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Gamma ray bursts at high energies: detection ranges and event rates

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Abstract The Gamma-Ray Burst (GRB) detection rates at energies $\geq 20GeV$, have been estimated for the 3 atmospheric Cerenkov telescope systems of the GRACE project at Mt.Abu, under the assumption that the bursts have a cosmological origin and a continuous power-law spectrum in the MeV-TeV energy range. The attenuation of high energy gamma-ray photons in a burst, during its propagation in the intergalactic space, has been taken into account by assuming two extreme scenarios of the Extragalactic Background Radiation (EBR) fields.

Key words: Gamma ray bursts, High energy tails, Detection range , Event rate

1. Introduction

Cosmic Gamma-ray bursts, which represent short time-scale outbursts of non-solar gamma radiation with individual photon energies between ~ 10 keV and 10 MeV and with durations between $10^{-2}s - 10^{3}s$, have been detected at a rate of ~1 day^{-1} by the BATSE (Burst and Transient Source Experiment) on the Compton Gamma Ray Observatory (CGRO) satellite (Meegan et al, 1996). The observed lack of a significant anisotropy in the angular distribution of these events and a clear deficiency of weaker bursts (spatial inhomogeneity) has been interpreted as implying either an extended galactic halo or a cosmological origin for the GRB (Meegan et al, 1996, Balazs et al, 1998). Several independent routes are currently being followed for seeking guidance to choose between the galactic halo and cosmological origin models. The most successful experimental attempt in this direction so far, involves near-contemporaneous searches for x-ray and optical afterglows from the burst directions which has proved that the GRB sources (or at least most of them) are cosmological objects with energy outputs of the order of $\sim 10^{51} - 10^{54}$ ergs per event (Akerlof et al, 1999).

Although most of the GRB emit the bulk of their energy at $\sim$ 100 keV, a few ($\sim$ 5) events (strongest BATSE events at 300 keV) have also been detected by the EGRET experiment on the CGRO above 1 GeV (Hurley, 1996), implying that all the bursts could have a high energy component below the presently available detection sensitivities. The observed spectra are consistent with a power law upto the maximum energy observed, with no indication of a high energy cut-off. In fact, several recent burst models predict that some GRB's may contain photons of upto $\sim$ 10 TeV energy (Meszaros and Rees, 1993; Katz, 1994). A positive detection of GeV-TeV emission in a GRB is likely to provide new insights about the burst mechanism and also constrain the distance limits on the likely sources by invoking photon-photon pair-production interactions in the intergalactic space. A number of searches have been made for the detection of VHE gamma-ray tails in GRB's, using the gound-based atmospheric Cerenkov technique (Vrba, 1995 and references therein). However, the need to contunue with the observation of GRB's for a possible VHE tail is apparent, as such a detection would naturally impose severe constaints on the conditions in and near GRB sources. The present study is mainly about estimating the detection ranges and the expected GRB event rates for the three GRACE experiments, namely, MACE ($E_\gamma \geq 20GeV$) TACTIC ($E_\gamma \geq 0.5TeV$)and MYSTIQUE ($E_\gamma \geq 20TeV$), which are being set up by our group at Mt. Abu.

2.The GRACE Facility at Mt. Abu

The Bhabha Atomic Research Centre is setting up 3 gamma-ray telescope systems, under the project GRACE, at Mt.Abu (72°.43 E ; 24.36° N ; 1700 m asl), Rajasthan, to observe cosmic gamma-ray sources over almost the entire gamma-ray energy band (100's of keV - 100's of TeV). Brief descriptions of the three systems are given below:

2.1 MACE

This experiment (Major Atmospheric Cerenkov Experiment) essentially comprises a 17 m diameter parabolic light collector, equipped with a high-resolution Cerenkov light imaging camera (Kaul et al, 1999). The threshold energy of MACE is estimated to be $\sim$ 20 GeV for primary gamma-rays and $\sim$ 85 GeV for cosmic ray protons. The minimum detectable gamma-ray flux (MDF), for a 5σ detection has been estimated to be 5×10^{-8} photons $cm^{-2}s^{-1}$ for a GRB of 10 s duration. The MDF decreases by a factor of $\sim$ 3 for every order of magnitude increase in the burst duration and is estimated to be $\sim 1.3 \times 10^{-9}$ photons $cm^{-2}s^{-1}$ for a GRB of $10^4 s$ duration.

2.2 TACTIC

The 4-element TACTIC array comprises $4\times9.5m^2$ area, alt-azimuth mounted, tracking reflectors, deployed at the centre and vertices of an equilateral triangle of side $\sim$ 20 m (Bhat et al, 1997). The central element is equipped with a 349-pixel Cerenkov imaging camera (pixel resolution $\sim 0.3°$) while the three vertex elements carry a special duplex-detector focal plane instrumentation (Sapru et al, 2001 for details). The MDF for the detection of a GRB of 10s duration at 5σ level is estimated as 7.2×10^{-9} photons $cm^{-2}s^{-1}$. For a 10^4s duration GRB, the MDF decreases to 3.3×10^{-11} photons $cm^{-2}s^{-1}$.

2.3 MYSTIQUE

This is an array of 256 wide-angle Cerenkov detector cells, each cell comprising 3×20 cm diameter photomultiplier tubes, designed to have a gamma-ray threshold detection energy of $\sim$ 10 TeV. The intercell separation is 40 m. Background cosmic ray proton rejection is achieved through its intrinsic angular resolution of 0.2° as well as extrinsic data cuts based on time and polarization characteristics of the detected Cerenkov events. The MDF for the detection of a GRB of 10s duration at 5σ level is estimated to be 1.4×10^{-9} photons $cm^{-2}s^{-1}$, which decreases by a factor of $\sim$ 10 for every order of magnitude increase in the burst duration.

3.Expected GRB integral fluxes:

Here we estimate the integral gamma-ray fluxes expected for the three experiments, in presence of intergalactic absorption, from a typical GRB whose spectrum is assumed to extend unchanged from the MeV to the GeV-TeV band. The unattenuated differential flux of the GRB, represented by

$$\frac{dN}{dE} = k_\Gamma E^{-\Gamma} cm^{-2} s^{-1} MeV^{-1} \tag{1}$$

has been estimated in the three energy domains ($E_\gamma \geq 20GeV - 5TeV; 0.5TeV - 10TeV; 20TeV - 50TeV$), corresponding to the sensitive energy bands of the three experiments respectively. Using two values of the spectral index ($\Gamma = 2.0$ and $\Gamma = 2.4$), the value of k_Γ has been evaluated from

$$k_\Gamma = \frac{L_{\gamma E}}{4\pi {d_L}^2 \int_{E_1}^{E_2} E^{1-\Gamma} dE} \tag{2}$$

where

$$L_{\gamma E} = L_{\gamma B} \frac{\int_{E_1}^{E_2} E^{1-\Gamma} dE}{\int_{50keV}^{5MeV} E^{1-\Gamma} dE} \tag{3}$$

Here $L_{\gamma B} = \frac{E_0}{T}$ is the GRB luminosity in the BATSE energy range ($E_\gamma = 50keV - 5MeV$), E_0 is the total burst energy in ergs and T is the burst duration in seconds. E_1 and E_2 represent the lower and upper bounds of the sensitive energy domain of the experiment under consideration and d_L is the luminosity distance of the GRB source, given by

$d_L = 8000[(1+Z_s) - (1+Z_s)^{0.5}]$ Mpc for a flat universe ($\Omega = 1$)and Hubble constant $H_O = 75 kms^{-1} Mpc^{-1}$

The integral flux expected for a particular experimental system (sensitive energy range E_1 to E_2), in the presence of attenuation due to photon pair production interactions with the Extragalactic Background Radiation (EBR) field, is given by

GRB detection rates for the MACE, TACTIC and MYSTIQUE systems, for different spectral exponents and time durations and the two EBR spectra (case 'a' and 'b')

SPECTRAL EXPONENT	BURST DURATION	MACE EVENT RATE PER YEAR		TACTIC EVENT RATE PER YEAR		MYSTIQUE EVENT RATE PER YEAR	
Γ	T(s)	a	b	a	b	a	b
2.0	10	40	50	2	23	0.05	14
2.0	100	37	45	2	23	0.05	14
2.0	1000	32	38	1.6	21	0.05	14
2.0	10000	25	28	1.4	17	0.05	13
2.4	10	16	18	0.35	2.5	0.015	0.7
2.4	100	9	13	0.3	2.2	0.015	0.7
2.4	1000	5	6	2.5	1.5	0.015	0.7
2.4	10000	2	2.5	1.5	0.75	0.015	0.6

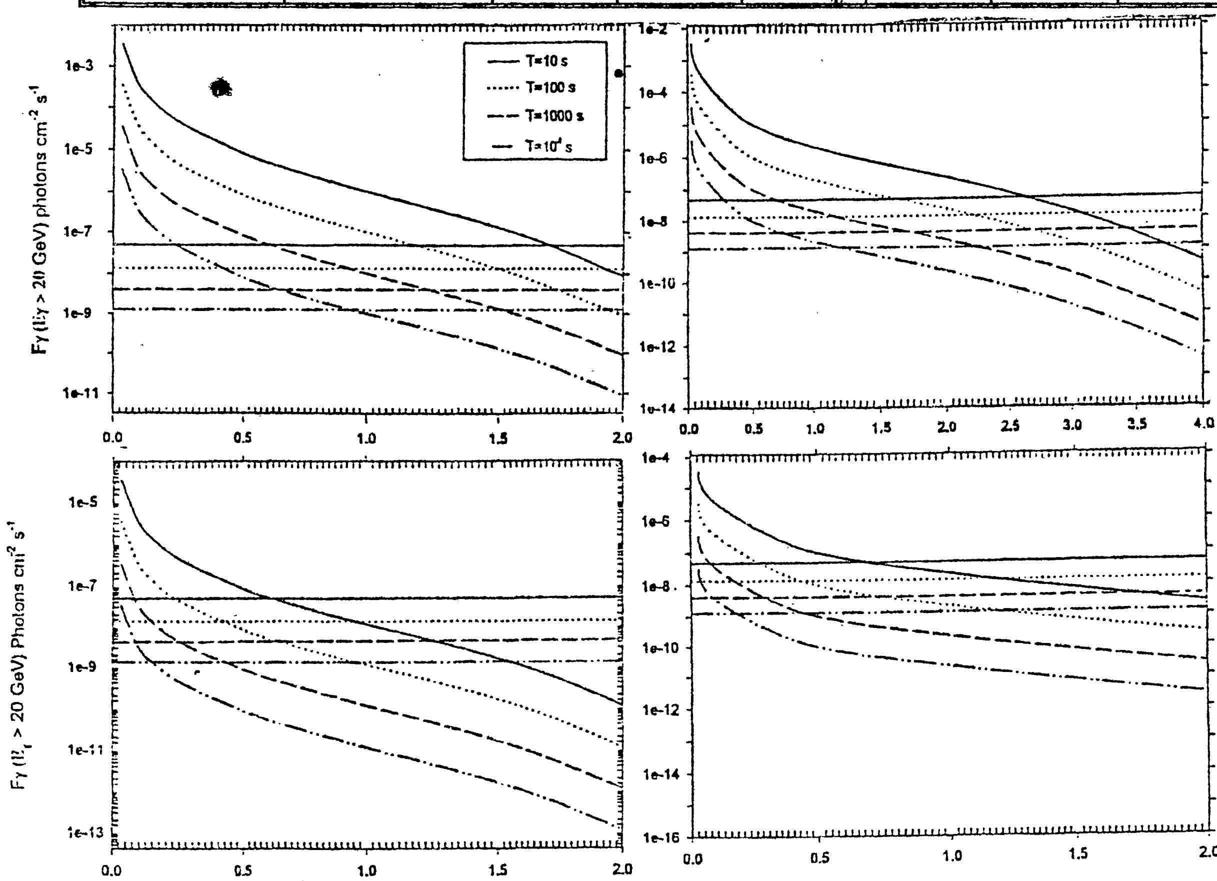

Fig.1 . Estimated integral gamma-ray fluxes at (Eγ ≥ 20 GeV) as a function of burster redshift for case a (left) and case b (right) of EBR spectrum. The four curves in each diagram correspond to four representative values of burst duration T(10,100, 10^3 and 10^4 s). The MDF for MACE is shown as the full straight line. The top panel in each case refers to Γ =2 and the bottom panel to Γ = 2.4.

$$F_\gamma(> E_1) = \int_{E_1}^{E_2} \frac{dN}{dE} e^{-\tau(E_\gamma, Z_s)} dE \quad photons \quad cm^{-2} s^{-1} \tag{4}$$

where $\tau(E\gamma, Z_s)$ is the optical depth for $\gamma + \gamma \rightarrow e^+ + e^-$ interaction, and is given by

$$\tau(E_\gamma, Z_s) = \frac{c}{2H_0} \int_0^{Z_s} dz (1+z)^{\frac{1}{2}} \int_0^2 x dx \int_{\frac{2m^2c^4}{E_0 x (1+z)^2}}^{\infty} n(\epsilon) \sigma(\epsilon, x, E_\gamma, Z) d\epsilon \tag{5}$$

The cross-section for this interaction $\sigma(\epsilon, x, E_\gamma, Z_s)$ is given by

$$\sigma(\epsilon, x, E_\gamma, z) = 1.25 \times 10^{-25} (1-\beta^2)[2\beta(\beta^2-2) + (3-\beta^4) ln(\frac{1+\beta}{1-\beta})] cm^2 \tag{6}$$

where

$$\beta(\epsilon, x, E_\gamma, z) = [1 - \frac{2m^2c^4}{E_\gamma \in (1+z)^2}]^{-0.5} \tag{7}$$

Equation (4) has been numerically integrated to obtain integral fluxes as a function of source red-shift Zs . Two extreme cases of the EBR spectrum n($\in$) have been considered over the wavelength region $\lambda = 10^{-1} - 10^3 \mu m$ (12.43 - 1.2$\times 10^{-3} eV$), one (case a) corresponding to the observed spectrum (likely to be contaminated by detector noise) and the other (case b) corresponding to the lowest theoretical estimate. The detailed structure of the EBR spectrum is given in Kaul et al (1999). Fig 1 shows the variation of the expected integral flux $F_\gamma(\geq E)$ in the sensitive energy range of the MACE system ($E_1 = 20GeV$) as a function of the burster red-shift for case a and b of the EBR spectrum (Figs. 1a and 1b, respectively).The four curves in each diagram correspond to four representative values of burst duration T $(10, 100, 10^3$ and $10^4 s)$. The straight lines in Fig.1 represent the MDF levels of the MACE system for bursts with these durations. Clearly, the intersection of the integral flux curve for a given T value with its corresponding MDF line gives the detection range (in z) of this system for GRB of duration T s. Using Fig.1 and similar curves obtained for the TACTIC and MYSTIQUE systems, we have estimated the effective detection ranges of the three experimental systems for bursts with duration T s and for the two assumed values of Γ and the two background EBR spectra. The number of detectable bursts per year at a given threshold energy E_γ for a volume burst rate n_o is given by (Mannheim et al, 1996),

$$N(\geq E_\gamma) = 16_0 (\frac{c}{H_0})^3 [\frac{1}{6} + \frac{1}{2(1+Z_s)^2} \frac{2}{3} \frac{1}{(1+Z_s)^3/2}] \tag{8}$$

Equation (8) is applicable in case of a flat universe ($\Omega = 1$) and cosmological constant $\Lambda = 0$, while Z s represents the limiting red-shift upto which brusters can be seen by the system. The volume brust rate n_o is given by,

$$n_0 = 2.9 \times 10^{-9} \text{ Mpc}^{-3} \text{ yr}^{-1} \tag{9}$$

for $H_0 = 75$ kms^{-1} Mpc^{-1} which is consistent with the BATSE delection rate of ~ 300 yr^{-1} for a trigger efficiency of ~ 0.3 and limiting redshift of $Z_s = 2.0$. Using equations (5) and (8) and Z s values calculated from Fig.1(and similar curves for TACTIC and MYSTIQUE), we have calculated the expected burst detection rates $N(> E\gamma)$ for the three systems, separately for the different values of Γ, T and the two EBR spectra. Table I gives a summary of the results.

4. Results and Conclusions

The GRB detection rates for MACE ($E_\gamma \geq 20$ GeV) vary in the range $2 - 50$ yr^{-1}, while in the case of TACTIC the range is $1.5 - 23$ yr^{-1}. The detection rate is $0.014 - 14$ yr^{-1} for the MYSTIQUE experiment. The lower values in the respective detection rates correspond to T= $10^4 s, \Gamma = 2.4$ and the case 'a' of the EBR spectrum. These event rates have been obtained after taking due account of the restricted zenith angle coverage ($\leq 50°$).

References

Akerlof, C. et al, 1999, *Astro-ph,* **990,** 3271
Balazs, L. G. et al, 1998, *AA,* preprint
Bhat, C. L. et al, 1997, *Proc. Perspectives in the High Energy Astronomy Astrophysics, TIFR, India*
Hurley, K. 1996, *Sp.Sci.Rev,* **75,** 43
Katz, J. 1994, *APJ,* **432,** L107
Kaul, C. L. et al, 1999, *Exp.Astron.,8, 187*
Mannheim, K. et al, 1996 *ApJ* **467**, 532
Meegan, C. A. et al, 1996, *ApJS,* **106**, 65
Meszaros, P. and Rees, M, 1996, *ApJ,* **418**, L59
Sapru, M. L. et al, 2002, *This proceedings*
Vrba, F.J. 1995, *3rd Huntsville Symp. on Gamma Ray Bursts, AIP Conf. Proc.* **384,** 565