Detection of gamma-ray bursts in the 1 GeV–1 TeV energy range by ground-based experiments

Silvia Vernetto [a]

[a] *Istituto di Cosmogeofisica del C.N.R., Corso Fiume 4, 10133 Torino, Italy*

Abstract

Ground-based extensive air shower arrays can observe Gamma Ray Bursts in the 1 GeV–1 TeV energy range using the ''single particle'' technique. The sensitivity to detect a GRB as a function of the burst parameters and the detector characteristics are discussed. The rate of possible observations is evaluated, making reasonable assumptions on the high energy emission, the absorption of gamma-rays in the intergalactic space, the distribution of the sources in the universe and the bursts luminosity function. We show that a large area detector located at high mountain altitude has good prospects for positive detections, providing useful information on the high energy component of GRBs. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

Thirty years after their discovery Gamma-Ray Bursts (GRBs) still remain one of the most intriguing mysteries of the universe. The successful observations of BATSE aboard the Compton Gamma Ray Observatory and the exciting detections in X, optical and radio bands during the last two years put an end to the discussions about their distance, proving that the sources of GRBs (or at least most of them) are cosmological objects. Supposing an isotropic emission, the measured distances imply an amount of radiated energy as large as $\sim 10^{51}$–10^{54} erg, setting GRBs among the most powerful astrophysical phenomena in the universe. According to most theoretical models, gamma-rays can be produced by the synchrotron radiation of charged particles accelerated in the shock wave of a fireball, the relativistic explosion due to a still unknown catastrophic event, presumably the formation of a black hole through a coalescence of a compact binary system or a ''hypernova'' [1].

GRBs have been well studied in the KeV–MeV energy range, where they show a spectrum with a power law tail, in agreement with synchrotron models. The extension of measurements in the GeV–TeV range would be of major importance, since it could impose strong constraints on the physical conditions of the emitting region. Theoretical predictions of the high energy emission in relativistic fireball models are given in Refs. [2–4]. Unfortunately the gamma-

---

E-mail address: vernetto@lngs.infn.it (S. Vernetto).

rays absorption in the intergalactic space by interaction with starlight photons prevents the study of GRBs above ~ 1 TeV.

So far, only 7 GRBs have been observed at energy $E > 30$ MeV by EGRET on the Compton Gamma Ray Observatory, and in 3 of them photons of energy $E > 1$ GeV have been detected [5]. The observed spectra are consistent with a power law behaviour with no high energy cutoff up to the maximum energy observable by the instrument. It is important to note that these 7 GRBs are as well the most intense events observed by BATSE at energy $E > 300$ KeV; taking into account the small field of view of the EGRET detector ($\Omega \sim 0.6$ sr) and its limited sensitivity, the small number of high energy detections does not contradict the idea that all GRBs could have a high energy component.

Less constrained in size than space-born detectors, ground-based experiments can explore the energy region above ~ 10 GeV, measuring the secondary particles generated by gamma-rays interactions in the atmosphere ($e^{\pm}$ or Cherenkov photons) that reach the ground. Cherenkov telescopes detect the Cherenkov light emitted by $e^{\pm}$ in the high atmosphere. Although several successful observations of steady gamma-ray sources at energies of a few hundreds GeVs have been performed with Cherenkov measurements, the small fields of view of telescopes (few squared degrees) and the limited live time (constrained by weather and darkness conditions to be of the order of 10%) make the Cherenkov technique not suitable for observations of transient and unforeseeable events as GRBs (the probability for a GRB to happen by chance in the field of view of a telescope is less than 10^{-4}). However, while observations of the burst onset are highly improbable, delayed observations are feasible and they could be of great interest [6] (recall the delayed high energy emission observed by EGRET more than one hour after the famous event GRB940217 [7]).

Air shower arrays detect the charged particles (mostly $e^{\pm}$) of the showers reaching the ground; they have a much larger field of view (about π sr) and a live time of almost 100%. In the next section we will discuss the possibility to detect GeV–TeV photons from GRBs using air shower arrays, in particular using the "single particle" technique. In Section 3 the expected rate of positive observations will be evaluated, making reasonable assumptions on the luminosity and distance distribution of GRBs.

2. The "single particle" technique

The simplest way to observe the high energy component of GRBs with a ground-based experiment is using an air shower array working in "single particle" mode. Air shower arrays, made of several counters spread over large areas, usually detect air showers generated by cosmic rays of energy $E > 10$–100 TeV; the arrival direction of the primary particle is measured by comparing the arrival time of the shower front in different counters, and the primary energy is evaluated by the number of secondary particles detected. Air shower arrays can be used in the energy region $E < 1$ TeV working in single particle mode, i.e. counting all the particles hitting the individual detectors, independently on whether they belong to a large shower or they are the lonely survivors of small showers. Because of the cosmic ray spectrum steepness, most of the events detected in this mode of operation are in fact due to solitary particles from small showers generated by 10–100 GeV cosmic rays.

Working in single particle mode, an air shower array could in principle detect a GRB in the energy range 1–10^{3} GeV, if the secondary particles generated by the gamma-rays give a statistical significant excess of events over the all-sky background due to cosmic rays. The beauty of this technique consists in its extreme simplicity: it is sufficient to count all the particles hitting the detectors during fixed time intervals (i.e., every second, or more frequently depending on the desired time resolution) and to study the counting rate behaviour versus time, searching for significant increases; the observation of an excess in coincidence with a GRB seen by satellites would be an unambiguous signature of the nature of the signal.

The single particle technique does not allow the measurement of the energy and the direction of the primary gamma-rays, because the number of particles (often only one per shower) is too small to reconstruct the shower parameters. However, it can allow the study of the temporal behaviour of the high energy emission, and, with some assumptions on the spectral slope (possibly supported by satellite mea-

surement at lower energy) it can give an evaluation of the total power emitted at high energy.

Fig. 1 shows the mean number n_e of electrons and positrons reaching the ground at different altitudes h above the sea level generated by a gamma-ray, as a function of the gamma-ray energy, according to the Greisen analytical expression [8]. The curves are given for two different zenith angles of the primary gamma-ray, $\theta = 0°$ and $\theta = 30°$. The number of particles strongly increases with the altitude, in particular at low energies, and decreases at high zenith angles, in particular at low altitude. Actually, due to the gamma-rays photoproduction, a small number of muons is produced as well; however, in the energy range $E = 1 - 10^3$ GeV, the number of muons is negligible compared with the number of electrons and positrons (except for $h < 1$ km, where they are comparable) and they will not be considered in the following discussion.

A possible way to increase the number of detectable particles is to exploit the air shower photons, that are much more numerous than $e^\pm$. Fig. 2 shows the ratio $r_s = n_{ph}/n_e$ of the mean number of photons and the mean number of $e^\pm$, as a function of the altitude. The values have been obtained simulating electromagnetic cascades induced by gamma-rays with a zenith angle $\theta = 30°$. The detector is as-

Fig. 2. Ratio of the number of photons and the number of $e^\pm$ reaching the ground, as a function of the altitude. The points are given for different gamma-ray energies: 10 GeV (circles), 100 GeV (squares), 1 TeV (triangles). The photon energy threshold is 3 MeV.

sumed with an energy threshold $E_{th} = 3$ MeV. The ratio r_s range from ~ 6 to ~ 11 depending on the altitude and on the primary gamma-ray energy. The conversion of a fraction of photons in charged particles (by pair production or Compton effect) would increase the detectable signal. Placing a suitable layer of lead over the detector, a small fraction of $e^\pm$ would be absorbed, but a large number of photons would interact and increase the GRB signal, by a factor depending on the converter geometrical characteristics. An interesting possibility to avoid the absorption of $e^\pm$ is to adopt a thick scintillator detector: it would work both as a target for photons and as a detector for charged particles [9].

2.1. The background

The background is due to secondary charged particles from cosmic rays air showers. The rate depends on the altitude h and, to a lesser extent, on the geomagnetic latitude λ of the observer. The latitude effect is almost negligible at sea level and increases with the altitude: at $h = 5$ km a.s.l. the background at $\lambda > 45°$ is about 1.6 times larger then near the magnetic equator [10].
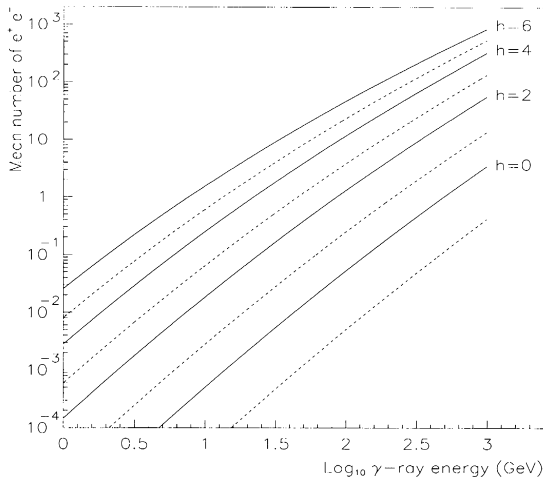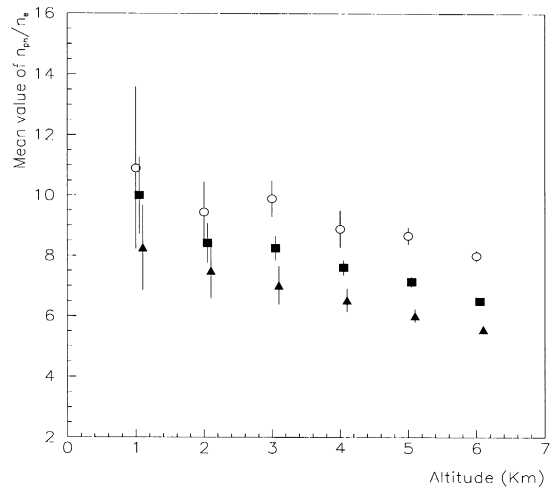

Fig. 1. Mean number of charged particles reaching different altitudes h above the sea level (in km), generated in the atmosphere by a photon of zenith angle $\theta = 0°$ (full line) and $\theta = 30°$ (dashed line), as a function of the photon energy.

The dependence of the background on the altitude is more important. Fig. 3 shows the flux of $e^{\pm}$, $\mu^{\pm}$ and charged hadrons as a function of the altitude above the sea level, for an observer located near the geomagnetic equator, obtained simulating with the CORSIKA code the atmospheric cascades generated by protons and Helium nuclei with an energy spectrum according to [11] and using a dipole model for the geomagnetic field. The detector energy threshold is $E_{th} = 3$ MeV. The total background rate ranges from ~ 250 to 2000 events m^{-2} s^{-1} increasing the altitude from 0 to 5000 m. The rates obtained by the simulations are in good agreement with the counting rates measured at 2000 m [12] and 4300 m [13]. Most of the background is due to muons for $0 < h < 3.5$ km and to $e^{\pm}$ at higher altitude (note that a detector able to separate the electron and the muon components would allow the reduction of the background by the rejection of muons).

It is worth noting that the number of $e^{\pm}$ generated by a primary gamma-ray (see Fig. 1) increases much more rapidly with the altitude than the background does. This is due to two factors: (1) given a primary energy, the electromagnetic shower generated by a proton penetrates more deeply in the atmosphere than the gamma-ray shower does, (2) the $\mu^{\pm}$ flux, that strongly contributes to the background

rate, is less dependent on the altitude than the $e^{\pm}$ flux.

The possible conversion of secondary photons in detectable particles (introduced in the previous section as a method to increase the GRB signal) would produce an increase in the background as well. Fig. 3 also shows the number of photons reaching the ground due to cosmic rays. However, the ratio r_b of the number of photons and the number of charged particles is considerably smaller than the corresponding value r_s for primary gamma-rays ($r_b < 3$ at any altitude, while $r_s \sim 6$–11, as shown in Fig. 2).

The background rate is not strictly constant and several mechanisms are responsible for variations on different time scales with amplitudes up to a few percent. First of all, variations in the atmospheric pressure affect the secondary particle flux: an increase (decrease) of the ground level atmospheric pressure results in a reduction (enhancement) of the background rate, because of the larger (smaller) absorption of the electromagnetic component. The pressure and the background rate are linearly anti-correlated (e.g., the correlation coefficient between the counting rate percent increase and the pressure variation measured at 2000 m a.s.l. is $\sim -0.5\%$ per millibar [14]). By monitoring the pressure at the detector position it is possible to correct the data for this effect.

The 24 hours anisotropy (due to the rotation of the Earth in the interplanetary magnetic field), and the solar activity (e.g. large solar flares) modulate the low energy primary cosmic ray flux. Although the amplitudes of these variations are not negligible (up to a few percent of the counting rate in some cases) the time scales of these phenomena (hours) are too long to simulate short duration events as GRBs.

Shorter variations in the single particle counting rate have been measured in coincidence with strong thunderstorms and have been ascribed to the effects of atmospheric electric fields on the secondary particles flux [14,15]; however, the occurrences of these events are very rare and also in this case the observed time scales (~ 10–15 minutes) are longer than the typical GRB duration.

From the experimental point of view, more troublesome are possible instrumental effects, such as electrical noises, that could simulate a GRB signal
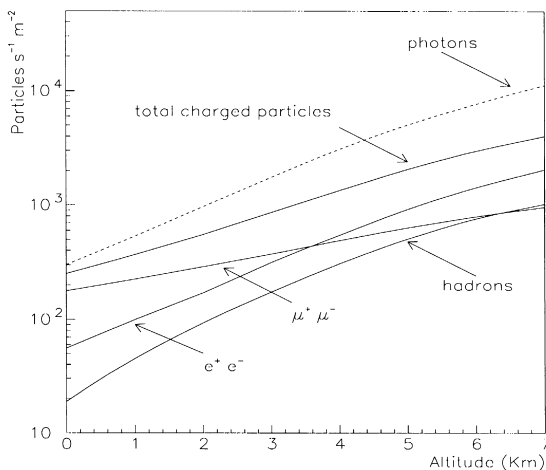

Fig. 3. Background rate due to secondary charged particles as a function of the altitude. The kinetic energy threshold used in the simulation is 3 MeV for electrons and photons and 50 MeV for muons and hadrons.

producing spurious increases in the background rate. Working in single particle mode require very stable detectors, and a very careful and continuous monitoring of the experimental conditions. By comparing the counting rate of the single detectors (i.e. the scintillator counters, in the case of an air shower array) and requiring simultaneous and consistent variations of the rate in all of them, it is possible to identify and reject the noise events due to instrumental effects.

3. Sensitivity to detect high energy GRBs

The aim of this section is to quantify the actual possibilities of observing high energy GRBs using the single particle technique. First, we present a simple model of high energy emission, in order to define a GRB using a limited set of parameters. Subsequently, the response of the detector is evaluated as a function of the burst parameters and detector features. We conclude with an estimation of the possible rate of positive observations.

3.1. Parametrization of the high energy emission

In this simple model a GRB is assumed to release a total amount of energy L in photons of energy $E > 1$ GeV; the emission spectrum is assumed constant during the emission time Δt_e and represented by $dN/dE = KE^{-\alpha}$ (number of photons emitted per unit energy) up to a cutoff energy E_{max}. The value of E_{max} depends on the emission processes and the physical conditions at the source; a sharp cutoff at E_{max} is probably unrealistic, but for our purposes such a simple model is sufficient. The total energy L and the spectrum are related by $L = K \int_{1\,GeV}^{E_{max}} E^{-\alpha + 1}\, dE$.

If the GRB source is located at a cosmological distance corresponding to a redshift z, the observed burst duration is $\Delta t = \Delta t_e (z + 1)$ due to time dilation, and the shape of the observed spectrum is determined by two factors: (a) the photons energies are redshifted by a factor $(z + 1)$ due to the expansion of the universe (the spectrum slope α does not change); (b) the high energy gamma-rays are absorbed in the intergalactic space through $\gamma + \gamma \rightarrow e^+ e^-$ pair production with starlight photons; the probability of reaching the Earth for a photon emit-

ted by a source with a redshift z is $e^{-\tau(E,z)}$, where τ increases with E and z. The absorption becomes important when $\tau > 1$; according to [16], τ reaches the value of unity at $z \sim 0.5$ for $E = 100$ GeV, and at $z \sim 2$ for $E = 20$ GeV. Fig. 4 shows a spectrum with a slope $\alpha = 2$ affected by the absorption, for different z, obtained according to [16] up to 500 GeV (at higher energy the curves are extrapolated).

As a consequence, the flux of photons at Earth is a power law spectrum with the same slope of the emission spectrum up to a certain energy depending on the distance, followed by a gradual steepening, with a sharp end at the energy $E'_{max} = E_{max}/(z + 1)$. Assuming an isotropic emission, the number of photons per unit area and unit energy at the top of the atmosphere is

$$\frac{d\Phi_\gamma}{dE} = \frac{K}{4\pi r^2} \left[E(z + 1) \right]^{-\alpha} (z + 1) e^{-\tau(E,z)}, \quad (1)$$

r is the cosmological comoving coordinate [17]

$$r = c \frac{z q_0 + (q_0 - 1)\left(-1 + \sqrt{2 q_0 z + 1}\right)}{H_0 q_0^2 (1 + z)}, \quad (2)$$

H_0 is the Hubble constant and q_0 the deceleration parameter (we will use $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$, i.e. flat universe with $\Omega = 1$).

In this simple parametrization, L, z, α and E_{max} determine the energy fluence of gamma-rays above 1 GeV at Earth, $F = \int_{1\,GeV}^{E'_{max}} (d\Phi_\gamma/dE) E\, dE$. The possi-
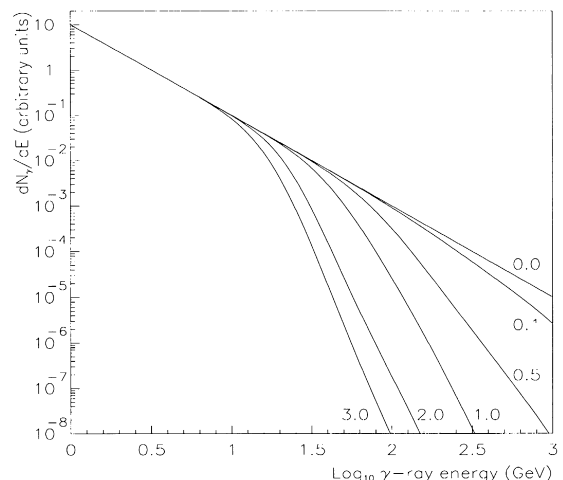

Fig. 4. A power law gamma-ray spectrum with a slope $\alpha = 2$ affected by $\gamma + \gamma \rightarrow e^+ e^-$ pair production, for different redshifts of the source.

ble range of variability of these parameters can be reasonably deduced by lower energy measurements:

z: up to now, the distance of GRBs host galaxies has been measured for 6 events and the observed redshifts are respectively 0.8, 3.4, 1.0, 1.1, 1.6, 1.6 [18–23] (a further one, GRB980425, probably associated with a Supernova explosion at $z = 0.0085$ seems a peculiar and non standard event [24]); basing on these data, we will take z in the interval 0-4;

α: most of the events observed by BATSE show power law spectra at energies $E > 100$ KeV–1 MeV, with exponent $1.5 < \alpha < 2.5$ [25]; since the few GRBs detected by EGRET at energies $E > 30$ MeV also show a similar behaviour [5], one can expect a higher energy component with the same spectral slope observed in the MeV-GeV energy region;

L: assuming an isotropic emission, the energies released by these 6 bursts range between $\sim 5 \cdot 10^{51}$ and $\sim 2 \cdot 10^{54}$ ergs in the BATSE energy range $E > 20$ KeV; it is not unreasonable to assume the energy L emitted above 1 GeV being of the same order of magnitude (recall that a spectrum with a exponent $\alpha = 2$ means equal amount of energy release per decade of energy);

$E_{\max}$:   the value of the maximum energy of gamma-rays depends on unknown physical conditions and in fact is one of the quantity that we hope to measure with this technique; we will consider $E_{\max}$ as a parameter ranging in the interval 30 GeV–1 TeV.

3.2. The GRB signal

In this section we evaluate the response of a detector to a GRB, as a function of the burst parameters and the detector characteristics. A detector can be simply defined by the area A_d and the altitude h above the sea level. Note that the detector sensitivity does not depend on its geometrical features, as the

area of the single counters or their relative positions, but only on the total sensitive area (e.g., for an air shower array A_d is the sum of the single counters areas). The latitude of the detector geographic location will not be considered due to its small effect on the background rate.

Given a GRB, defined by the parameters L, z, Δt_e, α and $E_{\max}$ previously discussed, and with an arrival direction corresponding to a zenith angle θ, the flux of secondary particles (number of particles per unit area) reaching the altitude h above the sea level induced by the gamma-rays of energy $E > 1$ GeV is

$$\Phi_{e^\pm} = \int_{1\,GeV}^{E'_{\max}} \frac{d\Phi_\gamma}{dE} \, n_e(E,\theta,h) \, dE, \qquad (3)$$

where $n_e(E,\theta,h)$ is the mean number of particles reaching the altitude h generated by a gamma-ray of energy E and zenith angle θ.

As an example, Fig. 5 shows the particles flux as a function of the altitude, produced by a vertical GRB with $L = 10^{53}$ erg, for different distances. The spectrum is assumed with a slope $\alpha = 2$ and $E_{\max} =$
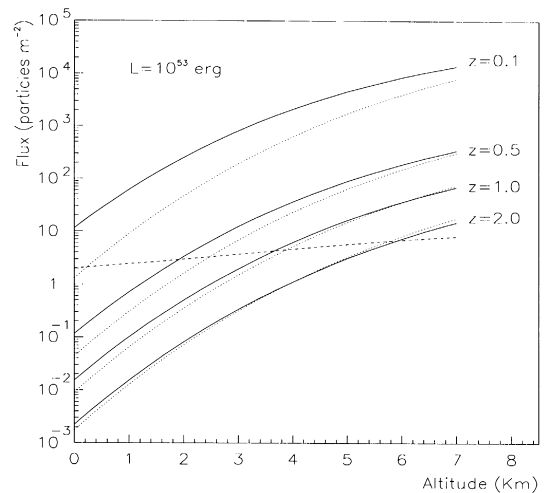

Fig. 5. Ground level secondary particles flux produced by a vertical GRB with $L = 10^{53}$ erg, located at different distances z, as a function of the altitude. The GRB spectrum is assumed with a slope $\alpha = 2$ and $E_{\max} = 1$ TeV (solid line) and $E_{\max} = 30$ GeV (dotted line). As an example of a detector sensitivity, the dashed line represents the minimum ground level flux observable by a detector of area $A_d = 1000$ m, from a GRB with $\Delta t = 1$ s and zenith angle $\theta = 0°$.

30 GeV and 1 TeV. The flux strongly increases with the altitude; at 5000 m it is about 3 orders of magnitude higher than at sea level. For distances less than $z \sim 1$, the flux increases with $E_{\max}$, while at higher distances, due to the absorption of the most energetic gamma-rays, the flux is almost independent on $E_{\max}$. The ground level flux decreases at higher zenith angles, in particular at lower altitude (see Fig. 1); as an example at $h = 4000$ m the flux at $\theta = 30°$ is ~ 3 times lower than the vertical flux, while at $\theta = 50°$ the flux is reduced by almost 2 orders of magnitude.

The number of particles giving a signal in the detector[1] is $N_s = A_d \cos\theta \Phi_{e\pm}$. The signal must be compared to the noise $\sigma_b = \sqrt{A_d B(h) \Delta t}$, given by the background fluctuations during the time $\Delta t = \Delta t_e (z + 1)$, where $B(h)$ is background rate (number of events per unit area and unit time). A GRB is detectable with a statistical significance of n standard deviations if $N_s / \sigma_b > n$. The minimum value of n necessary to consider an excess as a significant signal depends on the search strategy. In the case of a search in coincidence with satellites, since the frequency of GRBs occurring in the field of view of a ground-based detector is about one event every few days, a level of 4 standard deviations is sufficient to give a high reliability to the observation. In the following discussion we set $n = 4$. A detector of a given area A_d and altitude h is therefore sensitive to GRBs with a ground level particle flux

$$\Phi_{e\pm} > \frac{n}{\cos\theta} \sqrt{\frac{B(h)\Delta t}{A_d}} \ . \qquad (4)$$

As an example, in Fig. 5 the minimum detectable ground level flux as a function of the altitude is

---

[1] This is true assuming that all the particles hitting a detector give a signal; actually in a standard air shower array, two or more particles of the same shower hitting the same counter give only one signal, due to the limited time resolution; however, working in the < 1 TeV energy range n_e is so small that the fraction of showers giving two or more particle in the same counter is negligible.
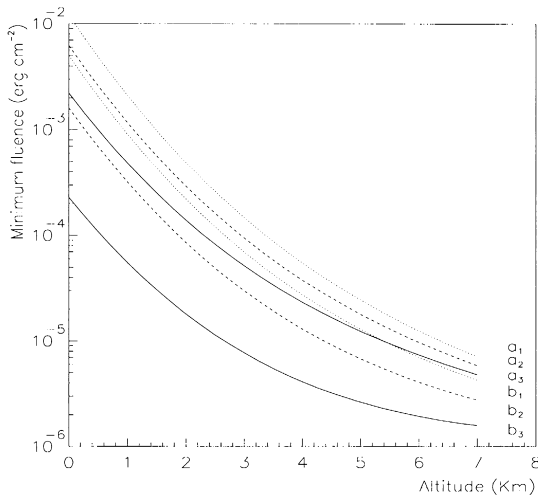
shown for a detector of area $A_d = 10^3$ m^2 and a GRB with a time duration $\Delta t = 1$ s and zenith angle $\theta = 0°$. The minimum flux ranges from ~ 2 to ~ 6 particles m^2 for altitudes from the sea level to 5000 m.

Conversely, if one aims to be sensitive to a certain ground level flux $\Phi_{e\pm}$, the requirement for the minimum detector area is

$$A_d > \frac{n^2 B(h) \Delta t}{\Phi_{e\pm}^2 \cos^2\theta} \ . \qquad (5)$$

To give an estimate of the magnitude of the largest fluxes that one can reasonably expect, we have extrapolated the power law fits of 15 GRBs spectra obtained by the TASC instrument of EGRET [5] up to a maximum energy E_{cut}, and we have calculated the secondary particle flux at the ground level using Eq. (3) (setting $E'_{\max} = E_{\mathrm{cut}}$ and $d\Phi_\gamma/dE$ equal to the EGRET spectra). The maximum flux is given by GRB910709 ($\alpha = 1.76$), which would produce a flux $\Phi_{e\pm} \sim 450(6500)$ particles m^{-2} at $h = 2000(5000)$ m assuming $E_{\mathrm{cut}} = 1$ TeV, and $\Phi_{e\pm} \sim 12(420)$ particles m^{-2} for $E_{\mathrm{cut}} = 30$ GeV. In total, the number of GRBs (out of 15) giving a flux $\Phi_{e\pm} > 10$ particle m^{-2} at the altitude $h = 2000(5000)$ m is $N = 3(10)$ for $E_{\mathrm{cut}} = 1$ TeV, and $N = 1(4)$ for $E_{\mathrm{cut}} = 30$ GeV. As expected the ground level signals are very sensitive to the maximum energy E_{cut}, that is determined by the maximum emitted energy at the source and by the absorption in the intergalactic space. Our analysis of the EGRET events indicates that even if the GRBs spectra at Earth do not extend to very high energy, the most powerful events can give ground level fluxes at mountain altitudes $\Phi_{e\pm} > 10$ particles m^{-2}. The minimum sensitive area required to detect a flux of 10 particles m^{-2} can be deduced by the expression (5) using the background estimates given in Fig. 3. For example, at $h = 4000$ m, $A_{\min} = 214(\Delta t/1\,\mathrm{s})(1/\cos^2\theta)$ m^2.

So far we have expressed the sensitivity of the single particle technique in terms of the ground level particles flux. To discuss the sensitivity in terms of the primary gamma-rays flux at the top of the atmosphere, it is useful to introduce $F_{\min}$, the minimum energy fluence of gamma-rays above 1 GeV required to give a detectable signal. We considered a detector of area $A_d = 10^3$ m^2 and a GRB with a zenith angle $\theta = 0°$, $\Delta t = 1$ s, and z sufficiently small to make

Fig. 6. Minimum energy fluence in the range 1 GeV–E_{max} detectable by a 10^3 m^2 detector as a function of the altitude. The curves are given for different GRB spectral slopes α and E_{max} values: curves *a* correspond to $\alpha = 2.5$, curves *b* to $\alpha = 1.5$; subscripts 1, 2, 3 refers respectively to $E_{max} = 30$, 100, 1000 GeV.

the distortions of the spectrum (absorption and redshift) negligible. Fig. 6 shows the minimum energy fluence F_{min} in the range 1 GeV–E_{max} as a function of h, for different spectral parameters. If the detector is located at very high mountain altitude ($h > 4000$ m) fluences of few 10^{-5} erg cm^{-2} are observable also from soft spectra ($\alpha = 2.5$, $E_{max} = 30$ GeV), while fluences of few 10^{-6} erg cm^{-2} are detectable only from hard spectra ($\alpha = 1.5$, $E_{max} = 1$ TeV). The minimum observable fluence for a detector with a generic area $A_d = k \cdot 10^3$ m^2 and for a GRB with a generic time duration $\Delta t = T$ s scales as $\sqrt{T/k}$.

It is worth noting that in the evaluation of the sensitivity we have not taken into account the possibility to increase the GRB signal by converting a fraction of photons in detectable charged particles as discussed in Section 2.

3.3. Expected rate of observations

A rough evaluation of the expected rate of positive observations, as a function of the unknown spectral parameters at high energies, can be performed by making assumptions on the luminosity function and the spatial distribution of GRBs in the universe.

As a first step we evaluate the probability to detect a GRB with a given luminosity[2] L as a function of z. Due to the absorption, the luminosity L required to observe a GRB increases with the distance more rapidly than what is expected by simple geometrical effects. Fig. 7 shows the minimum luminosity L necessary to make a burst detectable by a 10^3 m^2 detector located at different altitudes, as a function of the redshift z. The burst is assumed at a zenith angle $\theta = 0°$, with a time duration $\Delta t_e = 1$ s, $\alpha = 2$ and $E_{max} = 30$ and 1000 GeV. Obviously, for a detector of a generic area $A_d = k \cdot 10^3$ m^2 the minimum observable luminosity scales as $1/\sqrt{k}$. From these curves one can deduce the maximum distance observable by the detector, for a given L. As an example, if $L = 10^{51}(10^{54})$ erg and $E_{max} = 1$ TeV, a 10^3 m^2 detector at the sea level could see the burst if the source is located within a distance $z \sim 0.003(0.4)$ while a detector at $h = 4$ km could see up to $z \sim 0.2(3.0)$.

As a matter of fact not all GRBs with a given L are observable if z is less than a certain value: the detection depends on the zenith angle θ. A correct approach to the problem is to calculate the probability $P(L,z)$ to observe a burst of luminosity L and distance z taking into account all possible arrival directions

$$P(L,z) = \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_0^{\pi} J(L,z,\theta) \sin\theta \, d\theta, \qquad (6)$$

where $J(L,z,\theta) = 1$ if the burst is detectable, i.e. if the statistical significance of the signal is larger then the required value, otherwise $J(L,z,\theta) = 0$.

As a second step we evaluate the fraction $\epsilon(L)$ of observable events over the total number of GRBs of luminosity L distributed in the universe. For this purpose one should know the form of the GRBs density $n(z,L)$ (number of bursts per unit volume and unit time). We will adopt the simplest model: (a) GRBs are distributed in the universe with constant density and frequency in a comoving coordinate

---

[2] The luminosity is usually defined as the amount of energy emitted per unit time, while here we call luminosity the energy emitted during the total emission time Δt_e.
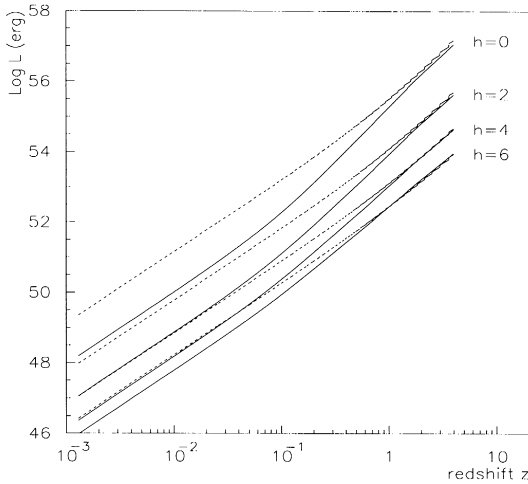
Fig. 7. Minimum amount of energy L released above 1 GeV by a GRB at distance z necessary to make the event observable by a 10^3 m^2 detector located at different altitudes h (in km), as a function of z. The curves are calculated for a GRB spectrum with slope $\alpha = 2$ and $E_{max} = 1$ TeV (solid line) and $E_{max} = 30$ GeV (dashed line).

frame up to a maximum distance z_{max}, (b) GRBs show no evolution, i.e. the luminosity distribution is independent on z.

With these assumptions $n(z,L) \propto (1+z)^3/(1+z)$; the term $(1+z)^3$ takes into account that the universe at a time corresponding to a redshift z was smaller than now by a factor $(1+z)$; the term $1/(z+1)$ represents the frequency decrease due to time dilation. The fraction of observable events within the distance z_{max} is

$$\epsilon(L) = \frac{\int_0^{z_{max}} P(L,z)(1+z)^2 \frac{dV}{dz} dz}{\int_0^{z_{max}} (1+z)^2 \frac{dV}{dz} dz}, \qquad (7)$$

where $dV(z)$ is the volume element, according to [17]

$$
\begin{aligned}
dV(z) &= \frac{4\pi c^3}{(1+z)^6 H_0^3 q_0^4} (1 + 2q_0 z)^{-1/2} \\
&\times \left[zq_0 + (q_0 - 1)\left(-1 + \sqrt{2q_0 z + 1}\right) \right]^2 dz.
\end{aligned}
\qquad (8)
$$

Fig. 8 shows $\epsilon(L)$ for a 10^3 m^2 detector at different altitudes, calculated setting $z_{max} = 4$. The burst is assumed with an emission time $\Delta t_e = 1$ s, a slope $\alpha = 2$ and $E_{max} = 30$, 100 and 1000 TeV. The corresponding fraction of observable events for a detector area $A_d = k \cdot 10^3$ m^2 is $\epsilon(L\sqrt{k})$. It is interesting to note that, for a given detector altitude, a GRB with $E_{max} = 100$ GeV becomes more easily observable than a GRB with the same luminosity and $E_{max} = 1$ TeV, if L is larger than a certain value; this is due to the fact that increasing the luminosity one can observe at larger distances and consequently the absorption of high energy photons becomes more important.

The final step is the calculation of the total rate of observable events, considering all the possible luminosities L,

$$R_{obs} = R_{tot} \int_{L_{min}}^{L_{max}} \frac{dN(L)}{dL} \epsilon(L) \, dL, \qquad (9)$$

where R_{tot} is the total bursts rate in the universe within a distance z_{max} and $dN(L)/dL$ is the luminosity distribution of GRBs. A rough evaluation of R_{tot} is given from BATSE data. Since BATSE ob-
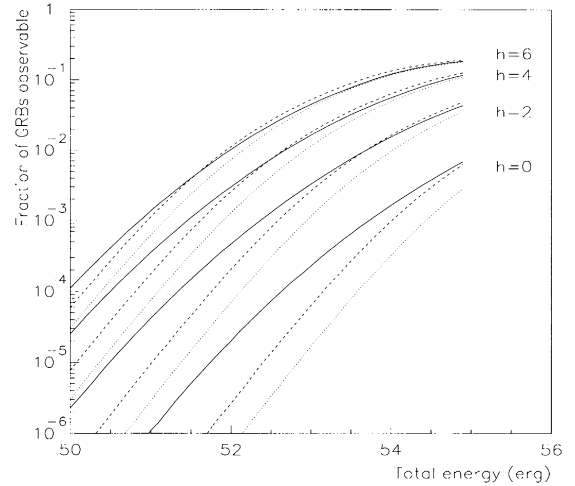

Fig. 8. Fraction of GRBs observable up to a distance $z_{max} = 4$ as a function of the luminosity L, for a 10^3 m^2 detector located at different altitudes h (in km). The curves are calculated for a GRB spectrum with slope $\alpha = 2$ and $E_{max} = 1$ TeV (solid line), 100 GeV (dashed line) and 30 GeV (dotted line).

serves ~ 1 burst per day, with a detection efficiency of ~ 0.3, the rate deduced from BATSE obervations is $R_B \sim 1000 \ y^{-1}$. In the assumption that BATSE can observe GRBs up to a distance $z \sim 4$, we set $R_{tot} = R_B$.

The luminosity distribution is a more troublesome topic: in the KeV–MeV energy region a large number of studies has been done in order to deduce a luminosity function suitable to reproduce the flux distribution of BATSE bursts but a general agree-

ment about the subject does not exist. Different forms of $N(L)$ could reproduce the BATSE data and so far there exist too few luminosity measurements to put stringent constraints on the distribution. One point is clear: the 6 events whose distance has been measured show that GRBs are not standard candles and the luminosity distribution at low energy is a very broad function, ranging over almost 4 orders of magnitude. Lacking more compelling data we will assume the luminosity function in the form $dN(L)/dL = CL^{-\beta}$ with $L_1 < L < L_2$; tentatively, we set $L_1 = 10^{51}$ erg and $L_2 = 10^{55}$ erg, and consider β as parameter ranging in the interval 1–4.

Fig. 9 shows the expected rate of observation as a function of β for a $10^3 \ m^2$ detector at different altitudes. The burst spectrum is assumed with $\alpha = 2$ and $E_{max} = 30$, 100 and 1000 GeV. The rates are given for the emission times $\Delta t_e = 1$ s and $\Delta t_e = 10$ s. The curves show that a $10^3 \ m^2$ detector located at $h \sim 4$ km, could observe a number of bursts per year ranging from ~ 1 to 20–30 if the slope of the luminosity function is not steeper than 2–2.5.
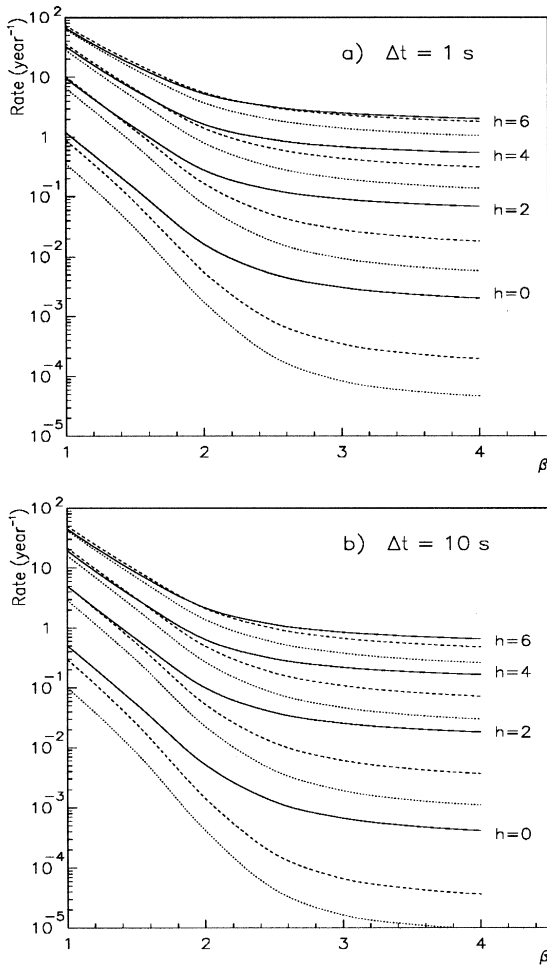

Fig. 9. Expected rate of observable GRBs as a function of the slope β of the luminosity function, for a $10^3 \ m^2$ detector located at different altitudes h (in km). The curves are calculated for a GRB spectrum with a slope $\alpha = 2$ and $E_{max} = 1$ TeV (solid line), 100 GeV (dashed line) and 30 GeV (dotted line). The emission time is $\Delta t_e = 1$ s (upper figure) and 10 s (lower figure).

4. Conclusions

The single particle technique provides a simple method of observing GRBs in the energy range $1–10^3$ GeV using large air shower arrays located at high mountain altitude. The observation of a significant excess in the counting rate in coincidence with a burst seen by a satellite would provide, in a very simple and economical way, important informations on the GRB high energy component. Besides the study of the temporal behaviour of the high energy emission, the single particle observation could allow the evaluation of the total energy L emitted above 1 GeV (or equivalently the maximum energy of the spectrum E_{max}) provided that the spectral slope is deduced by a complementary lower energy observation and the redshift is measured with optical instruments.

The expected rate of observation depends on bursts parameters that are so far poorly known, as the high energy spectrum shape, the distribution of the sources in the universe, and in particular the luminosity function. However, making reasonable assumptions,

we conclude that a detector of $A_d \sim 10^3$ m^2 at an altitude of ~ 4000 m above the sea level could be expected to detect at least few events per year if the GRB spectrum extends up to ~ 30 GeV and the luminosity function slope is not too large.

An attempt to detect high energy GRBs using the single particle technique was performed by G. Navarra about 15 years ago using a small detector located at Plateau Rosa at 3500 m a.s.l. [26]. At present two experiments are using this technique: the 350 m^2 air shower array EASTOP, working at 2000 m a.s.l. at the Gran Sasso Laboratory (Italy) and INCA, a 48 m^2 detector located at Mount Chacaltaya (Bolivia) at 5200 m a.s.l.

EASTOP has been searching high energy GRBs since 1991, showing the possibility to perform the single particle measurement with the necessary stability over long periods of time, monitoring with very good reliability short time fluctuations in the counting rate. In a search for high energy gamma-rays in coincidence with about 300 BATSE events detected during 1992–1998, EASTOP obtained upper limits to the 10 GeV–1 TeV fluence as low as $F \sim 10^{-4}$–$5 \cdot 10^{-3}$ erg cm^{-2}, for small zenith angle GRBs ($\theta < 30°$) [27]. In a similar search performed with about 2 years of data, INCA obtained upper limits to the 1 GeV–1 TeV fluence $F \sim 5 \cdot 10^{-5}$–10^{-4} erg cm^{-2}, also for small zenith angle GRBs [28,29]. The limited area of INCA is highly compensated by its extreme altitude.

The single particle technique has been adopted as well by the CYGNUS collaboration using water Cherenkov detectors, with a total sensitive area of ~ 210 m^2 at an altitude of 2130 m. They reported upper limits on the 1 GeV–30 TeV energy fluence $F \sim 10^{-4}$–$2 \cdot 10^{-1}$ erg cm^{-2} s^{-1}, in coincidence with 9 strong GRBs with zenith angles up to 60° [30].

Good possibilities of positive detections come from the new generation air shower arrays consisting of very large sensitive surfaces, as ARGO and MI-LAGRO, conceived to detect small air showers with the aim of observing gamma-ray sources at energy $E < 1$ TeV. ARGO, under construction at the Yang-bajing Laboratory (Tibet) at 4300 m, will consist of a carpet of 7500 m^2 of Resistive Plate Chambers, covered by a layer of lead 0.5 cm thick to convert a fraction of shower photons and increase the number of detectable particles [31]. MILAGRO, a Cherenkov detector using a 4800 m^2 pond of water, is located at 2600 m, near Los Alamos. An interesting feature of the water Cherenkov technique is the possibility to perform a calorimetric measurement of the shower particles and to detect most of the photons, due to their interactions in the water [30,32]. The two future experiments have about the same sensitivity in observing GRBs by using the single particle technique. The lower altitude of MILAGRO, that reduces its sensitivity by a factor ~ 3 with respect to ARGO, is compensated by the higher capability of detecting the shower photons. If the assumptions that we have made on high energy GRBs are correct, both the experiments likely will detect at least few events per year.

Acknowledgements

References

[1] S. Piran, Astro-ph/9810256 (1998), for a review of experimental and theoretical results.

[2] P. Meszaros, M. Rees, H. Papathanassiou, Astrophys. J. 432 (1994) 181.

[3] M. Vietri, Astro-ph/9705061 (1997).

[4] M.G. Baring, Astro-ph/9711256 (1997).

[5] J.R. Catelli, B.L. Dingus, E.J. Schneid, AIP Conf. Proc. 428 (1997) 309.

[6] V. Connaughton et al., Astrophys. J. 479 (1997) 859.

[7] K. Hurley et al., Nature 372 (1994) 652.

[8] K. Greisen, Progress in Cosmic Rays Physics, Vol. III (North Holland, Amsterdam, 1956).

[9] G. Navarra, P. Vallania, Internal Report of Ist. Cosmogeofisica CNR, 379/98 (1998).

[10] B. Rossi, Rev. Mod. Phys. 20 (1948) 537.

[11] W. Menn et al., Proc. 25th ICRC, Vol. 3 (1997) p. 409.

[12] M. Aglietta et al., Astrophys. J. 469 (1996) 305.

[13] S. Vernetto et al., Astro-ph/9906185 (1999).

[14] M. Aglietta et al., Proc. 26th ICRC, SH 3.6.16 (1999), in press.

[15] V.V. Alexeenko et al., Proc. 20th ICRC 4 (1987) 272.

[16] M.H. Salomon, F.W. Stecker, Astrophys. J. 493 (1998) 547.

[17] S. Weinberg, Gravitation and Cosmology (Wiley, New York, 1972).

[18] M.R. Metzger et al., Nature 387 (1997) 878.

[19] S.R. Kulkarni et al., Nature 393 (1998) 35.

[20] S.G. Djorgovski et al., GRB Coordinate Network Circular no. 139 (1998).

[21] S.G. Djorgovski et al., GRB Coordinate Network Circular no. 189 (1998).

[22] D.D. Kelson et al., IAUC 7096 (1999).

[23] P.M. Vreeswijk et al., GRB Coordinate Network Circular no. 324 (1999).

[24] T. Galama et al., GRB Coordinate Network Circular no. 60 (1998).

[25] D. Band et al., Astrophys. J. 413 (1993) 281.

[26] C. Morello, G. Navarra, L. Periale, Il Nuovo Cimento 7C (1984) 682.

[27] M. Aglietta et al., A&A Suppl. Series 138(3) (1999) 595.

[28] A. Castellina et al., AIP Conf. Proc. 428 (1997) 914.

[29] R. Cabrera et al., A&A Suppl. Series 138(3) (1999) 599.

[30] G.E. Allen, Proc. XXIV International Cosmic Rays Conference, Vol. 2 (1995) p. 140.

[31] C. Bacci et al., A&A Suppl. Series 138(3) (1999) 597.

[32] G.E. Allen, Proc. XXIV International Cosmic Rays Conference, Vol. 3 (1995) p. 516.