IL NUOVO CIMENTO VOL. 20 C, N. 2 Marzo-Aprile 1997

Search for gamma-ray bursts in the GeV energy range at Mt. Chacaltaya (5200 m)

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(ricevuto il 3 Luglio 1996; approvato il 23 Settembre 1996)

Summary. — Observations of gamma-ray bursts in the 1 GeV–1 TeV energy region are of great interest for the understanding of these mysterious events. The detection of GeV-TeV gamma-ray bursts is feasible using extensive air shower arrays monitoring the fluctuations of the single-particle counting rate. The sensitivity is strongly increased working at mountain altitudes, in particular above 5000 m. In this paper we discuss the possibility to exploit the existing BASJE EAS array operating at Mt. Chacaltaya (Bolivia) at 5200 m a.s.l. Simulations of electromagnetic showers in the atmosphere have been performed in order to evaluate the sensitivity of this experiment to detect gamma ray bursts of different time duration, spectrum slope and energy cut-off. The detector can observe events of energy fluence $F(E>1\text{ GeV})\sim$ few 10^{-5} erg cm^{-2}, comparable to that measured by satellite instruments during the most intense gamma-ray bursts, provided they occurr at low zenith angles and assuming that the energy spectrum at least extends up to ~ 1 TeV. In the case of events below the sensitivity of the experiment, upper limits on the high-energy tail of the spectrum can be obtained by measurements in coincidence with satellite observations.

PACS 96.40 – Cosmic rays.

1. – Introduction

The origin of gamma-ray bursts (GRBs), inadvertently discovered more than 20 years ago by the military satellites Vela [1], is still an unsolved problem in spite of the large amount of data collected up to now by several satellite detectors operating in the keV-MeV energy region; in particular, the Burst and Transient Source Experiment (BATSE), onboard the Compton Gamma-Ray Observatory (GRO) launched in 1991, with a detection rate of about one burst per day, already collected a dataset of more than 1500 events [2].

Gamma-ray bursts counterparts have been searched for at all wavelenghts, with no success. The only positive observations outside the keV-MeV energy range have been reported by EGRET (the Energetic Gamma-Ray Experiment Telescope aboard the GRO) that detected photons up to a few GeV during the occurrence of 3 very intense events: GRB910503 [3], GRB930131 [4] and GRB940217 [5]. In particular, a delayed high-energy emission (including a photon of 18 GeV) lasting about one hour, was observed after GRB940217. This atypical temporal behaviour shows how the burst phenomena can still be more complex and tangled at high energy, suggesting that the observation in the GeV energy range could give information of great interest for the understanding of these events.

The study of the GRB spectrum at high energy could as well provide strong constraints to the source distances. Gamma rays travelling in the intergalactic space interact with the low-energy photon of the Cosmic Microwave Background and the infrared radiation field, through photon-photon pair production. In particular, 1 GeV–1 TeV photons are absorbed by the infrared radiation, whose magnitude cannot be directly measured. According to recent evaluations of the opacity of the Universe to gamma rays, based on reasonable models of the low-energy photon background [6], the optical depth τ for a gamma ray of 20 GeV is ~ 1 for a distance corresponding to a redshift $z \sim 1.5$; more energetic photons are absorbed in smaller distances: for a 100 GeV photon $\tau \sim 1$ at $z \sim 0.5$. Hence, the observation of a GRB at ~ 100 GeV could exclude a cosmological origin of these events.

The small sensitive area of EGRET can account for the exiguous number of bursts observed in the GeV region. Hence the possibility that high-energy gamma rays are present in all bursts, but are not detectable with the sensitivity of the present experiments, cannot be discounted.

Due to the low fluxes at higher energies, requiring larger and larger detection areas, the observations above a few tens of GeVs cannot be performed by satellite instruments but are feasible only by ground-based detectors measuring the secondary particles generated by the primary photons in the atmosphere.

Extensive air showers (EAS) arrays are largely used in gamma astronomy in the energy range $E > 10$ TeV. At these energies, showers with a large number of particles reach the detector level hitting several detector modules in temporal coincidence. The primary photon energy is evaluated by the number of detected secondary particles and its arrival direction is reconstructed by measuring the time of flight between different modules. Several searches for gamma-ray bursts have been performed by EAS arrays studing time and direction distributions of showers. Upper limits have been reported by different groups (recent results are given in ref. [7-9]).

The same technique cannot be used below 1 TeV because of the small number of secondaries reaching the detector level. At these energies, using the EAS arrays, one can detect a GRB as a significant excess in the single-particle counting rate; obviously the primary arrival directions are not measured.

The sensitivity largely increases by operating at high mountain altitude, being most of the secondary particles reabsorbed before reaching the sea level. As an example, the mean number of charged particles n_c reaching the level of 5000 m a.s.l. from a shower generated by a vertical photon of 50 GeV is ~ 9, while at 2000 m $n_c \sim 0.3$, and at the sea level $n_c \sim 0.03$.

The background is mostly due to secondary particles from cosmic rays with energy just above the geomagnetic cutoff. In this energy range the primary cosmic-ray intensity is modulated by both the solar activity and the 24-hour anisotropy, while the secondary flux is affected by changes in the atmospheric pressure. However, the time scales of these modulations are much larger than the typical time duration of a gamma-ray burst and do not affect the GRB search. This method has been exploited by the EAS array at Plateau Rosa at 3500 m a.s.l. [10] and presently by the EAS-TOP array at Gran Sasso at 2000 m a.s.l. [7, 8, 11].

2. – **Sensitivity of** BASJE

We discuss the possibility to apply the same technique to the air shower array BASJE (Bolivian Air Shower Joint Experiment) located at Mt. Chacaltaya at 5200 m of altitude, corresponding to an atmospheric depth of 538 g cm^{-2} (lat. -16.32, long. 291.85 E, geomagnetic cut-off for a vertical particle $= 13.1$ GV).

The apparatus consists of 16 scintillator modules distributed over a $60 \times 60\ \mathrm{m}^2$ area (fig. 1). Each detector, made up of 4 plastic scintillators ($50 \times 50 \times 5\ \mathrm{cm}^3$ each) for a total sensitive area of 1 m^2, operates with an energy threshold of 10 MeV.

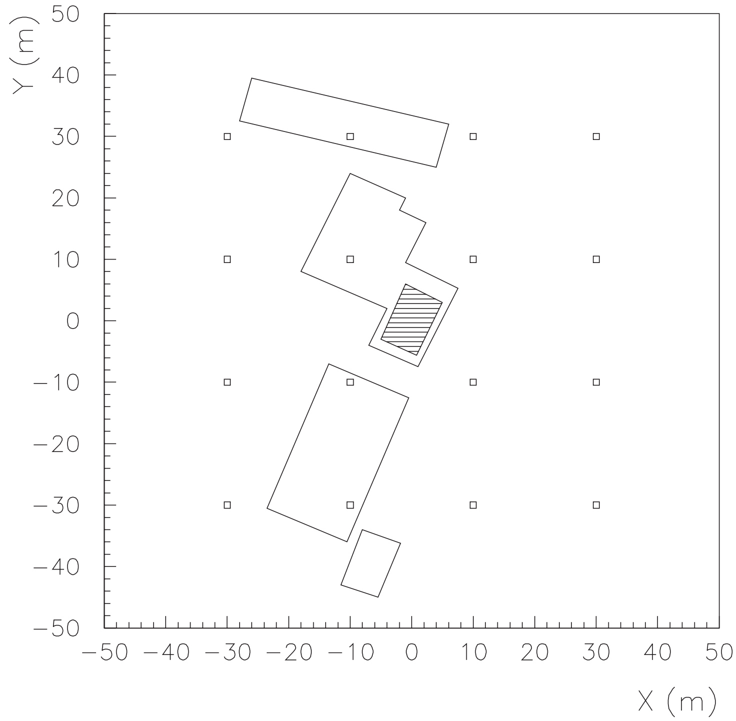

Fig. 1. – Schematic view of the Chacaltaya laboratory and the BASJE air shower array. The 16 squares represent the scintillator modules.

The search will be performed studying the fluctuations of the sum of the single-particle counting rate of the modules during the occurrence of gamma-ray bursts detected by satellites. In order to have a good time resolution, we will record the counting rate every second. Moreover, to be able to reject possible electronic noises localized in some counters, we intend to record the counting rate of each module by 16 independent channels.

In the following the sensitivity of BASJE to detect a gamma-ray burst is evaluated as a function of various burst parameters. Assuming a GRB with a time duration Δt and a differential energy spectrum $\mathrm{d}I/\mathrm{d}E = KE^{-\alpha}$ ph cm^{-2} s^{-1} GeV^{-1} extending from $E =$ 1 GeV up to a cutoff energy $E_{\max}$, we compare the number of «signal» events N_s, *i.e.* the number of single counts in the detector due to the burst, with the background fluctuations. The number of events from the burst is given by

$$N_s = K\,\Delta t \int_{1\ \mathrm{GeV}}^{E_{\max}} A_{\mathrm{eff}}(E)\,E^{-\alpha}\,\mathrm{d}E\,, \tag{1}$$

where $A_{\mathrm{eff}}(E)$ is the effective area of the detector for a primary photon of energy E.

The mean measured background single-particle counting rate is $B = 560$ counts m^{-2} s^{-1}. At 5200 m a.s.l the electron and muon contributions to the background are almost equivalent.

Requiring a significance of n standard deviations for the signal, the burst can be observed if $N_s > n\sqrt{16 B\,\Delta t}$. In the following calculation we set $n = 4$. This condition determines the minimum value of K for a detectable burst, given the time duration Δt, the spectral slope α and the energy cut-off $E_{\max}$.

The evaluation of the effective area A_{eff} is done as follows. Given a shower generated by a vertical primary photon of energy E whose axis falls at a distance r from a module, the probability to see a signal in it is

$$P(r) = \sum_{N_e = 0}^{\infty} f(N_e)(1 - \exp[-N_d])\,, \tag{2}$$

where $f(N_e)$ is the normalized multiplicity distribution of charged particles with energy larger than the detection threshold at the level of observation produced by a primary photon of energy E, and N_d is the mean number of particles falling upon the module

$$N_d(r, N_e) = N_e\,\varrho(r)\,A_d\,, \tag{3}$$

A_d being the module area and $\varrho(r)$ the normalized density function of the particles (we can neglect the variation of the electron density over the area of the detector).

The term $(1 - \exp[-N_d])$ represents the probability to have one or more particles in the module (we remind that due to the electronic time resolution, if two or more particles of the same shower hit the same counter, the number of detected signals is only one).

Integrating $P(r)$ over the whole plane, one obtains the effective sensitive area of one module to a primary photon of energy E and zenith angle $\theta = 0°$

$$A^1_{\mathrm{eff}}(E, 0) = 2\pi \int_0^{\infty} P(r)\, r\,\mathrm{d}r\,. \tag{4}$$

If the number of electrons reaching the level of observation is small and the area of the detector is much smaller than the typical size of a shower, the mean number of particles hitting the same counter $N_d(r, N_e)$ is always $\ll 1$, hence $1 - \exp[-N_d] \approx N_d$ and

$$A^1_{\text{eff}}(E, 0) \approx A_d \overline{N}_e(E, 0), \tag{5}$$

where $\overline{N}_e(E, 0) = \sum_{N_e=0}^{\infty} N_e\, f(N_e)$ is the mean number of charged particles produced by a vertical photon of energy E reaching the level of observation.

This expression can be intuitively understood observing that if the typical distance between particles at the observation level is larger than the dimension of the detector, each particle can be counted separately as one event.

Obviously, for a generic zenith angle θ

$$A^1_{\text{eff}}(E, \theta) \approx A_d \cos\theta\, \overline{N}_e(E, \theta). \tag{6}$$

Since the 16 modules will work in single coincidence mode (*i.e.* if two or more particles of the same shower hit two different modules we count two events) one can evaluate the total effective area as $A_{\text{eff}} = 16 \times A^1_{\text{eff}}$.

The multiplicity distribution $f(N_e)$ of charged particles at the Chacaltaya altitude produced by photons in the 1 GeV–1 TeV energy range is obtained by simulating the

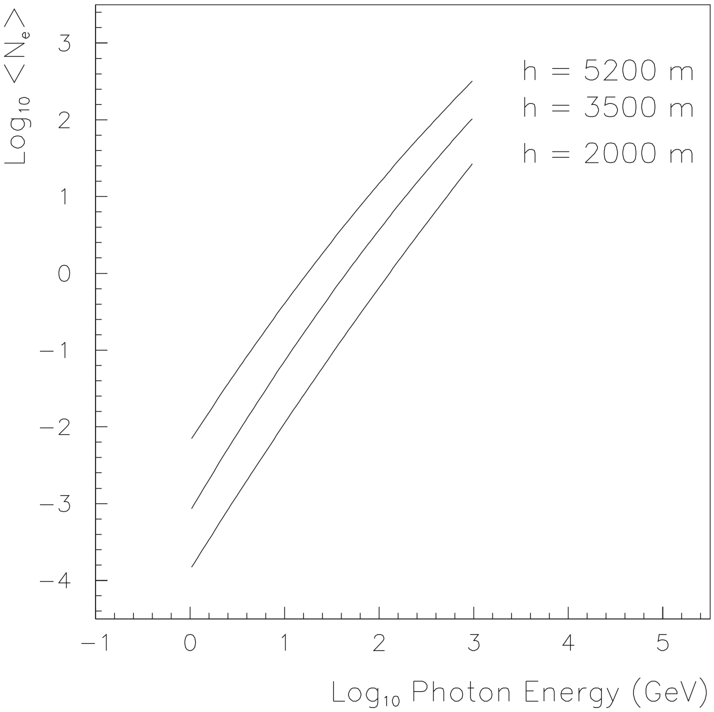

Fig. 2. – The mean number of charged particles with energy $E_e > 10$ MeV reaching the levels of 2000 m, 3500 m and 5200 m, generated by a primary photon in the atmosphere, as a function of the photon energy.

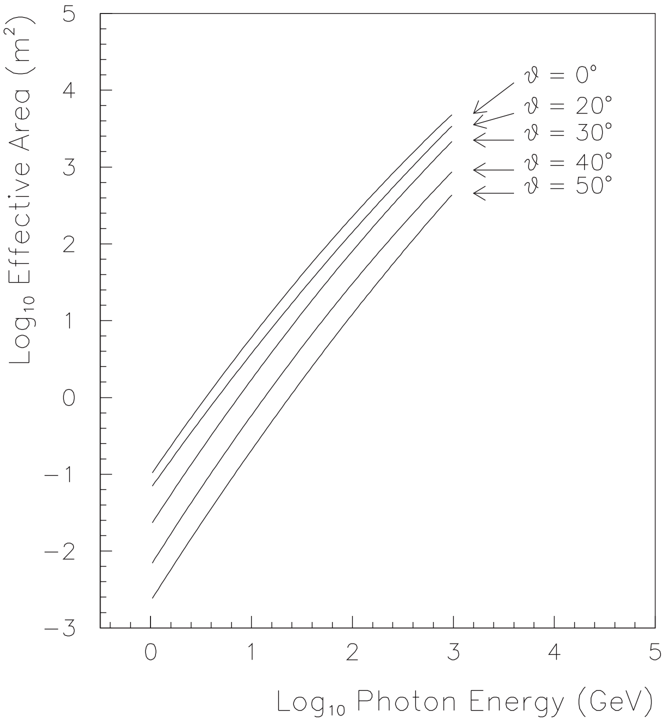

Fig. 3. – The effective area of the BASJE array to detect primary photons with different zenith angles θ, as a function of the photon energy.

cascade developement in the atmosphere, using the CORSIKA code. Figure 2 shows the mean number $\overline{N}_e$ of electrons and positrons with energy above 10 MeV reaching the detector level, as a function of the primary gamma energy, for zenith angle $\theta = 0°$. For a comparison, the corresponding values at the altitudes 2000 m and 3500 m a.s.l. are given in the same figure.

In our conditions, given the small area of the scintillators and as the mean number of particles reaching the detector level is relatively small in all the considered energy range, the effective area A_{eff} could be calculated using the approximated expression (5), with an error less than 10%. The results of the simulations show that the percentage of particles «lost» because of their hitting a counter in coincidence with other particles of the same shower is $\sim 5\%$ for energy < 100 GeV, increasing to 10% at $E \sim 1$ TeV. The effective areas A_{eff} corrected on the basis of these results are given in fig. 3, for different zenith angles θ.

A_{eff} is quite reduced for $\theta > 40°$. For a primary energy of 100 GeV, the ratio $A_{\text{eff}}(E, \theta)/A_{\text{eff}}(E, 0)$ is 0.35 at $\theta = 30°$ and 0.053 at $\theta = 50°$.

To give an idea of the energy of photons that contribute to the events in the detector, one can observe that the effective area A_{eff} is roughly $\propto E^{1.5}$, and consequently the number of events is $\propto E^{-\alpha + 1.5}$. It follows that if one takes for examples a GRB with a spectrum slope $\alpha = 1.5$, the contribution is uniform in the range 1 GeV–$E_{\max}$, while for a spectrum slope $\alpha = 2.5$ the contribution is equal for each energy decade.

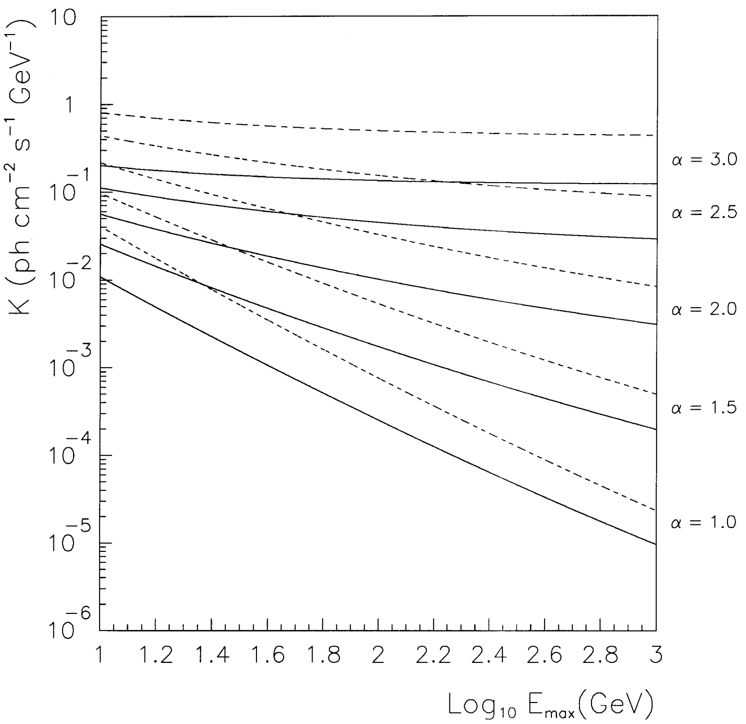

Fig. 4. – The minimum value of K for a detectable burst of time duration $\Delta t = 1$ s as a function of the energy cutoff E_{max}. K is the coefficient of the assumed burst spectrum $\mathrm{d}I/\mathrm{d}E = KE^{-\alpha}$ ph$\cdot$ $\cdot$cm^{-2} s^{-1} GeV^{-1} valid in the energy range 1 GeV $< E < E_{\mathrm{max}}$. K is given for 5 different values of the spectrum slope α and for two zenith angles $\theta = 0°$ (full line) and $\theta = 30°$ (dashed line).

Figure 4 shows the obtained minimum values of the spectrum coefficient K for a detectable burst of time duration $\Delta t = 1$ s as a function of the maximum energy of the spectrum E_{max}. The curves are calculated for five different slopes of the spectrum and zenith angles $\theta = 0°$ and $\theta = 30°$. The values of K for a generic time duration Δt can be obtained by dividing the given values by a factor $\sqrt{\Delta t}$.

The sensitivity strongly increases with the cutoff energy E_{max} if the spectrum is very «hard» ($\alpha \leqslant 1.5$); for a typical GRB spectrum slope $\alpha = 2$ the sensitivity increases by a factor ~ 6 if E_{max} goes from 10 to 100 GeV and by a factor ~ 20 if $E_{\mathrm{max}} = 1$ TeV; the sensitivity is almost indipendent of the cutoff energy in the case of «soft» spectra ($\alpha = 3$).

Figure 5 shows the minimum energy fluences in the range 1 GeV–E_{max} for a detectable gamma-ray burst of time duration $\Delta t = 1$ s as a function of E_{max}. The curves are calculated for different slopes of the spectrum and zenith angles $\theta = 0°$ and $\theta = 30°$. The fluence for a generic time duration Δt can be obtained by multiplying the given values by a factor $\sqrt{\Delta t}$.

Considering that during the occurrences of GRB930131 [4] and GRB940217 [5] EGRET measured a fluence of a few 10^{-5} erg cm^{-2} s^{-1} above 30 MeV, these results shows that the Chacaltaya detector can be sensitive to particularly intense

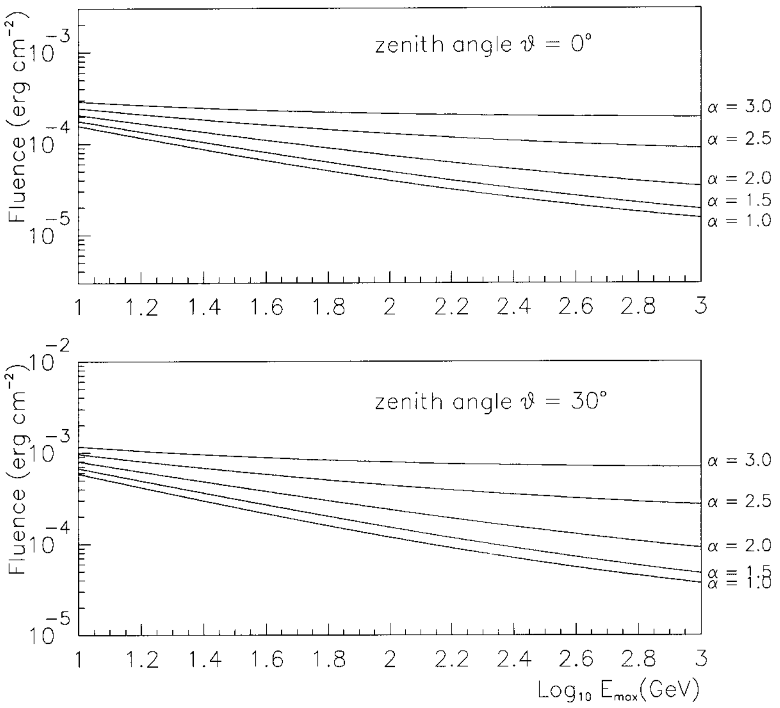

Fig. 5. – The minimum value F of the energy fluence in the range 1 GeV $< E < E_{\max}$, for a detectable burst of time duration $\Delta t = 1$ s. The burst spectrum is assumed to be a power law one extending in the energy range 1 GeV $< E < E_{\max}$. F is given for 5 different values of the spectrum slope α and for the zenith angles $\theta = 0°$ and $\theta = 30°$.

events occurring at small zenith angles and with an energy spectrum extending up to ~1 TeV.

As an example, let us consider GRB930131; during the 1 s peak EGRET measured a flux $\mathrm{d}I/\mathrm{d}E = 1.9E_{(\mathrm{MeV})}^{-1.97}$ ph cm^{-2} s^{-1} MeV^{-1}; the highest photon energy measured is 1.2 GeV and no visible energy cutoff was observed in the spectrum.

Assuming a spectrum extending with the same slope at least up to 750 GeV, the event—if occurring at a sky position near the zenith—would be observable by BASJE as an excess of $\geqslant 3$ standard deviations.

3. – Conclusions

Extensive air showers arrays can detect gamma-ray bursts in the 1 GeV–1 TeV energy range measuring the fluctuations in the single-particle counting rate.

Experiments operating at very high mountain altitudes are strongly favoured. The sensitivity of a generic detector to a primary gamma ray of energy E is proportional to the ratio between the effective area $A_{\mathrm{eff}}(E)$ and the background fluctuations $\sqrt{B}$. Being the effective area proportional—in this energy range—to the mean number of charged particles reaching the array level, one can infer the dependence of A_{eff} on the altitude from the curves of fig. 2. As an example, A_{eff} at 10 GeV increases by a factor ~7 going from 2000 m to 3500 m and by a factor ~ 40 going to 5200 m; this «gain» factor decreases a little as the primary energy increases.

The increase of the background rate with the altitude slightly lowers this gain. Going from 2000 m to 5200 m the single-particle counting rate increases by a factor ~ 3 (this value can change by $\sim 10\%$ depending on the geomagnetic latitude [12]), hence the sensitivity would decrease only by a factor ~ 1.7.

In conclusion, air shower arrays even with relatively small sensitive areas located at very high altitudes (and preferably at low geomagnetic latitudes), can compete with more extensive arrays located at larger atmospheric depths.

On the basis of these considerations, we plan to use the BASJE EAS array operating at Mt. Chacaltaya at 5200 m a.s.l. to measure gamma-ray bursts in the GeV energy range. Its geographic location allows the monitoring of a considerable part of the southern celestial hemisphere.

If the GRBs spectrum extends up to ~ 1 TeV with the same power law behaviour exhibited at lower energy, BASJE can detect signals from the most intense events, when they occurr at low zenith angles. Even in the case of events below the BASJE sensitivity, upper limits on the maximum photon energy can be obtained, if the intensity and the spectrum slope are measured at lower energy by satellite instruments.

A positive observation would be of great importance for the understanding of the nature of GRBs. According to recent evaluations of the opacity of the Universe to high-energy gamma rays, caused by the interactions off the intergalactic infrared radiation field, the detection of a burst at energies $E > 100$ GeV would constrain the source distances at redshifts $z < 0.5$, excluding the idea of a cosmological origin of gamma-ray bursts.

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This paper is dedicated to Prof. G. T. Zatsepin on the occasion of his 80th birthday, remembering his great contribution to cosmic ray physics.

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