Cosmic Ray Observations at Chacaltaya and Cerro la Negra Combined with the Pierre Auger and Milagro Observatories: GRBs and Search for Cosmic Ray Correlations

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Abstract. We consider the possibility to search for cosmic ray phenomena time correlated among distant experiments that are currently running in the world. In particular we consider the correlations of events detected by four experiments: between Milagro, operating in USA, and Cerro La Negra Cosmic Ray Laboratory, under construction in Mexico, and between Chacaltaya, in Bolivia, and Auger Observatory, under construction in Argentina. Almost complete sky coverage with fairly uniform celestial exposure of the northern and the southern hemispheres by the above four experiments at the same time could provide important information on astrophysical phenomena. Search for Gamma Ray Bursts and search for non random coincidence between these experiments seem to be feasible under an international extensive air shower joint experiment with the main goal to watch GRBs and other astrophysical phenomena.

INTRODUCTION

Energetic cosmic ray particles bring us information about the sources and processes in which the particles are accelerated to relativistic energies, about the nature of the particles and their accelerators, and about the distributions of matter and fields in distant regions of our galaxy and in distant galaxies throughout the universe. Understanding their origin and transport through the interstellar medium is a fundamental problem.

Although the field of cosmic ray physics has evolved sufficiently there are still many questions that need an answer. For example, what we know about cosmic

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rays is the primary energy spectrum which follows a power spectrum ($E^{-2.7}$) and extends up to very high energies $\geq 10^{20}$ eV. The energy spectrum above 10^{16} eV is significantly steeper than the spectrum below 10^{15} eV. This is the energy region of the enigmatic "knee", discovered by Kristiansen [1] for the first time, where the slope of all particle energy spectrum changes. The energy range $10^{14} - 10^{16}$ eV has long been recognized as crucial to the understanding cosmic ray acceleration, because it appears to mark a transition from one process of acceleration to another. Therefore the "knee" represents an important key to the understanding of the origin of galactic cosmic radiation. Another possible explanation of the "knee" may be a fundamental change in the physics of nuclear interactions at these very high energies (see for example the paper presented at this Workshop by Saavedra *et al.* [2]). Another crucial point in the cosmic ray spectrum is at extreme energies ($\geq 10^{18}$ eV) where the slope of the spectrum becomes again flatter. Excellent reviews on this topic have been presented at this Workshop by J. Cronin, L. Scarsi [3], and others.

The bulk of cosmic rays that arrive to the Earth is essentially isotropic over the celestial sphere. On the other hand the study of the high energy range has been severely restricted by the extremely low particle flux. So far the energy region above 10^{14} eV has been explored only by ground-based air shower experiments.

In this note we consider the possibility to detect by two or more ground based detector arrays, existing and/or under construction, cosmic rays correlated to astrophysical phenomena, At present two experiments are taking data, Milagro in USA and Chacaltaya in Bolivia, while Cerro La Negra in Mexico and the Pierre Auger Observatory in Argentina are under construction. We address our attention to the study of GRBs and search for correlations of non random cosmic ray events in the four above-mentioned experiments under a wide international extensive air shower joint collaboration with the main goal to watch GRBs and other astrophysical phenomena. This study should be feasible without neglecting the specific goals of each experiment.

GAMMA RAY BURSTS

GRBs are the strongest phenomena in the γ-ray spectrum observed so far and constitute one of the most exciting discoveries in high-energy astrophysics. They last between milliseconds and minutes; then they vanish, and the trail goes cold. The BATSE experiment (see for example Ref. 4) on board of the CGRO satellite observed 2703 bursts, coming from random directions in the sky. This observations suggested that the bursts have their origin at cosmological distances. What causes these sudden flares of radiation? How can they briefly outshine everything else in the Universe at γ-ray energies and then vanish without a trace? These are few of many questions about GRBs. In 1997 observations with the Italian-Dutch BeppoSax satellite [5] provided a rapid and accurate location of busters allowing to measure the associated radiation at X-ray, optical and radio wavelengths. These results confirmed the cosmological distances of the bursters and established them as extraordinary bright objects.

The measured γ-ray energy spectrum with BATSE extends up to a few MeV and becomes steeper at about one MeV. The EGRET experiment on board of CGRO observed 6 GRBs with energies $\geq$ 1 GeV, including the emission of a 18 GeV photon by the GRB940217 burst [6]. The question is now whether the GRB spectrum extends to higher energies suggesting the possibility that a high energy component is present in all GRBs. A positive detection would constrain the models on the emission mechanism and the range of the source distances.

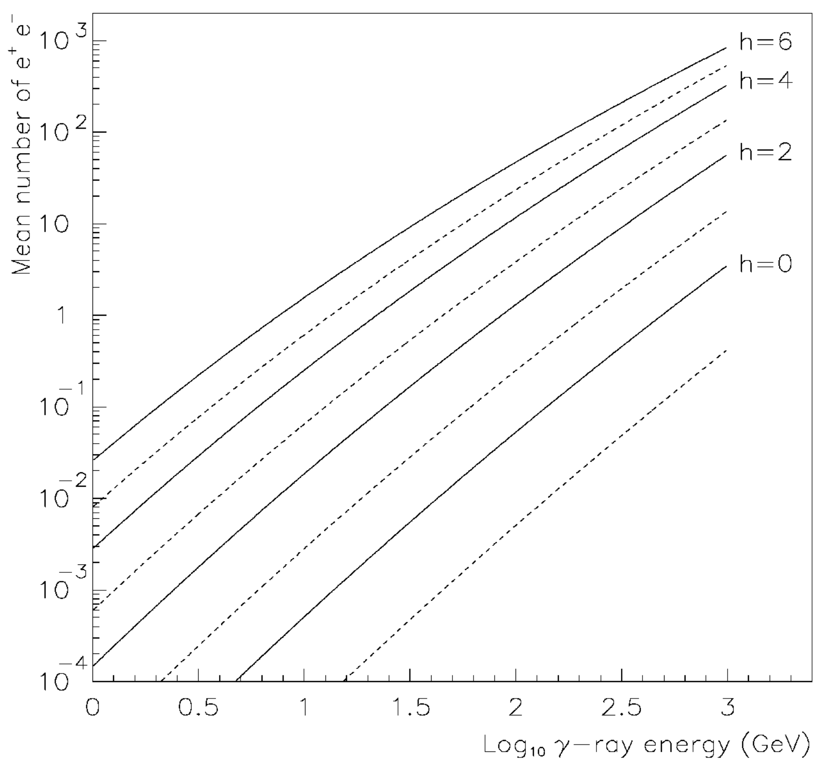

FIGURE 1. Number of electrons at four different altitudes h above sea level (in km) produced by a primary gamma ray of zenith angle $\theta = 0^o$(full line) and $\theta = 30^o$ (dashed line) as a function of the γ energy.

Detection technique

The detection of GeV γ-rays by ground based experiments can be performed using the single particle technique i.e. observing the fluctuations of single counting rates produced by secondary particles generated by the γ-ray entering at the top of the atmosphere. The sensitivity increases strongly with the altitude of observation. Results of simulations of pure electromagnetic cascades show, in fact, that the number of secondary particles in the EM shower produced by a primary γ-ray strongly increases with the altitude, as can be seeing in Figure 1. More details of simulations performed in order to evaluate the sensitivity of an extensive air shower detector for GRBs of different time duration, slope of the spectrum, energy cut-off, and for several altitudes of observation can be found in the paper by S. Vernetto [7]. An application of this method to the INCA (INvestigation of Cosmic Anomalies) experiment at Chacaltaya is given by Castellina et al. [8]. The single particle counting rate is usually monitored by most EAS experiments in order to have a continuous check of the stability of the experiment.

As an example, in Figure 1 we can see that the mean number of particles generated by a 16 GeV γ-ray reaching 5200 m is ≈ 1 while at 2000 m a.s.l. is only ≈ 0.03 particle, namely a factor ≈ 30 is gained by the altitude going from 2000 to 5200 m altitude. 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. The time scales of these modulations are much larger than the typical time duration of a GRB and therefore, do not affect the GRB search.

The sensitivity of a given detector is evaluated as a function of various burst parameters, as time duration and differential energy spectrum, and comparing the number of "signal" events, *i.e.* the number of single counts in the detector due to the burst, with the background fluctuations. By requiring a significance of n standard deviations for the signal, the burst can be observed if the number of particles is higher than the fixed standard deviations, in the case of INCA it is set to $n = 4$.

As an example we can give that reported by Castellina et al. [8]: if we consider the GRB930131, during the 1 s peak EGRET measured a flux $dI/dE = 1.9E^{1.97}(MeV)photons(cm^{-2}s^{-1}MeV^{-1})$; 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 in the field of view of INCA (near the zenith) - would be observable by INCA as an excess greater than 3 standard deviations.

The INCA experiment

Due to its great advantage of working at very high altitude, the INCA experiment (a collaboration between Italy, Bolivia and Japan running at Chacaltaya) searches for GRBs by using this single particle detection technique, i.e. recording the counting rates of all particles hitting the individual plastic scintillator detectors. A more detailed discussion about this technique is given by S. Vernetto [7]. The INCA experiment consists of 12 scintillation detectors from the BASJE experiment (4 m^2 each) for a total area of 48 m^2 distributed over a $\approx$ 20x20m^2 area. It is running since December 1996. The data analysis consists of the search for any significant excesses in the counting rates of each of the scintillation detectors during the GRBs observed by BATSE. As an example, in 20 months of data taking 70 BATSE events have occurred in the INCA field of view for zenith angle $\theta \leq 60^o$. For each BATSE event the INCA data recorded during 10000 s around the burst

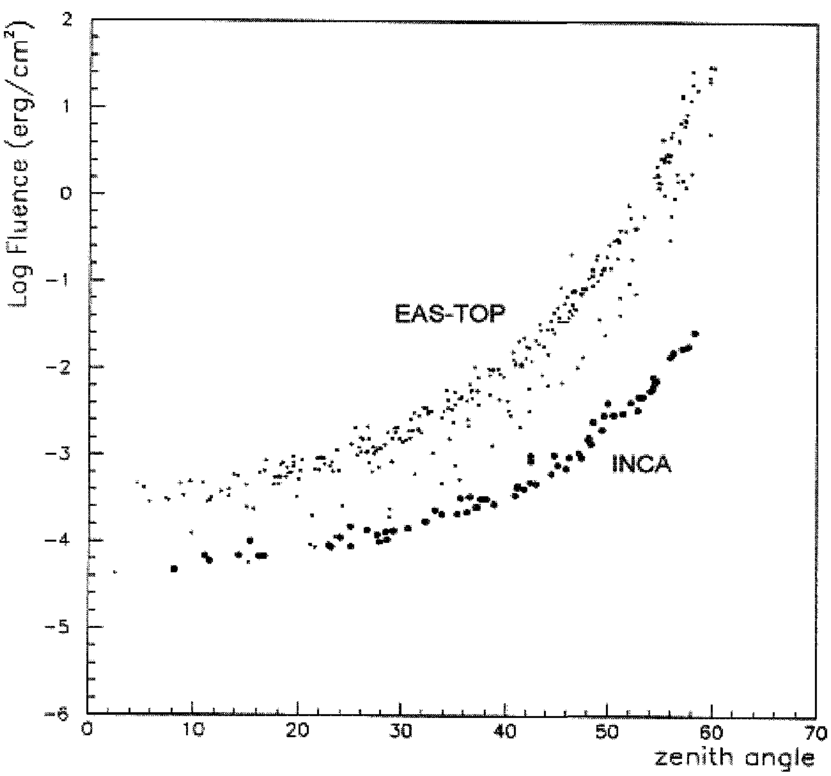

FIGURE 2. Upper limits on the energy fluence vs zenith angle in the energy range $1GeV-1TeV$ for 70 GRBs events in the field of view of INCA for a time window of 10 s starting from BATSE trigger time. The same for the EAS-TOP experiment but in the energy range $10GeV-1TeV$ obtained for 292 BATSE events in the field of view of EAS-TOP. The detector area of EAS-TOP is 350 m^2 while INCA's is only 48 m^2.

TABLE 1. Main characteristic of the Cosmic ray Observatories. Altitude (m a.s.l.), active area (m^2), primary energy (GeV)

Laboratory	country	altitude	area	energy
Chacaltaya	Bolivia	5220	48	1
Cerro la Negra	Mexico	4300	250	10
Milagro	USA	2000	4800	100
Auger	Argentina	1400	16000	50

time were selected. In this time interval the counting rates of each detector were carefully studied in order to identify possible electronic noises, local atmospheric interferences or anomalous behaviors. Finally, the detector counts were summed and the time distribution of the total counting rate was studied to single out statistically significant fluctuations. In Figure 2 we show the results of INCA, Cabrera et al. [10], compared with those of EAS-TOP, Aglietta et al. [9]. Both experiments use the same technique and analysis in terms of the upper limits of the fluence (erg/cm^2) *vs* the zenith angle of the GRB, for the those GRBs that were located in the field of view of each site. By comparing these results we can see that the sensitivity at Chacaltaya is better even though INCA's area (48 m^2) is considerable smaller than that of EAS-TOP (350 m^2). More recent and upgraded results have been presented by S. Vernetto at La Paz Meeting [11].

MAIN CHARACTERISTICS OF THE NETWORK OF DETECTORS

In this section we present the main characteristics of the four experiments which have the potential capability to watch for GRBs. In figure 3 we show the location of the four experiment sites. The distance between Milagro and Cerro la Negra is about 2500 km and it is more or less the same as that between Chacaltaya and the Pierre Auger observatory. The existence of such combinations is a very fortunate and unique opportunity. As we can see, both the northern and southern sites cover a large part of the sky. Therefore, a real GRBs watch by the four detectors is feasible. In the following subsections we describe the main capabilities of the four experiments whose main characteristics are summarized in table 1.

Chacaltaya Laboratory

The Chacaltaya Cosmic Ray Laboratory is located atop Mount Chacaltaya near La Paz, Bolivia, at an elevation of 5220 meters above sea level corresponding to 530 gr/cm^2. Note that this atmospheric thickness is equivalent to only 6.6 nuclear mean free paths and 14.1 radiation lengths. Its geographic position is 16° S, 291.8° E and −4° of geomagnetic latitude corresponding to a 13.1 GeV cut off rigidity.

Its geographic location in the Southern Hemisphere is also important in order to observe the part of the sky where γ-astronomy is not as well developed as it is in the Northern Hemisphere.

Cerro la Negra Laboratory

The Cerro la Negra Laboratory is under construction and it is located at 4300 m a.s.l. corresponding to 620 gr/cm^2. Its geographic position is 18.59° N, 97.1° W. As for the Chacaltaya, Cerro La Negra has a clear advantage due to its high altitude location.

Milagro Experiment

The MILAGRO Gamma Ray Observatory is the world's first large area water Cherenkov detector capable of continuously monitoring the sky at TeV energies.

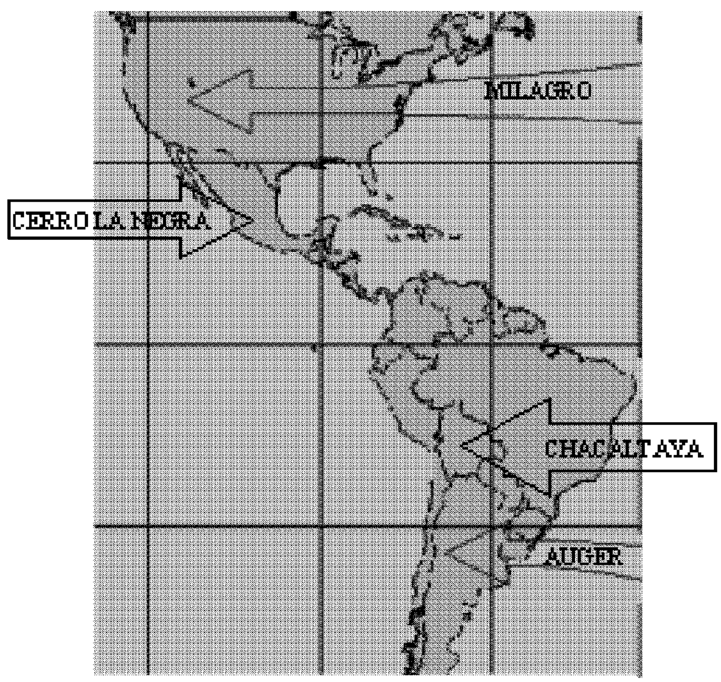

FIGURE 3. Geographic location of the network of observatories.

Milagro will perform an all sky survey of the Northern Hemisphere at energies between 250 GeV and 50 TeV; it has a large area (60x80 m^2) and a wide field of view (1 sr). It is located in the mountains of Northern New Mexico at 2650 m a.s.l., latitude 35.9° N. A prototype detector (Milagrito) was operated from February 1997 to May 1998. Milagrito was about 35x55 m^2 [12]. This prototype has taken data during the Mrk 501 very intense and long-lasting flare in 1997; it also detected solar energetic particles from the November 6th, 1997 solar flare with energies exceeding 10 GeV as well an excess of events coincident in time and space with GRB 970417a [13]. Simulations show that Milagrito was sensitive to showers produced by primary gamma rays with energies as low as $\approx$ 100 GeV. The trigger required at least 100 PMTs to register at least one photoelectron within a 300 ns time window. The observed excess implies a fluence above 50 GeV between 10^{-3} and $10^{-6} ergs/cm^2$ and a spectrum extended up at least a few hundred GeV. Then, if it is so, the γ rays observed by Milagrito from GRB 970417a imply that the source is relatively nearby.

The Pierre Auger Observatory

The Pierre Auger international collaboration is constructing the Observatory in Argentina with the main aim to search for ultra high energy cosmic rays. The detector will consist of a surface array made of about 1600 water Cherenkov tanks and a set of fluorescence detectors. The Auger observatory is located in the province of Mendoza, Argentina at $\approx$ 35° S, at 1400 m a.s.l. equivalent to 875 gr/cm^2. The capability to search for GRBs with the Auger observatory has been already considered by DuVernois and Beatty [14]. For the case of detection of short transients on single particle counting rates in the surface detector, the energy range of about $10 \leq E \leq 100$ GeV can be achieved. The huge active area of the Auger detectors largely compensate the altitude gain factor of Chacaltaya's. The paper by DuVernois and Beatty [14] describes in detail the potentiality of the Auger experiment to detect γ-ray signals from GRBs.

MAIN STRATEGY

As it has been demonstrated by the INCA experiment, the detection by the single particle technique is very convenient, and very inexpensive; scaler modules constitute all the electronics required to monitor the counting rate. Detection of bursts of low energy gamma rays ($\geq 10GeV$) by means of the single particle technique could be very useful for at least two reasons: 1) detecting the GRBs itself and looking for a coincidence among distant detectors and 2) because by monitoring the single particle counting rates for each detector or each sector (see for example the case of the Milagro experiment) could be a continuous check of the correct performance of the detector. In this second case, it could be used as pre-alert signal for higher energy triggers. It is necessary to remember that a GRB duration ranges from a fraction of a second to several minutes, therefore there is enough time for the pre-alert successive triggers at higher energies. The advantage of this system is obvious: an increase of the energy range at very low energy measurement by the same detector.

The geographic position of the 4 detectors considered in America is shown in Figure 3. With them, Milagro and Cerro la Negra in the northern hemisphere and Chacaltaya and Auger in the southern hemisphere, it is possible to monitor continuously the whole sky. Figure 4 shows the sky regions covered by all four experiments. The field of view for each experiment is set at 30^o of zenith angle. We can see that practically the whole sky is covered with the 4 detectors. The most interesting astrophysical sources of high energy γ-rays, like pulsars, AGN's and objects unidentified by EGRET, as well as the TeV γ-ray sources, are included in Figure 4.

For the pair Chacaltaya-Auger the position of the Galactic Center is well viewed by both observatories. Furthermore, in Figure 13 of Ref. 2. we can observe the location of 215 galactic SNRs from the Catalog of Galactic SNRs by Green D.A. [15]. We can see that a large number of potential high energy γ-ray sources is observable from both sites.

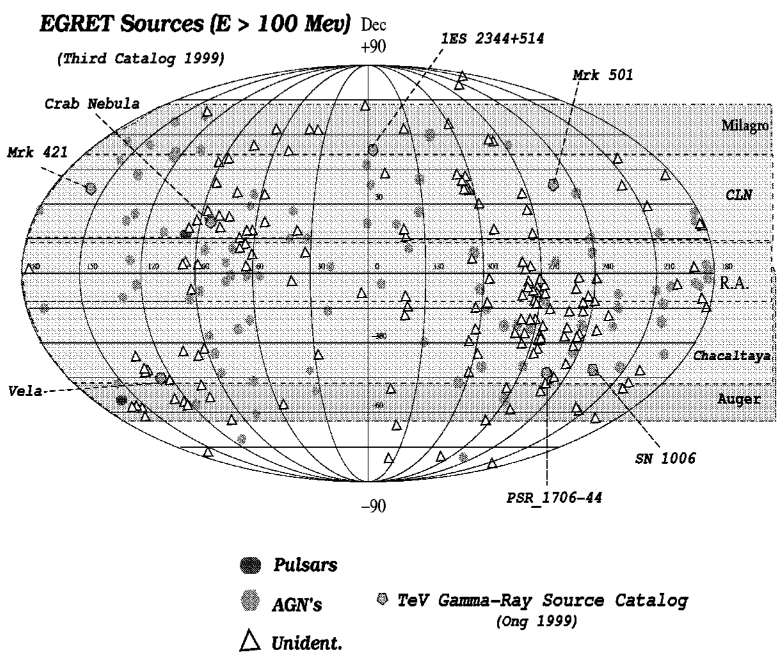

FIGURE 4. Coverage of the sky by the network of 4 observatories. Notice that the full sky is covered by the field of view of the 4 observatories.

TIME CORRELATIONS IN COSMIC RAYS

Another possibility to be explored is the observation of correlations in arrival times of air showers. As it is well known, the primary cosmic rays are accelerated at discrete sites in our Galaxy and roam around for millions of years before hitting the Earth. Since they are mostly charged particles (protons, helium, carbon up to iron ions), they are deflected by the interstellar magnetic fields and loose memory of their origin when they accidentally arrive. This circumstance implies that their directions of incidence are not related to the locations of the sources. Therefore, the arrival directions and the arrival times of EASs are completely random.

However, the existence of a non-random component of the air showers was suggested by C.L. Bhat in 1980 [16] and by Fegan et al. [17] on the basis of their observations of unusual increases of EAS rates. In particular the experimental results published by G.R. Smith et al. in 1983 [18] reported the observation of 32 EASs of mean energy ≈ 3 PeV within five minutes. The trigger rate of background cosmic rays was 1.1 per five minutes. Therefore the coincidental probability to observe such 32 EAS events was as low as 10^{-35}. Another work on searches for time correlations in cosmic rays has been done by O. Carrel and M Martin [19].

More recently, Katayose *et al.* [20] applied a sophisticated algorithm to arrival times of EAS in order to extract "clustered events" from them. They picked up five clustered events and by plotting their arrival direction they found that the events are concentrated around the direction of the galactic plane.

On the other hand, the Large Area Air Shower (LAAS) group (a joint collaboration of several Japanese institutions) is running with 13 air shower stations operated independently and spread over large distances (the more distant at more than 1000 km) in Japan. The LAAS collaboration is searching for non-random components in arrival times of EAS using a large amount of data collected by the network; it has reported, [21]- [23], results on successive air shower analysis using data from six LAAS stations. They suggest that the arrival directions of successive air showers (SAS) events are clustered around the galactic plane. This fact is still under debate and needs a confirmation. As has been pointed out by Aglietta *et al.* [24], if the results of LAAS are confirmed, they could lead to many intriguing speculations.

CONCLUSIONS

Detection of GRBs from ground-based experiments has enormous potential for revealing new information about the energy spectrum, origin and propagation of γ-rays through space. This potential is greatly increased if GRBs are detected by two or more ground-based experiments without ambiguity. The possibility of continuously monitoring GRBs by observing GeV γ-rays by the Milagro-Cerro la Negra-Chacaltaya-Auger network seems to be feasible. If we consider higher energies there exists a possibility of studying the non-random component of cosmic rays as well.

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