Mem. S.A.It. Suppl. Vol. 14, 26

Memorie della
Supplementi

Emission and ground based observation of high energy photons from GRB

A. Carosi, L.A. Antonelli, and S. Spiro

Istituto Nazionale di Astrofisica – Osservatorio Astronomico di Roma, Via di Frascati 33, I-00040 Monte Porzio Catone, Italy, e-mail: carosi@oa-roma.inaf.it

Abstract. Gamma Ray Bursts (GRBs) are short and intense pulses of soft gamma rays (<MeV) detected for the first time in the late 1960's. Within the theoretical picture of the fireball model, the electron synchrotron radiation is able to justify the observed sub-MeV emission while other processes like Inverse Compton (IC) and neutron pions decay predict a high energy emission component (>20 MeV). Observation in the very high energy range is particularly important because it allows discrimination between the many competing emission models. We investigated the conditions for the emission of photons in the GeV-TeV regime in GRB and the possibility of their detection with the new generation of space based and ground based instruments like the MAGIC telescope.

Key words. gamma-rays: bursts

1. Introduction

During the last 20 years, the knowledge of GRBs has been significantly improved thanks to the observation in different energy ranges performed by instruments such as BATSE, BeppoSAX and SWIFT. The majority of the observed bursts show their phenomenology in the 100 keV - 1 MeV energy range whilst the emission of high energy photons from GRB, predicted by several authors (Gupta & Zhang 2007; Galli & Guetta 2003; Zhang & Meszaros 2000) for both the prompt phase and the afterglow, have not yet been studied, although some hints of an high energy emission component (>10 MeV) were collected by several γ ray detectors. During the 90's, the observation of EGRET in the 20 MeV-30 GeV energy range of a tenth of GRBs in the GeV regime and in particular the detection of a 18 GeV photon 90 minutes after the prompt phase of GRB940217 represent, until today, the most energetic photon observed from a GRB (Hurley et al. 1994). Other hints of high energy emission were obtained with different kinds of instruments such as the EAS array GRAND (GRB971110) or the water Cherenkov MILAGRITO which detected 3σ signal from the sky region of GRB970417a (McEnery et al. 2000). In addition of this weak proof, the scientific research in the GeV-TeV energy range was significantly limited by the lack of adequate instrumentation. The recent beginning of the operation of a new generation of γ detector has opened the possibility of systematic observation in the VHE regime. Space based intruments like LAT on board of Fermi Gamma Ray Observatory have detected in few months of operations

Send offprint requests to: A. Carosi

some GRBs with emission of photons up to 15 GeV (GRB080916c) (Abdo et al. 2009) while in the last 5 years, new Atmospheric Imaging Cherenkov Telescopes (IACT) have started observation in the hundred of GeV energy range.

2. Emission processes

The idea that GRBs dynamics are governed by relativistic collisions between shells of plasma ejected by a central engine is usually accepted. The internal/external shock scenario within the theoretical picture of the fireball model (Piran 1999) provides the most simple justification of the observed photons, the conversion in radiation of the kinetic energy of ultrarelativistic particles. Several non thermal mechanisms are possible sources of high energy photons. Possible processes comprise both leptonic (electron synchrotron, Synchrotron Self Compton-SSC) and hadronic models (proton synchrotron, π^0 decay). The expected fluxes from the various processes are evaluated by several authors (Zhang & Meszaros 2000; Sari & Piran and Narayan 1998). Referring to (Zhang & Meszaros 2000) we used the theoretical spectrum to investigate the conditions for a positive detection with the MAGIC telescope of high energy photons during prompt emission. The evaluated spectra are usually multi segment broken power law and break energies are strongly dependent on the various parameters which are used to describe the fireball.

$$\nu F_\nu \propto \begin{cases} \nu_{\gamma,s}^{\frac{4}{3}} & \nu_{ssa} < \nu_{\gamma,s} < \nu_{\gamma,c} \\ \nu_{\gamma,c}^{\frac{5}{6}} \nu_{\gamma,s}^{\frac{1}{2}} & \nu_{\gamma,c} < \nu_{\gamma,s} < \nu_{\gamma,m} \\ \nu_{\gamma,c}^{\frac{5}{6}} \nu_{\gamma,m}^{\frac{(p-1)}{2}} \nu_{\gamma,s}^{\frac{(2-p)}{2}} & \nu_{\gamma,s} > \nu_{\gamma,m} \end{cases} \quad (1)$$

Eqn(1) shows the expected electron synchtron spectrum under the hypothesis of a power law distribution of electrons: $N(E_e)dE_e \propto E_e^{-p} dE_e$. The break energies are respectively: Self Absorption Energy (ν_{ssa}), the minimum injection energy ($\nu_{\gamma,m}$) and the cooling break energy ($\nu_{\gamma,c}$) which are dependent on parameters like the fireball bulk Lorentz factor (Γ), the isotropic luminosity of the burst (L_{iso}), the total energy equipartition paramenters (ϵ_e, ϵ_B, ϵ_p) and the variability time scale of the GRB (t_ν).

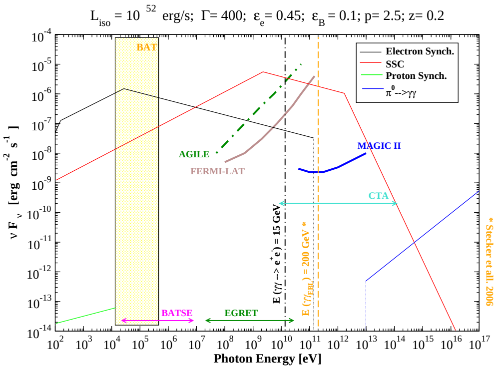

Fig. 1. Plot of the $\nu F\nu$ spectrum from typical prompt GRB. Synchrotron emission (black line), SSC (red line), proton synchrotron (green line) and π^0 decay (blue line) component are evaluated for $\Gamma = 400$, $\epsilon_e = 0.45$, $\epsilon_B = 0.1$ and $L_{iso}=10^{52}$ erg/s. Cut off energies for internal pair production (black vertical line) and for EBL absorption (orange vertical line) (Stecker at al. 2006) are also plotted. Sensitivities of AGILE, LAT (Galli & Guetta 2003) and MAGIC II are for an integration time of 60s.

Using the synchrotron spectrum as the source of seed photons it is possible to compute the resulting Inverse Compton (IC) emission.

$$\nu F_\nu \propto \begin{cases} \nu_{\gamma,i}^{\frac{4}{3}} & \nu_{ssa,i} < \nu_{\gamma,i} < \nu_{\gamma,c,i} \\ \nu_{\gamma,c,i}^{\frac{5}{6}} \nu_{\gamma,i}^{\frac{1}{2}} & \nu_{\gamma,c,i} < \nu_{\gamma,i} < \nu_{\gamma,m,i} \\ \nu_{\gamma,c,i}^{\frac{5}{6}} \nu_{\gamma,m,i}^{\frac{p-1}{2}} \nu_{\gamma,i}^{\frac{2-p}{2}} & \nu_{\gamma,m,i} < \nu_{\gamma,i} < \nu_{\gamma,k} \\ \nu_{\gamma,c,i}^{\frac{5}{6}} \nu_{\gamma,m,i}^{\frac{p-1}{2}} \nu_{\gamma,k}^{\frac{p-2}{2}} \nu_{\gamma,i}^{\frac{1}{2}-p} & \nu_{\gamma,i} > \nu_{\gamma,k} \end{cases}$$

IC scattering amplifies the energy of photons by a factor γ_e^2, so if synchrotron radiation is the dominant process in the sub-MeV range, SSC photons can reach the GeV-TeV domain. The shape of the spectrum is very similar to the previous one. SSC component can be approximated by a multi segment broken power law with new break in the photon spectrum which appears ($\nu_{\gamma,k}$) when the Klein Nishina effect becomes important (Fragile et al. 2004). We consider the equipartition parameters and the Γ factor as free parameters, whereas other quantities such as p, t_ν and T_{90} are for a typical long GRB (p=2.5; t_ν=0.01s; T_{90}=20s). We preliminarily investigate the situation of a standard GRB with $\Gamma = 400$ (Molinari et al. 2007),

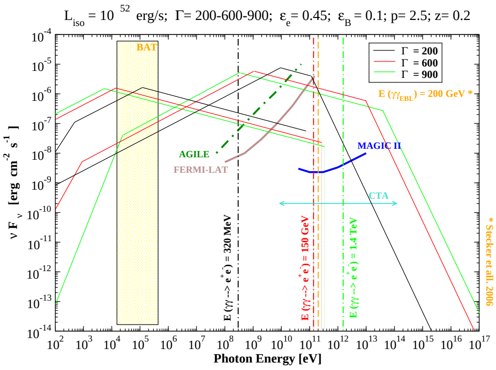

Fig. 2. Expected spectrum for different Lorentz factor. The black, red and green line corresponds respectively to Γ=200, 600, 900. Since hadronic components are usually irrilevant we only plot synchrotron and SSC emission.

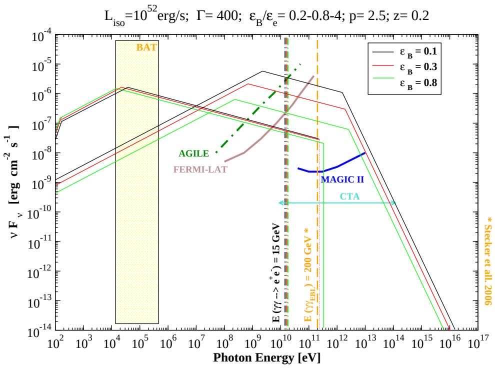

Fig. 3. Expected specrtum for different ϵ_B.

L$_{iso}$ = 10^{52} erg/s and the usually used option of 0.45 for ϵ_e and ϵ_p and 0.1 for ϵ_B. We also fixed the redshift of the source to z=0.2. The expected spectrum is shown in Fig. 1. It is evident that leptonic emission components are dominant processes with respect to the hadronic ones (they become comparable for $\frac{\epsilon_e}{\epsilon_p} \sim \frac{m_e}{m_p} \sim 10^{-3}$). The selected parameters reproduce the typical observed spectrum of GRB with a peak in the synchrotron component in the tenth of keV energy range. At higher energies, the IC component is the dominant emission mechanism up to TeV energy range where Klein-Nishina cutoff is expected. The MAGIC's observation capability is strictly limited by internal pair production which is expected to produce a cutoff at $E_{\gamma\gamma}$=15 GeV. In fig. 2 we investigate the effect of different choices of bulk Lorentz factor. The plot illustrates as larger values of Γshift the cutoff energy to higher energies and the peak energy of electron synchrotron radiation and SSC to lower ones. It is possible to conclude that high energy photons (>100-200GeV) can leave the fireball only if $\Gamma \gtrsim 500$ which implies $E_{\gamma,peak} < 10$ keV. Emission in the very high energy regime, therefore, is not very significant for typical GRB with $E_{\gamma,peak}$ in the BAT energy range but could be important in X-Ray Flashes (XRF) events. The relative importance of the two leptonic mechanisms which we consider is strictly linked to the fireball magnetic field which is parametrized through the value of ϵ_B. In Fig. 3 the synchtron and IC emission components are plotted for different values of ϵ_B. From the plot it is evident that observation with ground based and space based detector could discriminate between the different emission models while the future Cherenkov Telescope Array (CTA) will be able to perform analysis in a wider energy range with a sensitivity one order of magnitude greater than present IACTs.

3. The MAGIC telescope

The study of GRBs is a difficult task for Cherenkov telescopes. Due to the typical large distance (from z=0.01 up to z=8.1), the absorption of γ rays by Extragalactic Background Light (EBL) can make this kind of observation very hard. The MAGIC telescopes, with a diameter of 17m and total surface of 239m^2 are presently the largest mirrors in the world for astronomical use and they are the best IACT for the study of GRBs. Thanks to their light structure, the telescopes can slew to any position in the sky in less than 80 sec. On the other hand, the big reflecting surface allows MAGIC to reach a trigger threshold of about 50 GeV (at zenith). The performance of the telescope was proved by the observation of the most distant object emitting gamma rays above 50 GeV, the Blazar 3c 279 at z = 0.536 (Albert et al. 2008). Moreover, from mid 2008, a new electronic trigger was made available which further reduces the energy threshold to 25 GeV. The recent transition (spring 2009) to stereoscopic observation with the beginning of the operation of a second telescope will improve the sensitivity by a factor of 3 and allow MAGIC telescopes to reach sources up to a redshift value of aproximatively z = 1. MAGIC is able to react to GRB trigger by a dedicated automatic alert system connected to the GCN[1] which has been active since July 2004. The information from the GCN is managed by the MAGIC GRB alert program which validates the alert and sends the necessary instructions to the telescope central control system.

4. GRB observation with MAGIC

From January 2005, about 500 acceptable alerts were received from GCN. After the application of observability criteria, approximately one GRB per month has been observed. Data analysis is performed with Magic standard Analysis and Reconstruction Software (MARS) (Bretz et al. 2005) which is based on standard Hillas parameters (Hillas 1985) analysis. The first steps needed to reconstruct the event are directly done on site in La Palma, where calibration, cleaning and parametrization of the image are performed. γ/hadron separation is then performed with the Random Forest (RF) method. This is a multidimensional classification method that combines several parameters describing the shape of the image into a new parameter called hadronness correlated to the probability of an event to be of hadronic or γ origin which can be used for background suppression. The distribution of the alpha parameter, is subsequently used to select the γ signal and to evaluate its significance since hadronic showers produce flat alpha distribution with respect to electromagnetic ones which are expected to peak at $0°$ if the telescope points to a point-like source. Up to now, no significant excess was seen in any of the observed bursts and upper limits (UL) were evaluated (Albert et al. 2007).

[1] Gamma ray bursts Coordinates Network

5. Conclusions

Inside the fireball, several non thermal emission processes are able to give high energy photons (>MeV) . For a standard burst the emission is dominated by electron synchrotron radiation while SSC becomes important at higher energy. Hadronic emission component is generally negligible. The possible detection of a signal for prompt emission by ground based instruments is strictly connected to the opacity of the fireball to high energy photons. For a GRB with Γ >500 the MAGIC telescopes are able to detect high energy emission component from SSC. MAGIC is the best Imaging Atmospheric Cherenkov Telescope for the study of GRB. The capabilities of the instrument were recently proved and allow the observation of high energy photons both during the prompt phase and the early afterglow for a source up to z$\sim$1. Multiwavelength observations with space based instruments will play a key role in discriminating between different emission models and provide constraints to the physical parameters which describe the fireball. At the present time, there is no evidence of VHE emission above 80-100 GeV. As roughly one third of the observed bursts lie at an acceptable distance, it is a basic and fundamental need to collect large statistics for GRBs.

References

Abdo A.A. et al. (Fermi Collaboration), 2009 Science 10.1126/science.1169101
Albert J. et al. 2007 ApJ **667**, 358A
Albert, J. et al. 2008 Science **320**, 1752
Bretz, T. et al., 29th ICRC 2005, **4**, 315
Fragile et al., 2004 Astropart. Phys. **20**, 591
Galli, A., Guetta, D., 2003 A&A **480**, 5G
Gupta N., Zhang B., 2007 MNRAS **380**, 78
Hillas A.M., 19th ICRC 1985, **3**, 445
Hurley, K. et al. 1994 Nature **372**, 652
McEnery, J. et al. 2000 AIPC **526**, 240M
Molinari et al., 2007 A&A **469**, L13
Piran, T., 1999 PhR **314**, 575P
Sari, Piran, Narayan, 1998 ApJ **497L**, 17S
Stecker F. W. et al. 2006 ApJ **648**, 774
Zhang, B., Meszaros, P. ApJ **559**, 110