

# High energy emissions from gamma-ray bursts

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**Abstract.** Gamma-ray bursts are the brightest transient sources of MeV  $\gamma$ -rays in the sky and are the leading candidate sources of the GZK cosmic rays. Physical conditions required to accelerate elementary particles to such high energies also, inevitably, lead to expected TeV energy  $\gamma$ -ray and neutrino emission from these sources. Although  $\gamma$ -rays of energy only up to 18 GeV have been detected from a few bursts, upcoming space- and ground-based detectors will probe these sources in the GeV-TeV energy range revealing their particle acceleration and emission mechanism(s) as well as constraining their astrophysical model(s).

## 1. Introduction

Gamma-ray bursts (GRBs) are the most violent explosions in the universe sending out bright flashes of  $\gamma$ -rays outshining the entire universe for seconds [1]. The total energy output in visible 0.1-1 MeV non-thermal  $\gamma$ -rays is  $10^{49}$ - $10^{51}$  ergs. The GRBs are extra-galactic sources with a rate of about 1000/yr distributed isotropically over the whole sky. Highly variable (down to milliseconds)  $\gamma$ -ray emission implies that GRBs are compact sources and are divided into two main categories based on the duration of their “prompt” emission. The long bursts last for  $> 2$  s while the short ones last for  $\leq 2$  s implying a difference among their progenitors. Late time (hours-days) of  $X$ -ray, UV and optical emission from a GRB is collectively known as its afterglow which helps to identify the host galaxy and its distance.

Core-collapse, similar to supernovae, of massive stars ( $\geq 25M_{\odot}$ ); and binary mergers of neutron stars and/or a black hole and neutron star are currently the most favored progenitors of the long and short bursts respectively. In either cases a central engine (probably a few solar mass black hole) and a short-lived accretion disc are formed. Matter accreted from the disc are ejected due to radiation pressure along the rotational axes forming highly relativistic jets with bulk Lorentz factor  $\Gamma \geq 100$ . Observed  $\gamma$ -rays are emitted from such relativistic plasma outflow most probably by shock dissipation processes. The isotropic-equivalent total energy outflow is  $L_0 \sim 10^{50}$ - $10^{52}$  ergs/s with an initial radius  $R_0 \sim 10^6$ - $10^7$  cm and temperature  $T_0 \sim$  few MeV.

## 2. Prompt emission and afterglow

The time-averaged  $\gamma$ -ray spectra from both long and short bursts may be fitted by broken power-laws as  $dN_{\gamma}/d\epsilon_{\gamma} \propto \epsilon_{\gamma}^{-\alpha}$  and  $\propto \epsilon_{\gamma}^{-\beta}$  respectively below and above the peak energy  $\epsilon_{\gamma,\text{pk}} \sim 0.1$ -1 MeV. The average fit values are  $\alpha \approx 1$  and  $\beta \approx 2$ . Such non-thermal spectra may be described by synchrotron or inverse Compton (IC) scattering by a population of shock-accelerated (e.g., by Fermi mechanism) electrons. Collisions of plasma material inside the jet (internal shocks) may give rise to a power-law electron energy distribution  $dN_e/d\epsilon_e \propto \epsilon_e^{-\kappa}$  as well as describe

highly variable  $\gamma$ -ray spectra. The synchrotron and IC spectra in the fast cooling scenario, in which all shock-accelerated electrons lose energy by these processes within a dynamic time scale, is  $dN_\gamma/d\epsilon_\gamma \propto \epsilon_\gamma^{-(\kappa+2)/2}$  for  $\epsilon_\gamma \geq \epsilon_{\gamma,m}$ . An expected value of  $\kappa \approx 2$  from shock theories then may explain  $\beta = (\kappa + 2)/2 \approx 2$ . The observed peak value  $\epsilon_{\gamma,\text{pk}} \approx \epsilon_{\gamma,m}$ , the peak synchrotron photon energy by electrons of minimum random Lorentz factor  $\gamma_{e,\text{min}} \sim \epsilon_e(m_p/m_e)\Gamma$  with the model parameter  $\epsilon_e \sim 0.1$ . Assuming an equal number of protons and electrons in the pre-shocked jet, the GRB fireball then loses a fraction  $\epsilon_e$  of its energy to  $\gamma$ -rays with luminosity  $L_\gamma \approx \epsilon_e L_0$ . The turbulent magnetic fields in the shock region share another fraction  $\epsilon_B$  of  $L_0$ .

The broad band emission from the afterglow may be described with similar mechanism from external shocks arising from collisions of jet material with an external medium (e.g., ISM, wind). All the electrons, however, may not cool completely in the external shocks within the dynamic time. The resulting photon spectra thus show additional features which evolve with time in this slow cooling scenario, which help to understand underlying astrophysical model(s) better.

Currently the *Swift* satellite, a successor to the Compton Gamma-Ray Observatory (CGRO), is actively taking data from GRBs by rapidly slewing its narrow field of view X-ray and UV instruments (XRT and UVOT) to the burst position triggered by its wide field of view  $\gamma$ -ray detector (BAT). New data show previously unseen features such as afterglow of short bursts, late X-ray flares etc. [2].

### 3. GeV-TeV $\gamma$ -ray detection status

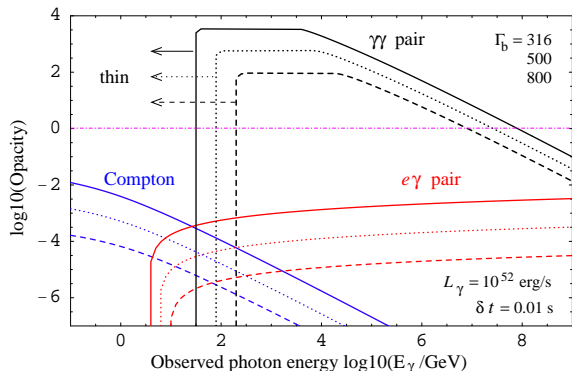
A confirm detection of TeV and higher energy  $\gamma$ -rays from a GRB has not been made yet. A tentative  $\geq 0.1$  TeV detection at the  $3\sigma$  level from GRB 970417a has been reported with the water Cherenkov detector MILAGRITO; another possible TeV detection of GRB 971110 has been reported with the GRAND array at the  $2.7\sigma$  level; and stacking of data from the TIBET array for a large number of GRB time windows has led to an estimate of a  $\sim 7\sigma$  composite detection significance [3]. A recent analysis of data from MILAGRO and MAGIC have produced interesting upper limits [4]. The MAGIC telescope has the ability to slew in less than 30 seconds to any location and has been responding to GCN alerts from *Swift* in search of prompt TeV emission. Better sensitivity is expected from HAWC, an upgrade to MILAGRO, as well as from atmospheric Cherenkov telescopes operating or under construction such as HESS, MAGIC, CANGAROO-III and VERITAS [5]. However, GRB detections in the TeV range are expected only for rare nearby events, since at this energy the mean free path against  $\gamma\gamma$  absorption on the diffuse IR photon background is  $\sim$  few hundred Mpc [6]. The mean free path is much larger below 100 GeV, and several dozens should be detectable with satellites such as AGILE, and hundred with large area satellites such as GLAST [7]. The EGRET experiment on CGRO detected up to 18 GeV energy photons from at least four GRBs [8]. A few generic features of GeV emission are their hard spectra and time-lag with prompt emission. The total energy in GeV component may be more than that in prompt MeV  $\gamma$ -rays. However, more data are necessary to understand the underlying emission mechanism(s) as we discuss next.

### 4. Theoretical models

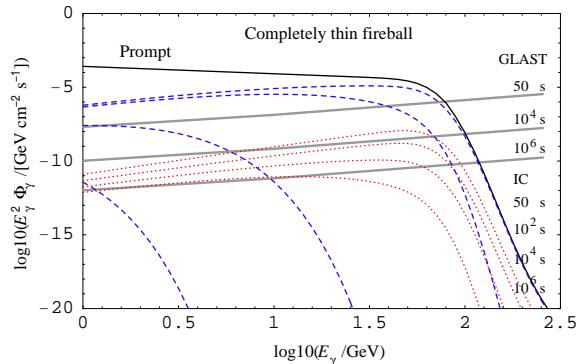
High energy (GeV-TeV)  $\gamma$ -ray emission from GRBs may be modeled by either electromagnetic (IC) or photo-hadronic ( $p\gamma$ ) processes or by both. While observed MeV photons are up-scattered by shock-accelerated electrons in the former process [9], the latter process requires protons to be co-accelerated with electrons and interact with observed MeV photons [10]. The  $p\gamma$  interactions leading to a  $\pi^+$  or a  $\pi^0$  produce GeV-TeV  $\gamma$ -rays by synchrotron and IC processes of secondary particles from hadronic and electromagnetic cascades. One of the characteristics of such hadronic mechanisms involving electromagnetic cascades is that since the hadrons lose energy slower than those of electrons, the afterglow predicted by  $p\gamma$  cascades stretches over a longer time-scale. The GeV light curves arising from such hadronic mechanisms would have a different shape from those

expected from leptonic mechanisms such as primary electron synchro-Compton [11]. One also expects to have a harder spectrum from  $p\gamma$  cascade than primary synchro-Compton, which is the basis of the argument for hadronic cascades in GRB 941017 [12]. It can however be argued that under some conditions a purely leptonic (primary electron) synchro-Compton mechanism can explain the same observations too [13]. One basically needs a “two zone” model, in a purely leptonic picture, for low energy emission from the prompt phase and high energy emission from a very early afterglow.

High energy  $\gamma$ -rays, above  $\sim 100$  GeV, are expected to attenuate by  $\gamma\gamma \rightarrow e^\pm$  production in the IR background as well as *in situ*, if they are produced in the internal shocks (see Fig. 1). Observation of photons of a maximum energy before producing  $e^\pm$  pairs, say 10-20 GeV with EGRET, have been used to put a lower limit, in the range 300-600, on the bulk Lorentz factor [14]. However ultra-high energy photons (PeV and above), produced by  $\pi^0$  decay, may escape the internal shocks without producing  $e^\pm$  pairs since the cross-section decreases with energy for a fixed target photon energy [15]. In some cases of very high Lorentz factor ( $\geq 800$ ) the fireball may become completely thin to  $\gamma\gamma$  attenuation. In both partially and completely thin cases ultra-high energy photons escaping from the GRB fireball may produce prompt and delayed emission, after attenuation and cascading in the IR/Microwave backgrounds, observable in the GeV-TeV energy range (see Fig. 2).

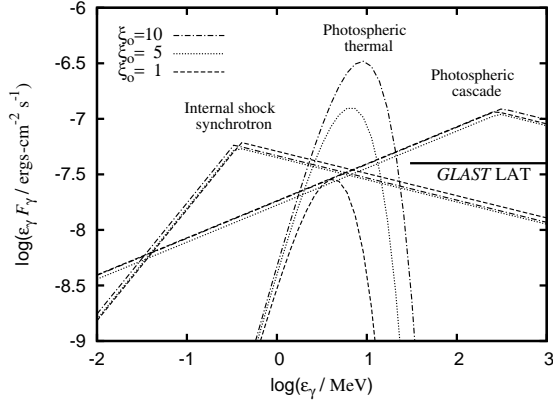


**Figure 1.** Opacities of high energy photons in the GRB fireball for various processes. The  $\gamma\gamma \rightarrow e^\pm$  pair production dominantly attenuate high energy  $\gamma$ -rays in the internal shocks. Photons below the  $e^\pm$  pair production threshold, in the comoving frame, escape freely both below 10-100 GeV and above 10 PeV. For other fixed parameters, the opacity decreases with increasing  $\Gamma$  ( $= 316, 500, 800$  for solid, dotted and dashed curves) and the GRB fireball may become completely thin to photons of all energy at a very high bulk Lorentz factor. (From Ref. [15]).



**Figure 2.** Prompt and delayed photon spectra from a completely thin GRB fireball at  $z = 1$ . The prompt spectrum (solid curve) is directly observable from the burst. The delayed spectra (IC) of 50,  $10^2$ ,  $10^4$  and  $10^6$  s durations are re-processed in the cosmic background photons for intergalactic magnetic field strength of  $10^{-20}$  G (dashed curves) and  $10^{-17}$  G (dotted curves). Sensitivities of GLAST are also plotted with thick gray lines for the same integration times. GRB parameters used are  $L_\gamma = 10^{52}$  ergs/s,  $\Gamma = 800$ . (From Ref. [15]).

A hadronic GeV photon component may also be expected in a baryonic GRB outflow since neutrons are likely to be present by their elastic  $pn$  scattering with protons. If these neutrons decouple from the protons, before any shocks occur,  $pn$  inelastic collisions will lead to pions, including  $\pi^0$ , resulting in tens of GeV photons which cascade down to the GeV range [16]. In case of short GRBs, the direct  $\pi^0$  decay 50 GeV photons may be detectable by future ground arrays and the cascade GeV spectrum should be detectable with GLAST (see Fig. 3) [17].



**Figure 3.** Photon spectra, from a nearby ( $z \approx 0.1$ ) short GRB, of the expected photospheric signals (thermal and IC cascade by pion decay electrons and photons) and the synchrotron spectrum from internal shocks, compared to the *GLAST* LAT sensitivity.  $\xi_o$  is the initial neutron to proton ratio in the GRB fireball. The peaks of the spectra are correlated with the final bulk Lorentz factor of the proton outflow:  $\Gamma_{p,f} = 519, 572$  and  $624$  respectively for  $\xi_o = 1, 5$  and  $10$ . (From Ref. [17]).

The recent detection of delayed X-ray flares during the afterglow phase with *Swift* suggests an inner-engine origin of these flares, at radii inside the deceleration radius characterizing the beginning of the forward shock afterglow emission [18]. Given the observed temporal overlapping between the flares and afterglows, one expects an inverse Compton (IC) emission arising from such flare photons scattered by forward shock afterglow electrons [19]. This IC emission would produce GeV-TeV flares, which may be detected by *GLAST* and ground-based TeV telescopes.

## 5. Acknowledgments

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## 6. References

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