'} \approx \frac{\epsilon_i - 1}{\epsilon_{\gamma, \text{pk}} (\epsilon'/\epsilon_{\gamma, \text{pk}})^{\delta}} \epsilon_i \geq \epsilon_{\gamma, \text{pk}}.$$

Here $\epsilon_{\gamma, \text{pk, th}}$ is the comoving threshold energy for pair production, which is similar to the threshold energy in equation (10) in the case of synchrotron peak photons as targets. The target (denoted by $t$) photon number density, in general, may have a different energy distribution $dN'_{\gamma, t}/d\epsilon'$. The total volume number density of pairs created in the fireball is thus

$$n'_{\pm} = c b t \Gamma \int_{\epsilon_{\gamma, t}}^\epsilon_{\gamma, \text{max}} d\epsilon' \frac{dN'_{\gamma, i}}{d\epsilon'} \int_{\epsilon_{\gamma, \text{th}}}^{\epsilon_{\gamma, \text{max}}} d\epsilon' \int_{\epsilon_{\gamma, \text{th}}}^{\epsilon_{\gamma, \text{max}}} d\epsilon' \sigma_{\gamma\gamma} \left( 2 \epsilon' E' \right) \frac{dN'_{\gamma, t}}{d\epsilon'},$$

where $\epsilon_{\gamma, \text{max}} \approx \gamma c_{\text{max}} m_e c^2$ is defined in equation (6), and $\epsilon_{\gamma, \text{th}} = m_e c^2 / 2 E_r$. For this estimate, we approximate the $\gamma\gamma$ cross section as $\sigma_{\gamma\gamma} \approx (3/8) \sigma_{\text{Th}}$, at $e^\pm$ pair production threshold with peak synchrotron photons ($\epsilon_{\gamma, \text{pk}}$). This leads to a simplified
expression for the total volume number density of pairs created in the fireball by integrating over the photon energy distribution above \( \gamma_e, \)

\[
n'_e = \frac{3}{8} \sigma_{\text{Th}} \left( \frac{c \beta t}{\alpha - 1} \right) \ln \gamma_e^2 \left( \frac{2e^2 \gamma_{\text{pk}}}{m_e^2 c^4 \Gamma_b^2} \right)^{-\alpha - 1}.
\] (15)

The total number density of target photons in equation (7) increases by a factor \( \sim \ln \gamma_e \gamma_{\text{pk}} \) as the target photon energy decreases from \( \gamma_e, \) to \( \gamma_{\text{pk}} \) in the case of \( \alpha = 2 \). However, one needs incident photons of energy much higher than \( \gamma_{\text{pk}} \) to produce \( e^+e^- \) pairs with photons at \( \gamma_{\text{pk}} \), and the incident number decreases \( \propto \gamma_{-\alpha} \). Thus, equation (15) is estimated for targets that are at threshold with incident photons of energy \( \geq \gamma_{\text{pk}} \). We can express the secondary pair density as the ratio to the incident electron density in the fireball, 

\[
n'_e \approx \left\{ \begin{array}{ll}
3 \sigma_{\text{Th}} L_{\gamma, \text{iso}} \left( \frac{c \beta t}{\alpha - 1} \right) \ln \gamma_e^2 \left( \frac{2e^2 \gamma_{\text{pk}}}{m_e^2 c^4 \Gamma_b^2} \right)^{-\alpha - 1} & \alpha = 2, \\
786L_{\gamma, \text{iso}} \left( \frac{c \beta t}{\alpha - 1} \right) \ln \gamma_e^2 \left( \frac{2e^2 \gamma_{\text{pk}}}{m_e^2 c^4 \Gamma_b^2} \right)^{-\alpha - 1} & \alpha = 2.5, \\
2.3L_{\gamma, \text{iso}} \left( \frac{c \beta t}{\alpha - 1} \right) \ln \gamma_e^2 \left( \frac{2e^2 \gamma_{\text{pk}}}{m_e^2 c^4 \Gamma_b^2} \right)^{-\alpha - 1} & \alpha = 3,
\end{array} \right.
\] (16)

using equation (1).

Shock-activated high-energy electrons may also induce 

\( e^+e^- \) pairs interacting with synchrotron photons \( (e\gamma \rightarrow e^+e^-) \). (The cross section for this process is given by eq. [12] with the replacement \( E'/m_e \rightarrow \gamma_{\gamma'} E'/m_e \)). However, the number of secondary pairs produced in this case is negligible compared to the initial lepton number density because of the lower number density of high-energy incident electrons.

The secondary pairs can annihilate with themselves or with the leptons originally carried in the fireball, \( e^+e^- \rightarrow \gamma\gamma \), if the number density of pairs increases substantially. The cross section for this process is (Jauch & Rohrlich 1955)

\[
\sigma_{\gamma\gamma} = \frac{3}{8} \sigma_{\text{Th}} \left( \frac{c \beta t}{\alpha - 1} \right) \ln \gamma_e^2 \left( \frac{2e^2 \gamma_{\text{pk}}}{m_e^2 c^4 \Gamma_b^2} \right)^{-\alpha - 1}.
\] (17)

Because of a decreasing cross section with energy, low-energy \( e^+e^- \) pairs annihilate faster. The annihilation time for an incident electron can be estimated as \( t_{\text{ann}} = 1/(e \sigma_{\gamma\gamma} n'_e) \) in the comoving frame. However, synchrotron cooling is even faster, and the ratio of the pair annihilation time to the synchrotron cooling time, for example at \( \gamma_e = 5 \) (where the electron is still relativistic and synchrotron loss formula applies), \( \Gamma_b = 10^{2.5} \), \( \beta t = 0.01 \) s, and in the \( \alpha = 2 \) case in equation (16), is \( t_{\gamma\gamma}^*/t_{\text{ann}} \approx 0.1 \) using equations (5) and (17). This ratio decreases at higher energy. Hence, electrons lose most of their energy to synchrotron photons within a dynamical time \( \delta t \) in the comoving frame. As a result, secondary pairs produced in the fireball cool down to nonrelativistic values and drift along roughly with the bulk Lorentz factor \( \Gamma_b \). We consider here situations in which the secondary pair density (eq. [16]) is at most comparable to the original fireball lepton density, in which case the scattering depth is not substantially changed, and any photons from annihilation of cold pairs lead to higher generation pairs whose number similarly does not affect the scattering optical depth. We note that in the Thomson limit, the IC cooling time is of the same order as the synchrotron cooling time \( t_{\gamma\gamma}^*/t_{\text{ann}} \approx e_{\gamma}/e_{\beta} \), with an increasing value at higher energy and in the Klein-Nishina limit.

4. HIGH-ENERGY PHOTON SPECTRUM AND INTERACTION WITH THE DIFFUSE BACKGROUND

Using the phenomenological Band function spectrum for the intrinsic high-energy photon flux from the GRB, the spectrum that would reach the observer after taking into account in-source \( \gamma\gamma \) attenuation at a luminosity distance \( D_L \) is

\[
\frac{d^2 N_{\gamma}}{d\epsilon_{\gamma} d\Omega} = \frac{(\alpha - 1)L_{\gamma, \text{iso}}}{4\pi D_L^2 e_{\gamma, \text{pk}}} \left( \frac{e_{\gamma}}{e_{\gamma, \text{pk}}} \right)^{-\alpha - 1} e^{-\tau_{\gamma\gamma, \text{GRB}}(e_{\gamma})}, \quad e_{\gamma} \gtrsim e_{\gamma, \text{pk}},
\] (18)

where \( \tau_{\gamma\gamma, \text{GRB}}(e_{\gamma}) \) is the \( e^\pm \) pair production optical depth (see Fig. 1) in the GRB fireball. The high optical depth in the fireball, however, reduces substantially the ultra-high-energy photon flux above the energy \( E_{\gamma, \text{pk}, \text{th}} \) given in equation (10) and below the energy \( E_{\gamma, \text{med}} \) given in equation (11), while for some parameters the GRB is in the region of Figure 2 where the escaping spectrum is optically thin at all energies. Here we consider high-energy photon emission from the GRB fireball for two cases. One is an example in which the escaping spectrum is optically thin at all energies (e.g., \( L_{\gamma, \text{iso}} = 10^{52} \) ergs s\(^{-1}\), \( \beta t = 1 \) s, \( e_{\gamma, \text{pk}} = 1 \) MeV, and \( \Gamma_b = 10^{2.5} \) in Fig. 2). The other example is a case in which the fireball is opaque to photons in an energy range between \( E_{\gamma, \text{pk}, \text{th}} \) and \( E_{\gamma, \text{med}} \) (e.g., \( L_{\gamma, \text{iso}} = 10^{52} \) ergs s\(^{-1}\), \( \beta t = 0.1 \) s, \( e_{\gamma, \text{pk}} = 0.5 \) MeV, and \( \Gamma_b = 10^{2.5} \)).
For typical GRB locations at redshift $z = 1$, most high-energy photons above $\sim 70$ GeV produce $e^\pm$ pairs (Salamon & Stecker 1998), reaching an energy up to $\sim m_e c^2 / 2$, because of $\gamma\gamma$ interactions with cosmic infrared background (CIB) photons (in the $\sim 100$ GeV–TeV range) and cosmic microwave background (CMB) photons (in the PeV range). These high-energy pairs, in turn, cause delayed high-energy photon emission by IC scattering of CMB photons (Dai & Lu 2002). Here we follow the treatment of Dai et al. (2002) to calculate the delayed high-energy photon spectrum in the GeV–TeV range.

The corresponding time integrated flux of electrons (and positrons) from high-energy GRB photons interacting with CIB and CMB photons is

$$\frac{dN_e}{d\gamma_e} = \frac{L_{\gamma,\text{iso}} \alpha}{2 \pi D_L^2} \frac{\Gamma \gamma_e^{-2}}{(2m_e)^{1/2}} \frac{\gamma_e}{\gamma_e^{\gamma_{\gamma,\text{GRB}(2\gamma_e m_e)}}} \times \left(1 + \frac{m_e}{4\gamma_e \gamma_{\gamma,\text{CMB}}} \right) \frac{\gamma_e}{\gamma_{\gamma,\text{BKG}}(2\gamma_e m_e)} \leq \gamma_e \leq \gamma_{\gamma,\text{max}}/2, \quad (19)$$

where $\Theta$ is a step function. We have assumed that each electron and positron of the $e^\pm$ pair share one-half the photon energy, i.e., $\gamma_e = \gamma_e / 2 m_e$. We calculate the pair production optical depth with background photons (CIB and CMB) at threshold $(2\epsilon_\gamma \gamma_{\gamma,\text{CMB}} CMB = m_e^2)$ as

$$\tau_{\gamma,\gamma,BKG}(\epsilon_e) = \frac{\text{n}_{\text{CIB}} \left( \frac{m_e^2}{2 \epsilon_\gamma \gamma_{\gamma,\text{CMB}}} \right) + \text{n}_{\text{CMB}} \left( \frac{m_e^2}{2 \epsilon_\gamma \gamma_{\gamma,\text{CMB}}} \right)}{8 \sigma_{\text{T\theta}} D_L}, \quad (20)$$

The total number density of CIB photons is fitted from the intensity $I$ (in W m$^{-2}$ sr$^{-1}$) given in Malkan & Stecker (2001) as

$$\text{n}_{\text{CIB}}(\epsilon_\gamma, \gamma_{\gamma,\text{CMB}}) = \frac{4\pi I(1 + z)^3}{c \epsilon_\gamma \gamma_{\gamma,\text{CMB}}}. \quad (21)$$

The CMB photons, on the other hand, have a blackbody distribution peaking at an energy of $2.7(1 + z)$ K and a total volume number density $\propto (1 + z)^3$.

The secondary electrons in equation (19) are cooled by IC scattering on CMB photons on a timescale $\tau_{\text{IC}}(\gamma_e) = 3 m_e c / (4 \epsilon_\gamma \sigma_{\text{T\theta}} \gamma_{\gamma,\text{CMB}}) \approx 7.3 \times 10^{13} (\gamma_e / 10^{10})^{-1}$ s in the local frame (Dai et al. 2002), where $\epsilon_{\gamma,\text{CMB}}$ is the local blackbody CMB photon energy density. The total integrated, first generation, IC photon spectrum in the observer’s frame, convolving the electron spectrum with the IC spectrum from a single electron in the Thomson limit (Blumenthal & Gould 1970), is then

$$\frac{d^2 N_{\text{IC}}}{d\epsilon_e dE_{\gamma}} = \int d\gamma_e \frac{dN_e}{d\gamma_e} \frac{d^2 N_{\gamma}}{d\epsilon_e dE_{\gamma}} = \frac{3 \sigma_{\text{T\theta}}}{32 \pi D_L^2} \frac{\epsilon_e^{-2}}{(2m_e)^{1/2}} L_{\gamma,\text{iso}} \sigma_{\text{T\theta}} \text{GRB}[2m_e \epsilon_e] \times \left(1 + \frac{m_e}{4\epsilon_e \gamma_{\gamma,\text{CMB}}} \right) \frac{\epsilon_e}{\epsilon_{\gamma,\text{CMB}}} \times \left\{ 1 - \exp\left[-\frac{\epsilon_{\gamma,\text{BKG}}(2m_e \epsilon_e)}{\epsilon_{\gamma,\text{GRB}}(2m_e \epsilon_e)} \right] \right\} \frac{\epsilon_{\gamma,\text{GRB}}(2m_e \epsilon_e)}{\Delta \epsilon_{\gamma}(\epsilon_e)} \times \frac{\text{n}_{\text{CIB}}(\epsilon_\gamma, \gamma_{\gamma,\text{CMB}})}{\epsilon_\gamma^{2 \gamma_{\gamma,\text{CMB}}}} \times \left(2 \epsilon_e \ln \frac{E_{\gamma}}{4 \epsilon_e \gamma_{\gamma,\text{CMB}}} + \epsilon_{\gamma} + 4 \epsilon_e^2 \gamma_{\gamma,\text{CMB}} - \frac{E_{\gamma}^2}{2 \epsilon_e^2 \gamma_{\gamma,\text{CMB}}} \right). \quad (22)$$

Here the integration over $\gamma_e$ ranges from $\gamma_{\gamma,\text{min}} = \gamma_{\gamma,\text{CMB}}(2m_e \epsilon_e)$ to $\gamma_{\gamma,\text{max}}/2$, where $\gamma_{\gamma,\text{max}}$ is the maximum electron energy in equation (6). The maximum timescale for delayed emission is $\Delta t(\gamma_e) = \gamma_{\gamma,\text{GRB}}(2m_e \epsilon_e)^{-1}$, corresponding to a case in which the primary fireball escaping the GRB isophase is optically thick to $\gamma\gamma$ against its own photons in a band of photon energies, shown in Figures 4 and 5, respectively. The prompt primary spectra, using equation (18) multiplied by $\exp\left[-\tau_{\gamma,\gamma,\text{BKG}}(\epsilon_e)\right]$ to allow for attenuation in the background radiation fields, are plotted as the dark solid curves in both figures. We have also plotted the first-generation delayed spectra from IC scattering of secondary leptons on the CMB, by numerically integrating equation (22) for two different IGM magnetic field strengths ($B_{\text{IG}}$) of $10^{-20}$ and $10^{-17}$ G. For the same two sets of parameters above, these are $10^{-20}$ $B_{\text{IG}} = 20$ G intergalactic (IG) magnetic field, the deflection angle, for $\theta_{B} < 1$, is $\gamma_{\gamma,\text{max}} \approx \lambda_{\gamma}/R_{\text{BB}} \approx 1.3 \times 10^{-5} (\gamma_{\gamma,\text{GRB}} / 10^{10})^{-2}$ ($B_{\text{IG}} = 10^{-20}$ G), where $R_{\text{BB}} = \gamma_{\gamma,\text{max}} c / (\epsilon_{\gamma,\text{GRB}} E_{\gamma})$ is the Larmor gyroradius of the electron. We have plotted different timescales as a function of secondary pair Lorentz factor ($\gamma_{\gamma}$) in Figure 3 for $t_{\text{GRB}} = 50$ s and several IG magnetic field values, at $DL = 10^{28}$ cm corresponding to redshift $z \approx 1$ in an $\Omega_m = 0.3, \Omega_{\Lambda} = 0.7$, and $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ cosmology.

We used two parameter sets ($L_{\gamma,\text{iso}} = 10^{52}$ ergs s$^{-1}$, $\delta t = 1$ s, $\epsilon_{\gamma,\text{GRB}} = 1$ MeV and $\Gamma_{\text{BB}} = 10^{-2}$), and $L_{\gamma,\text{iso}} = 10^{52}$ ergs s$^{-1}$, $\delta t = 0.1$ s and $\epsilon_{\gamma,\text{GRB}} = 0.5$ MeV and $\Gamma_{\text{BB}} = 10^{-2}$). These correspond to a case in which the primary spectrum escaping from the GRB fireball is optically thin to photons of all energies and a case in which the primary fireball escaping spectrum is optically thick to $\gamma\gamma$ against its own photons in a band of photon energies, shown in Figures 4 and 5, respectively. The prompt primary spectra, using equation (18) multiplied by $\exp\left[-\tau_{\gamma,\gamma,\text{BKG}}(\epsilon_e)\right]$ to allow for attenuation in the background radiation fields, are plotted as the dark solid curves in both figures. We have also plotted the first-generation delayed spectra from IC scattering of secondary leptons on the CMB, by numerically integrating equation (22) for two different IGM magnetic field strengths ($B_{\text{IG}}$) of $10^{-20}$ and $10^{-17}$ G. For the same two sets of parameters above, these are given by the dashed and dotted curves, respectively. The delayed spectra for 50 s duration (topmost dashed and dotted curves) corresponds to the GRB duration ($t_{\text{GRB}}$), and we have calculated them using the full range of secondary pair energy $\gamma_{\gamma} = \epsilon_{\gamma,\text{GRB}} / 2m_e$, created with CMB, allowed by the maximum primary photon energy $\epsilon_{\gamma} \approx \gamma_{\gamma,\text{max}} m_e \Gamma_{\text{BB}}$ from equation (6). We
have also calculated the delayed spectra for $10^2$, $10^4$, and $10^6$ s durations by numerically integrating equation (22) up to a maximum $\gamma_c$, corresponding to that time from Figure 3.

5. DISCUSSION

We have calculated the spectrum and time dependence of the high-energy ($\gtrsim$GeV) spectrum emerging from GRB internal shocks as a function of the luminosity, time variability, and bulk Lorentz factor, using exact cross sections. For typical burst parameters the internal shock spectrum cuts off above a threshold energy $E_{\gamma,\text{th}} \sim 10$–100 GeV because of $\gamma\gamma$ interactions within the shock region. There is a qualitative difference with the results of Baring & Harding (1997), who discussed the $\gamma\gamma$ absorption in external shocks and did not consider the secondary spectra from interactions with background radiation. More recently Wang et al. (2004) also discussed the $\gamma\gamma$ absorption in external shocks, including interactions against background photons. The main difference with our work is due to the much lower $\gamma\gamma$ optical depth from the lower photon density at the radii of external shocks, which are much larger than the radii of internal shocks considered here. Internal shock $\gamma\gamma$ absorption using approximate cross sections was discussed by Pilla & Loeb (1998) and Lithwick & Sari (2001) without interactions against external background photons, as well as by Dai & Lu (2002), including such interactions. These authors did not consider the effects of synchrotron self-absorption. The main qualitative difference between the emerging internal shock spectra of these authors and our work arises from our use of accurate cross sections and, more importantly, our inclusion of synchrotron self-absorption. The cutoffs in the emerging spectra that we obtain are compatible with more detailed numerical calculations of the self-consistent pair creation and annihilation spectrum in internal shocks of Pe'er & Waxman (2004), without inclusion of interactions against external background photons. The main difference between their final spectra and ours is due to their using an ab initio spectrum instead of a phenomenological Band spectrum as here, as well as the additional effects of our inclusion here of interactions against external photons, leading to a delayed secondary spectrum.

A new feature discussed in this paper is that the spectrum that emerges from the GRB internal shock region shows, besides the expected high-energy cutoff due to pair-production $E_{\gamma,\text{th}}$, a reemergence of the spectrum at a higher energy $E_{\gamma,\text{th}} > E_{\gamma,\text{th}}$, where the shock becomes optically thin again to $\gamma\gamma$ interactions. This is due to our inclusion of synchrotron self-absorption, which reduces the internal photon target spectral density, causing absorption of the highest energy emerging photons. For high enough bulk Lorentz factors (typically $\Gamma > 800$), the fireball is optically thin to internal $\gamma\gamma$ interactions at all energies, and there is no internal $\gamma\gamma$ cutoff band in the emerging spectrum.

The emerging GRB spectrum is modified, on its way to the observer, by interactions with the diffuse infrared background (CIB) and the diffuse microwave background (CMB). Here, we have used the GRB internal shock emerging spectra, including synchrotron self-absorption as the source of input photons, and calculate their interaction with a CIB spectrum redshifted to $z \sim 1$, based on that of Malkan & Stecker (2001). We then calculated the secondary GRB spectrum from the resulting secondary pairs, which are up-scattered by CMB photons. We used two different escaping GRB primary spectra, one with an internal $\gamma\gamma$ cutoff band (for a typical burst bulk Lorentz factor $\Gamma_b \sim 300$) and one without an internal $\gamma\gamma$ cutoff band (for a burst with a larger $\Gamma_b \sim 800$). We used two different isotropic-equivalent luminosities and different intergalactic magnetic field strengths ranging between $B_{\text{IG}} = 10^{-20}$ and $10^{-17}$ G. This leads to a secondary spectrum, mainly in the 1–100 GeV range, in addition to and delayed with respect to the prompt unabsorbed internal shock spectrum. We also calculated the further interaction of the secondary gamma-ray spectrum with the CIB, which gives a spectral shape attenuated similarly to that of the primary spectrum. We did not...
consider the delayed spectrum of the tertiary and higher order pairs, since the delay timescales are longer and the fluxes of these components are much lower.

A different delayed GeV component can arise in the afterglow phase, when the inverse Compton spectrum peak energy in the external shock region sweeps across the GeV band (Mészáros & Rees 1994; Dermer et al. 2000; Sari & Esin 2001; Zhang & Mészáros 2001). This delayed GeV emission from IC upscattering on external shock electrons is predicted to be detectable by GLAST at z ∼ 1 (Zhang & Mészáros 2001), as long as the shock parameters are such that the IC component is prominent (which is the case for the typical parameters inferred from broadband modeling of some well-studied bursts [Wijers & Galama 1999; Panaitescu & Kumar 2002; Yost et al. 2003]). The IC duration can be up to a few hours, which could overlap with the earlier part of the delayed spectra discussed here. The temporal evolution of the IC spectral component is such that it hardens with time initially but softens with time after the IC peak crosses the band. The delayed GeV component discussed in this paper has a rather different temporal evolution behavior. Since Δt(γ_e) is essentially anticorrelated with γ_e (see Fig. 3), the hard spectrum (due to the more energetic electrons) lasts a shorter timescale than the soft spectrum. In addition, the harder photons arrive earlier than the softer photons. Throughout the whole delayed phase, the hardest photons emerge first, followed by progressively softer photons. Later, the hardest photons drop out first from the spectrum. The delayed spectrum always progressively softens with time. This distinct spectral evolution behavior can be used to distinguish the delayed emission from IC scattering in external shocks from the delayed emission of secondary spectra due to pair-production and IC scattering on the diffuse background discussed here. The secondary external spectrum from such an IC spectrum, however, should be similar to what we have discussed here, on timescales longer than a few hours, since the absorbed energy undergoes similar reprocessing.

The time delays and the flux level of the secondary spectra are sensitive to the intergalactic magnetic field strength. The best prospects for detection of such secondary delayed GeV spectra occurs for bursts with bulk Lorentz factors ≥800 and intergalactic magnetic fields ≤10^{-17} G, which might be typical of intergalactic void regions. Since the mean free path of the first-generation high-energy photons against γγ absorption typically exceeds several to tens of megaparsecs (Coppi & Aharonian 1997; Malkan & Stecker 2001), it is plausible that a substantial fraction of the pair formation will occur in void regions near the burst, even if the latter occurred in a cluster galaxy. The corresponding time delays are in the range 10–100 s, and the fluxes are within the sensitivity range of GLAST and, at the high-energy end, also of VERITAS, HEGRA, and other air Cerenkov telescopes. A detection of this secondary delayed GeV spectrum in GRB would provide a valuable diagnostic for the IGM magnetic field strength, as well as the bulk Lorentz factor, and would provide valuable clues for the typical size of the shocks responsible for the radiation.

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