IL NUOVO CIMENTO Vol. 24 C, N. 4-5 Luglio-Ottobre 2001

Search for gamma-ray bursts at Chacaltaya(*)

A. Castellina(1), P. L. Ghia(1), F. Kakimoto(3),T. Kaneko(4), C. Morello(1)
G. Navarra(2), K. Nishi(5), O. Saavedra(2), G. Trinchero(1), D. Urzagasti(6)
P. Vallania(1), A. Velarde(6), S. Vernetto(1) and H. Yoshii(7)

(1) *Istituto di Cosmogeofisica del CNR - Torino, Italy*
(2) *Dipartimento di Fisica Generale dell'Università - Torino, Italy*
(3) *Department of Physics, Tokyo Institute of Technology - Meguro, Tokyo 152, Japan*
(4) *Department of Physics, Okayama University - Okayama 700, Japan*
(5) *Institute of Physical and Chemical Research - Wako, Saitama 351-01, Japan*
(6) *Instituto de Investigaciones Fisicas, Universidad Mayor de San Andres - La Paz, Bolivia*
(7) *Department of Physics, Ehime University - Ehime 790, Japan*

(ricevuto il 10 Novembre 2000; approvato il 12 Febbraio 2001)

Summary. — A search for gamma-ray bursts in the GeV–TeV energy range has been performed by INCA, an air shower array working at 5200 m of altitude at the Chacaltaya Laboratory (Bolivia). The altitude of the detector and the use of the "single-particle technique" allows to lower the energy threshold up to few GeVs. No significant signals are observed during the occurrences of 125 GRBs detected by BATSE, and the obtained upper limits on the energy fluence in the interval 1–10^3 (1–10^2) GeV, range from 3.2 (8.6) $\times 10^{-5}$ to 2.6 (7.0) $\times 10^{-2}$ erg cm^{-2} depending on the zenith angle of the events. These limits, thanks to the extreme altitude of INCA, are the lowest ever obtained in the sub-TeV energy region by a ground-based experiment.

PACS 98.70.Rz – Gamma-ray sources; gamma-ray bursts.
PACS 01.30.Cc – Conference proceedings.

1. – High energy gamma-rays from GRBs

Since their discovery in 1973 most of our knowledge on Gamma Ray Bursts (GRBs) has been confined to the keV–MeV energy region; only during the last 3 years the observations extended to other wavebands, namely X, optical, infrared and radio, yielding a lot of exciting results and producing a breakthrough in our understanding of these misterious events (for a review see [1] and [2]). Now we know that GRBs are huge

---

(*) Paper presented at the Chacaltaya Meeting on Cosmic Ray Physics, La Paz, Bolivia, July 23-27, 2000.

explosions occurring in far galaxies and are probably the most energetic events in the universe, exceeding even Supernovae. The cause of the release of such amount of energy is still unknown and what we observe is probably only the effect of relativistic shock waves produced by the explosion interacting each other or with the surrounding interstellar medium. Even if the "central engine" remains hidden the study of the radiation emitted in all wave bands by the interacting shock waves gives important information on the acceleration mechanisms and on the ambient medium in which the shock propagates (see [3] for a theoretical review).

So far the radiation emitted by GRBs in the GeV–TeV band has been very poorly studied due to the extremely low fluxes. EGRET, the high energy detector aboard the satellite GRO, during its life detected only few very intense events containing some GeV photons [4]. However all GRBs could contain a GeV energy component, so far not measured only because of the low flux. In fact, many models [5-10] predict emissions in the GeV–TeV region. Upper limits in the 10–100 TeV region has been obtained by several air shower arrays [11-14]. An interesting TeV candidate has been observed by the ground-based Milagrito detector in coincidence with GRB970417 [15].

The paucity of the flux is not the only problem to face when studing the high energy component of the GRB spectrum. The major problem (and unsolvable) is the absorption of gamma-rays in the intergalactic space. GeV and TeV gamma-rays interact with the infrared photons emitted by stars and dust producing electrons and positrons pairs. The flux of photons of energy E decreases as $\mathrm{d}N/\mathrm{d}E = (\mathrm{d}N_0/\mathrm{d}E)e^{-\tau(E,z)}$, where z is the redshift of the source. The optical depth τ increases with E and z but it is not easy to evaluate, due to the difficulty of measuring the infrared field in the far universe. According to a model [16] the optical depth becomes equal to 1 for energies as low as $E \sim 40$–70 (200–400) GeV when $z = 1(0.2)$.

So far about 15 redshifts of GRBs hosts have been measured: they range between 0.4 and 4.5, clustering around $z \sim 1$. This implies that even if GRBs emit TeV–PeV gamma-rays we unlikely could detect them, unless we are so lucky to observe a rare event occurring very close to us. As a consequence, to study the high energy component of GRBs we are forced to concentrate our efforts in the region of energy less than 1 TeV.

Ground-based experiments can study high energy GRBs detecting the secondary particles of air showers generated by the interactions of gamma-rays with the atmosphere nuclei. They can be divided in two major classes: Čerenkov telescopes, detecting the Čerenkov photons emitted by the electrons and positrons traveling through the atmosphere, and air shower arrays, detecting the charge particles (mainly electrons and positrons) that reach the ground. Čerenkov telescopes are not suitable to detect transient events as GRBs, because of their small field of view (few squared degrees) and their limited duty cycle ($\sim 10\%$). On the contrary, air shower arrays have a larger field of view ($\sim \pi$ sr) and a duty cycle of $\sim 100\%$. They usually work with energy thresholds of ~ 10–100 TeV, but in searching for transient events as GRBs, they can lower the threshold to few GeVs using the "single-particle technique" and operating at very high altitude.

The single-particle technique [17, 11] consists in counting all the particles giving a signal in the detector (not requiring any coincidence between particles as it is usually done to detect air showers). In this way it is possible to detect the lonely survivals of small showers produced by primaries of relatively low energy. Obviously with only one particle per shower it is not possible to reconstruct the arrival direction nor the energy of the primary and a GRBs is detectable only as a short duration excess over the single-particle background, possibly in coincidence with a GRB satellite detection. The

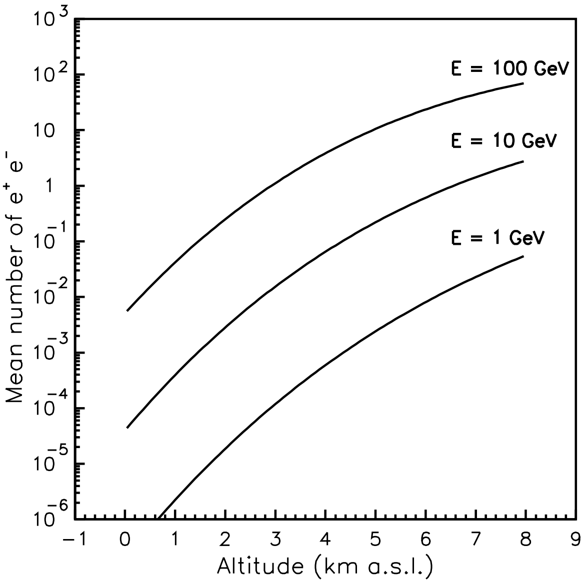

Fig. 1. – Mean number of e$^\pm$ reaching the ground generated by a gamma-ray of different energies as a function of the altitude ($\theta = 30°$).

background is due to all secondary cosmic rays from all the sky above the horizon.

The signal from a GRB strongly increases with the altitude of the detector [17]. Figure 1 shows the mean number of particles reaching the ground generated by a gamma-ray of different energies as a function of the altitude (the values refer to a zenith angle $\theta = 30°$). Going from 2000 to 5000 m, a 10 (100) GeV signal increases by a factor $f_s \sim 100(50)$; since the background increases only by a factor $f_b \sim 4$, the sensitivity will improve by a factor $f = f_s/\sqrt{f_b} \sim 50(25)$.

Following these considerations we decided to exploit the air shower array BASJE, operating since 1962 (with several upgrades since then) at the Chacaltaya Laboratory at 5200 m a.s.l., to develop the experiment INCA, to search for GeV GRBs using the single-particle technique.

2. – The INCA experiment and its sensitivity

The INCA experiment [18, 19] consists of 12 scintillator detectors of 2×2 m^2 area distributed over an area of $\sim 20 \times 20$ m^2. Each detector is viewed by a photomultiplier of 15 cm diameter and works with an energy threshold of ~ 10 MeV. The experiment is running since December 1996. In August 2000 INCA has been upgraded with 16 muon detectors, each consisting of a 4 m^2 scintillator operating under a depth of 320 g cm^{-2}. The muon detectors are used as a sort of "anticoincidence" to reject possible excesses in the counting rate not due to a gamma-ray burst, since a true gamma-ray signal is expected not to contain muons. In the data presented in this paper the muon detectors are not yet implemented.

Every second the data acquisition records:

a) the number of counts of each detector

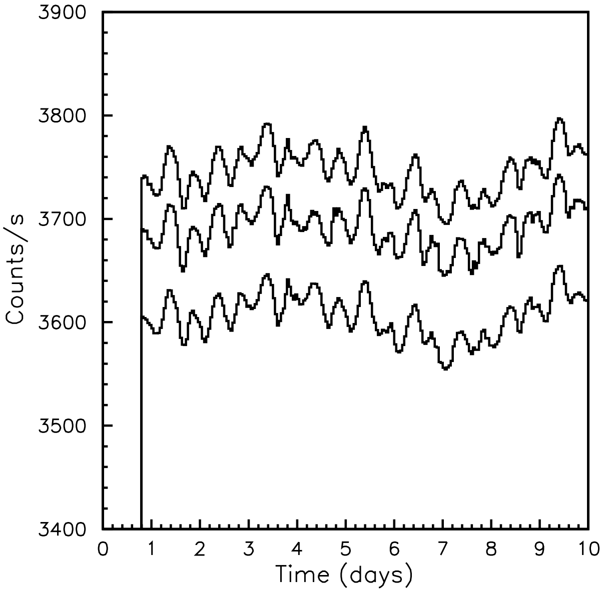

Fig. 2. – Counting rate of 3 INCA scintillator detectors during ∼ 10 days of measurement.

b) the atmospheric pressure

c) the universal time with a precision better than 1 μs.

The counting rate (mainly due to electrons, positrons and muons) from low energy cosmic ray air showers is $C_d \sim$ 3700–3800 count s^{-1} for each detector and it is modulated by the atmospheric pressure, the 24 hours anisotropy and the solar activity.

Figure 2 shows the behaviour of 3 detectors during ∼ 10 days of measurement, where variations of amplitude ∼ 2–3% on time scales ranging from a fraction of a day to several days are visible. However it is important to note that these modulations do not hamper the GRBs search because the time scales of the phenomena are quite different. More troublesome are electrical noises that can simulate short time variations in the single-particle flux. As a consequence it is very important to check accurately the behaviour of the detectors in order to avoid the presence of spurious signals.

The average INCA total background rate is $C_b \sim 4.5 \times 10^4\ \mathrm{s}^{-1}$. As a consequence, a GRB of time duration $\Delta t = 1$ s is detectable with a significance of 4 standard deviations if the number of detected particles is larger than $C_{\mathrm{th}} = 4\sqrt{C_b} \sim 840$, while for a generic $\Delta t = t$ s, C_{th} increases by a factor $\sqrt{t}$. To have an idea of the number of particles expected from a GRB, we considered 14 GRBs detected by EGRET whose spectrum has been published [4]. All the detected spectra show a power law behaviour without breaks up to the maximum energy that the EGRET sensitivity could observe, with an average slope $\alpha \sim -2.2$. For simplicity we have assumed that each spectra extends with a slope equal to the measured one up to a cutoff energy $E_{\max}$ and than zeroes (due to an intrinsic cutoff at the source or to the intergalactic absorption). We have calculated the number of particles produced by the EGRET bursts for different values of $E_{\max}$, assuming a burst zenith angle $\theta = 0°$, and we have compared it with the minimum number C_{th} necessary to give a significant signal. For $E_{\max} = 1$ TeV, 8 (4) bursts out of 14 are detectable if $\Delta t = 1(10)$ s, while for $E_{\max} = 100$ GeV the number of detectable bursts is reduced to 4

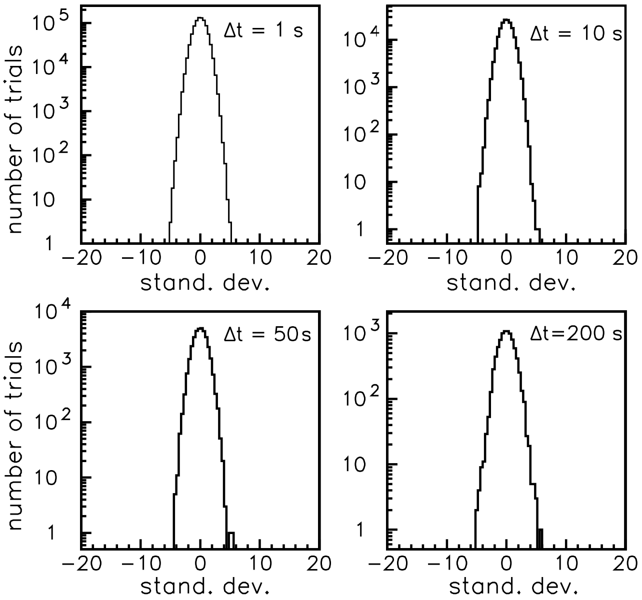

Fig. 3. – Distribution of the fluctuations of counting rates in 2 hours around the time occurrences of 125 BATSE GRBs, for 4 different time windows.

(3). These considerations show that INCA could detect GRBs of intensity comparable to the most intense observed so far by EGRET, provided that the energy spectrum extends at energy $E \geq 100$ GeV and that they occur at small zenith angles.

3. – Data analysis and results

The data analysis consists in the search for significant excesses in the scintillator counting rates during the occurrence of the bursts observed by the BATSE instrument aboard the CGRO satellite (orbiting since April 1991 to June 2000). In the period December 1996-March 2000 125 BATSE bursts have occurred in the INCA field of view (*i.e.* zenith angle $\theta < 60°$).

For each BATSE event the INCA data recorded during 10000 s around the burst time are selected and carefully analyzed to reject possible spurious event due to the noisy behaviour of some detectors. Finally the counts of each detector are summed and the total counting rate distribution is studied to identify possible statistically significant fluctuations.

We looked for excesses of different durations $\Delta t = 1, 2, 6, 10, 20, 50, 100, 200$ s, inside a time interval of 2 hours around the burst time, shifting the window position in step of $\Delta t/2$ (except the case $\Delta t = 1$ s, where the step is Δt). The number of counts C recorded in Δt are compared with the expected background B, calculated using the background rate during 30 minutes around Δt (in 30 minutes the background modulations are negligible). We found no excess for any BATSE GRB and for any window Δt; the obtained distributions of the fluctuations $f = C - B$ follow the expectations of a uniform background. Figure 3 shows the distribution of f in unit of standard deviations for four different time windows summed over 125 bursts. They are well fitted by Gauss

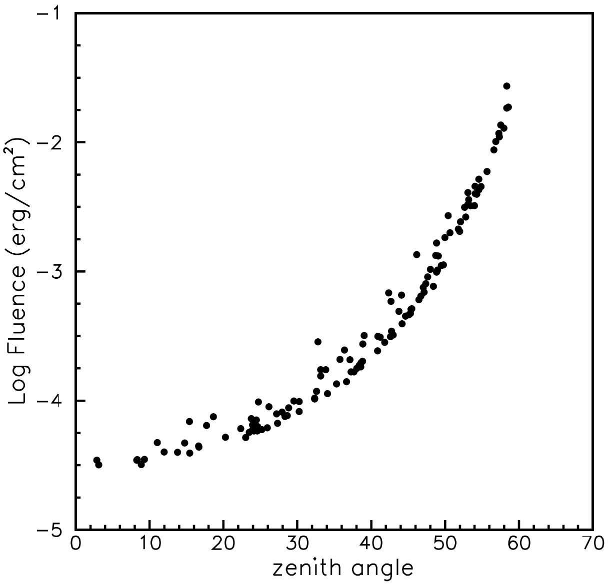

Fig. 4. – Upper limits on the energy fluence in the 1 GeV–1 TeV energy interval for 125 GRBs, in a time window $\Delta t = 10$ s starting from the onset of the burst, as a function of the zenith angle of the event.

distributions with r.m.s. ranging from 1.06 ($\Delta t = 1$ s) to 1.29 ($\Delta t = 200$ s).

Figure 4 shows the energy fluence upper limits in the energy range 1 GeV–1 TeV for the 125 bursts considered in this analysis, as a function of the zenith angle of the event. The fluences have been calculated at 4 standard deviations level assuming the GRBs spectra as $\mathrm{d}N/\mathrm{d}E \propto E^{\alpha}$ with $\alpha = -2$ extending up to 1 TeV and assuming a burst duration of 10 s. They range from 3.2×10^{-5} to 2.6×10^{-2} erg cm^{-2} depending on the zenith angle of the event. If the spectrum extends only up to 100 GeV (a more realistical assumption due to the intergalactic absorption) the upper limits in the 1–100 GeV energy region are a factor 2.7 higher than the previously given values.

A very simple technique as the single-particle detection, used by the highest air shower array operating in the world, has provided the lowest upper limits on the GRBs flux ever obtained in the ~ 1 GeV–1 TeV energy region by a ground-based experiment.

REFERENCES

[1] Galama T., astro-ph/0001465 (2000).
[2] Klose S., astro-ph/0001008 (2000).
[3] Piran T., *Phys. Rep.*, **314** (1999) 575.
[4] Catelli J. R., Dingus B. L. and Schneid E. J., *AIP Conf. Proc.*, **428** (1997) 309.
[5] Meszaros P. and Rees M. J., astro-ph/9404056 (1994).
[6] Vietri M., *Phys. Rev. Lett.*, **78** (1997) 4328.
[7] Baring M., astro-ph/9711256 (1997).
[8] Dermer C. D. and Chiang J., astro-ph/9912164 (1999).
[9] De Paolis F., Ingrosso G. and Orlando D., *Astron. Astrophys.*, **359** (2000) 514.
[10] Totani T., *Astrophys. J.*, **509** (1998) L81.

[11] AGLIETTA M. *et al.*, *Astrophys. J.*, **469** (1996) 305.
[12] ALEXANDREAS D. E. *et al.*, *Astrophys. J. Lett.*, **426** (1994) L1.
[13] PADILLA L. *et al.*, *Astron. Astrophys.*, **337** (1998) 43.
[14] AMENOMORI M. *et al.*, *Astron. Astrophys.*, **311** (1996) 919.
[15] ATKINS R. *et al.*, *Astrophys. J. Lett.*, **533** (2000) L119.
[16] SALAMON M. H. and STECKER F.W., *Astrophys. J.*, **493** (1998) 547.
[17] VERNETTO S., *Astropart. Phys*, **13** (2000) 75.
[18] CASTELLINA A. *et al.*., *Nuovo Cimento C*, **20** (1997) 137.
[19] CABRERA R. *et al.*, *Astron. Astrophys. Suppl. Series*, **138** (1999) 599.