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GEV TO PEV ENERGY PHOTON INTERACTIONS IN GAMMA-RAY BURST FIREBALLS AND SURROUNDINGS

SOEBUR RAZZAQUE and PETER MÉSZÁROS

Department of Astronomy and Astrophysics, Department of Physics
Pennsylvania State University, University Park, PA 16802

BING ZHANG

Department of Physics, University of Nevada, Las Vegas, NV 89154

Shock acceleration mechanism in gamma-ray bursts may produce photons up to a few PeV energy. Photons above 10-100 GeV and below a PeV energy are trapped inside the fireball due to a high opacity of electron-positron pair production with other photons. High energy photons escaping the fireball may interact with cosmic background radiation and provide delayed gamma-ray emission detectable by GLAST. Detection of the prompt and delayed emission may provide useful constraints on the gamma-ray burst model and also on the inter-galactic magnetic field.

1. Introduction

A number of experiments, both satellite-borne and ground-based, have detected GeV and higher energy photons from gamma-ray bursts (GRBs). Synchrotron radiation by shock accelerated electrons, in the internal shocks of GRB fireballs, is believed to be responsible for observed ∼MeV photons. Compton up-scattering of low energy photons by electrons and/or neutral pion decay ($\pi^0 \to \gamma\gamma$) from photomeson ($p\gamma$) interactions may produce photons up to the PeV energy range. However, emission of high energy photons from GRB fireballs is mainly limited by the opacity of $\gamma\gamma \to e^{\pm}$ interactions. Observation of photons in the ∼100 GeV - TeV energy range may thus put constraints on the bulk Lorentz factor (Γ_b) of the fireball which in turn determines the opacity.[1,2] Photons of energy $\gtrsim$TeV are expected to interact with cosmic infra-red background (CIB) photons and may not be detected directly. However, they may be detected indirectly from Compton up-scattering of cosmic microwave background (CMB) photons by the $e^{\pm}$ pairs they produce with CIB photons. This emission is delayed compared to ∼MeV emission and depends highly on the intergalactic magnetic field (IGMF) strength.[1]

2. GRB Fireball Model and Opacity

GRB fireballs are rapidly variable (with timescale $\delta t \sim 0.01 - 1$ s) and relativistic (with $\Gamma_b \gtrsim 100$) outflows of gas plasma shells.[3] Typical energy released from star

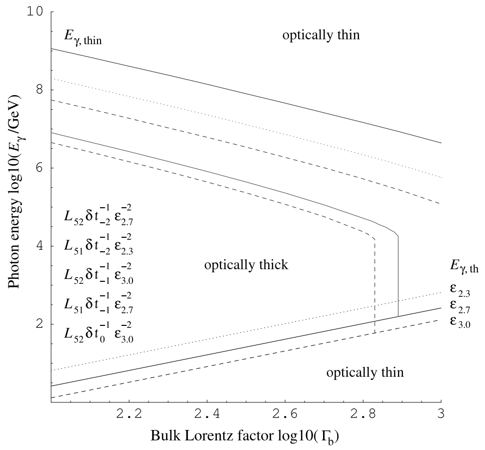

Fig. 1. Optically thick and thin regions for $\gamma\gamma \to e^{\pm}$ interactions in the GRB fireballs as functions of observable photon energy (E_γ) and the bulk Lorentz factor (Γ_b). Choice of parameters such as $L_\gamma = 10^{52} L_{52}$ erg/s, $\delta t = 0.1\delta t_{-1}$ s and $\epsilon_{\gamma,\rm pk} = 500\epsilon_{2.7}$ keV are shown for each curve. We used $\epsilon_{\gamma,\rm ssa} = 10$ keV for all curves. For a given choice of parameter set, photons with $E_\gamma > E_{\gamma,\rm thin}$ and $E_\gamma < E_{\gamma,\rm th}$ may escape the fireball. The GRB fireball becomes optically completely thin for photons of all energy in cases when $\Gamma_b > 10^{2.8}$ (closed dashed and dotted curves).

explosions which lead to the GRB fireballs is $\sim 10^{51} - 10^{52}$ ergs. After the initial expansion phase the kinetic energy is carried by the baryons in the fireball, since $m_p \gg m_e$ (where m_p and m_e are baryon and lepton masses respectively). Collisions of the relativistic plasma shells (so-called "internal shocks") with each other transfer a fraction ($\varepsilon_e \gg m_e/m_p$) of the energy to the leptons. High magnetic field created in the internal shocks carry another fraction ($\varepsilon_B < 1$) of the total energy.

The cooling time for shocked protons is much longer than the dynamic time ($\delta t/\Gamma_b$) of the fireball. Electrons, on the other hand, cool down rapidly by synchrotron radiation in the magnetic field. The total volume number density of synchrotron photons at the peak ($\epsilon_{\gamma,\rm pk}$) in the GRB fireball is $n'_\gamma = L_\gamma/(4\pi r_{\rm sh}^2 c\Gamma_b \epsilon_{\gamma,\rm pk})$. (We denote comoving variables with a prime and observables without a prime.) Here L_γ is the observed isotropic-equivalent γ-ray luminosity and $r_{\rm sh} = 2\Gamma_b^2 c\delta t$ is the radius of the fireball. Below $\epsilon_{\gamma,\rm pk}$, n'_γ increases logarithmically with energy (ϵ'_γ) down to a cutoff synchrotron self-absorption energy $\epsilon_{\gamma,\rm ssa} \approx 10$ keV. Above $\epsilon_{\gamma,\rm pk}$, n'_γ decreases as $\sim \epsilon_\gamma^{-\alpha+1}$ according to the Band spectrum.[4] The spectral index α is typically between 2 and 3.

We used the exact $\gamma\gamma$ cross section formula to calculate the GRB fireball opacity in Fig. 1 as a function of observed photon energy (E_γ) for different Γ_b. For a given low Γ_b, the fireball is optically thick for photons above threshold energy ($E_{\gamma,\rm th} = m_e^2 c^4 \Gamma_b^2/\epsilon_{\gamma,\rm pk}$) for $e^{\pm}$ pair production with peak synchrotron photons. The fireball may become optically thin again to very high energy photons ($> E_{\gamma,\rm thin}$) as the $\gamma\gamma$ cross section decreases with energy. As shown in Fig. 1, the fireball may be optically

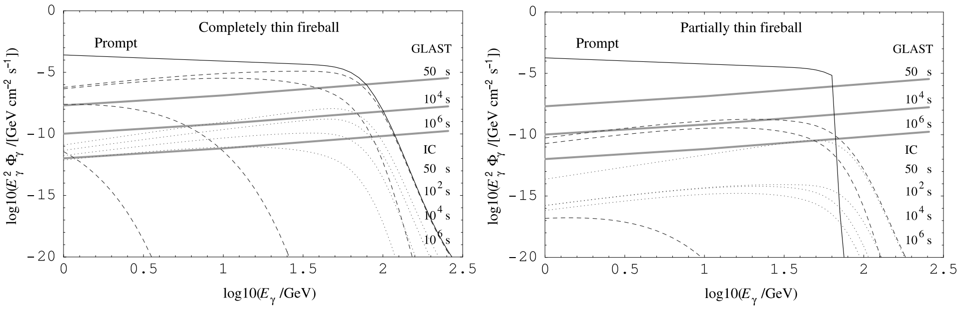

Fig. 2. Prompt and delayed photon spectra ($E_\gamma^2\Phi_\gamma = E_\gamma^2 d^2N_\gamma/dtdE_\gamma$) from completely thin (left panel) and partially thin (right panel) GRB fireballs. The prompt spectra (solid curves) are directly observable from the burst and the delayed spectra (dashed and dotted curves) are re-processed in the cosmic background photons. Parameters: $L_\gamma = 10^{52}$ ergs/s, $\alpha = 2.5$ and $z = 1$ are used in both plots. IGMF strengths of 10^{-17} G (dotted curves) and 10^{-20} G (dashed curves) are used to calculate delayed emissions (IC) of 50, 10^2, 10^4 and 10^6 s durations. Also used are $\delta t = 1$ s, $\epsilon_{\gamma,\rm pk} = 1$ MeV, $\Gamma_b = 10^{2.9}$ (left panel) and $\delta t = 0.1$ s, $\epsilon_{\gamma,\rm pk} = 0.5$ MeV, $\Gamma_b = 10^{2.7}$ (right panel). Sensitivities of GLAST are plotted with thick gray lines for 50, 10^4 and 10^6 s integration times.

thin to photons of all energy for very high Γ_b and shown choice of parameters.

3. Prompt and Delayed Photon Spectra

GRBs are located at cosmological distances (typically at redshift $z \sim 1$). High energy photons emitted from the fireball interact with CIB and CMB photons, in the $\sim$ 100 GeV-TeV and in the PeV energy range respectively, to produce $e^\pm$ pairs.[6] These pairs, in turn, Compton up-scatter (IC) numerous CMB photons to very high energy.[7] There are then a prompt spectrum directly from the GRB and a delayed photon spectrum re-processed in the background photon fields. These spectra are plotted in Fig. 2 for optically completely thin and partially thin GRB fireballs.

The duration of the delayed spectrum depends mostly on the angular spreading and deflection of the $e^\pm$ pairs in the IGMF at lower energy. At very high energy, the duration is limited by the GRB duration ($\sim$ 30 s for long bursts). GLAST is expected to detect both prompt and delayed spectra of high energy photons from GRBs in near future.

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