Observation of GRBs at tens of GeV with a full-coverage air shower array at 6000 M Elevation

ZHAOYANG FENG[1], YIQING GUO[1], YI ZHANG[1], TIANLU CHEN[2], HONG LU[1], HONGBO HU[1]
[1]*Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[2]*Department of Mathematics and Physics, Tibet University, Lhasa 850000, China*
fengzy@ihep.ac.cn
DOI: 10.7529/ICRC2011/V09/1122

Abstract: Fermi-LAT has observed 27 gamma-ray bursts (GRBs), four of which contain γ-rays with energies about tens of GeV. However, the multi-GeV photons are very rare because the photon flux decreases rapidly with the increase of photon energy. A large area, wide field of view detector with high duty cycle is needed in order to have a comprehensive study of such kind of high energy GRBs. In this paper we propose a large, full-coverage detector at 6000 m elevation to approach such a purpose. The site candidates, detector proposal and logistics are discussed. Preliminary sensitivity of such a detector are given according to a full simulation.

Keywords: GRB, tens of GeV, full-coverage, high altitude

1 Physical Motivation

The emission in the GeV$-$TeV photon energy range from gamma-ray bursts (GRBs) is expected through a number of processes which could occur either in the prompt emission [1] or the afterglow phase [2]. The (very) high energy emission opens a new window to probe the nature of GRBs, for instance the three component emission of GRBs [3] and the environment parameters of the GRB jets. It is also important for probing the quantum gravity effect [4] and the extragalactic background light induced absorption of high energy photons [5].

However, up to now only a limited sample of GRBs at multi-GeV energy range have been detected, with modest to low significance. For GRB940217, EGRET observed 2 photons with energies $\sim$3 GeV, and one photon with energy 18 GeV 90 minutes later [6]. As of February 2011, Fermi-LAT detected 27 GRBs in two and a half years' run [7], four of which (GRB080916C, GRB090510, GRB090902B and GRB090926) have γ-rays with energies up to tens of GeV. There are also many ground-based experiments around the world, including Air Shower Arrays (such as the ASγ experiment[8], ARGO-YBJ [9], Milagro [10] and Pierre Auger Observatory [11]) and Imaging Atmospheric Cherenkov Telescopes (IACTs) (such as Wipple [12], MAGIC [13] and HESS [14]), to search for GRBs. Among all these experiments, only the prototype of Milagro called Milagrito reported a possible detection of signals associated with GRB970417 with 3σ confidence level [15].

It will be very important to enlarge the sample of very high energy GRBs. However, as the photon energies increase, the flux decreases rapidly with a power law with an index of about -2. In general, the sensitivity of space-borne experiment to high energy γ-rays is limited by its finite area. The ground-based detector is a more promising technique for the detection of GeV$-$TeV gamma ray emission from GRBs due to the large detection area. However, the current Air Shower arrays suffer from the difficulty of poor γ/hadron discrimination, and the high threshold energy(hundreds of GeV) due to their low altitude. The search for GRBs with IACTs are also limited by the small duty cycle ($\sim$ 10%) and small field of view (FOV, $\sim$0.02 sr).

In this paper, we propose to build a full-coverage detectors at 6000 m elevation aiming to observe 10 GeV to sub TeV GRBs (mainly in tens of GeV energy range) that are coming from cosmological distance, We name it as Cosmological GAmma rays Observatory (CGAO). CGAO can work in both shower and single particle mode.

We noted that there was similar proposal of Large Aperture GRB Observatory (LAGO) [16] operating arrays of WCD with single particle technique in high altitude sites (above 4500m a.s.l.). CGAO and LAGO can be important for the complementary detection of GRBs with different sky coverage.

2 Cosmological GAmma rays Observatory

The CGAO project aims to observe GRBs at tens of GeV with a full-coverage air shower array at 6000 m elevation. In this section, we discuss one possible site in Tibet and the detector. The performance of CGAO is studied according to a full simulation.

2.1 Site

As early proposed by L.W. Jones and D.M. Mei [17], Sheta, a site accessible by road and with an elevation of about 6100 m near New Tingri in Tibet, about 100 km north of Mt. Everest, is a good candidate for CGAO. We have organized a team consisted of seven physicists and engineers to investigate this site at June 2011. Details (weather, etc.) of this site will be reported separately in this conference [18].

2.2 Detector

In principle the choice of detector type is site-dependent. Detectors of CGAO should be set up relatively easily, considering the difficulty to work at an altitude about 6000 m. The scintillator counter is a very mature technique. It can be very easy to be setup and maintained on site. If we want to go to a site above 6000 m elevation, scintillator counter is almost the only possible detector we can adopt. The shortcoming of scintillator counter is the high cost. Considering that the budget is of the order of RMB 100 millions, we design a 2500 m^2 scintillator counter array at 6100 m altitude in Sheta.

The similar scintillator counter as that used in the ASγ experiment [19] is adopted in this work. Each counter is set-up in an upside-down pyramidal style and has a plastic scintillator plate of 0.5 m^2 (0.707 m $\times$ 0.707 m) in area and 3 cm in thickness and is equipped with a fast timing photomultiplier tube (PMT). A lead plate of 0.5 cm thick is put on the top of each counter in order to increase the counters sensitivity by converting photons in an electromagnetic shower into electron-positron pairs. The recording of signals is made on time and charge information by the fast timing PMT. Detectors are symmetrically placed a $\sim$6000 m^2 foursquare region with $\sim$40% active area.

2.3 Simulation and Reconstruction

A full Monte Carlo (MC) simulation is performed for the air shower development in the atmosphere by Corsika (version 6.674) with QGSJET01c being chosen as the hadronic interaction model and for the detector response by special Geant4 code based on the AS simulation package [20].

All shower particles in the atmosphere are traced down to the minimal energy of 1 MeV. The cosmic ray (CR) events (only proton in this work) are generated with the zenith angle from $0^{\rm o}$ to $70^{\rm o}$, and the azimuthal angle from $0^{\rm o}$ to $360^{\rm o}$. The γ-ray events are generated with zenith angle less than $40^{\rm o}$ and azimuthal angle from $0^{\rm o}$ to $360^{\rm o}$. The differential energy spectrum of the primary γ-ray photons is assumed to be E^{-2}. Simulated energies are from 10 GeV to 100 TeV for CRs and 5 GeV to 1 TeV for γ-rays. All the events are generated uniformly within a 400 m $\times$ 400 m area from the center of the array, and the procedure is repeated 10 times in order to increase the data statistics.

Considering that the secondary particle number of tens of GeV CR shower in $\sim$6000 m elevation is about 3 time larger than that in 4300 m elevation, and that the measured noise rate at 4300 m (Yangbajing) is $\sim$450 Hz/m^2, we adopt 1500 Hz/m^2 background noise rate for detector simulation. The trigger condition is that any fourfold coincidence in 600 ns time window must occur in the scintillation counters recording 0.8 particles or more in charge. The trigger rate is $\sim$30 kHz.

The reconstructed arithmetic of Tibet Air Shower Array [19] is adopt in this work.

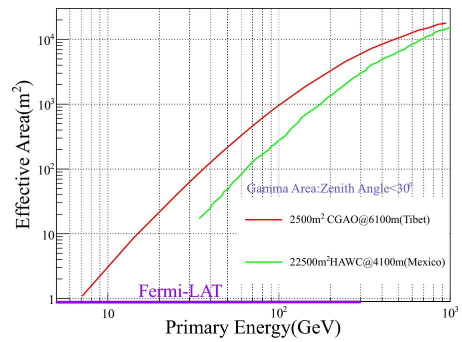

Figure 1: Effective area of CGAO, compared with Fermi [21] and HAWC [22].

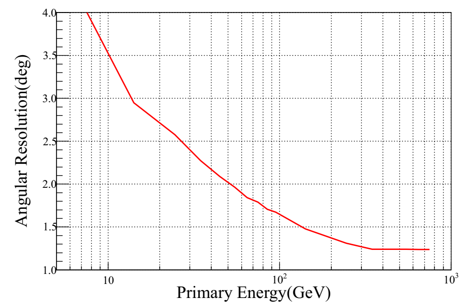

Figure 2: Angular resolution of CGAO.

2.4 Preliminary Performance

Only the events with residual errors of reconstructed arrival directions by means of the least-squares method less than 1.0 m are used for analysis. The preliminary performance is summarized as follows.

1) The effective area of CGAO is shown in Figure 1, compared with that of Fermi and HAWC. At 10 GeV the effective area of CGAO is only several square meters, but it increases rapidly to 100 square meters at $\sim$35 GeV and 1000 square meters at $\sim$100 GeV.

2) The angular resolution of CGAO (containing 50% events) with zenith angle smaller than 30^o is shown in

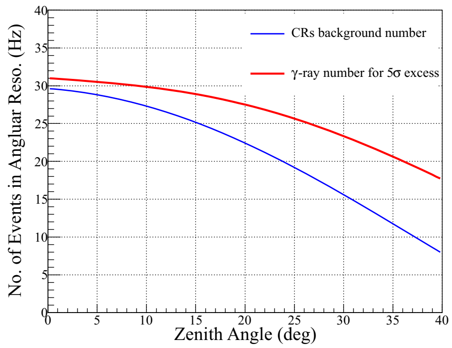

Figure 3: Event rate of CR background and the corresponding γ-ray event number for 5σ excess as functions of zenith angle. The time duration is adopted to be 1 second.

Figure 2. It is not very good but might be enough for the search of GRBs.

3) As a conservative and rough estimate, we use the average angular resolution of $10-100$ GeV γ-rays to calculate the CR background. The event number of CR background during one second as a function of zenith angle is shown in Figure 3. Also plotted is the corresponding event number of γ-rays for 5σ excess, calculated according to Poisson distribution. About 31 γ-rays are needed for 5σ excess for one GRB lasting $\sim$ 1s and coming from the zenith.

4) To estimate the sensitivity of CGAO, we take GRB090510, one of brightest GRBs observed, as an example. We assume the extension of power-law component measured by Fermi-GBM and Fermi-LAT (3.011×10^{-9}(E/GeV)$^{-1.6}$ cm^{-2}s^{-1}keV^{-1}) [23].

There are more than 10 photons with energies above 1 GeV being detected by Fermi-LAT, with the highest observed energy 33 GeV. While the source position is set at a zenith angle of 20^o, HAWC is expected to be able to detect it with 5σ significance if the spectrum extends to 50 GeV. If the spectrum extends to 125 GeV (and is attenuated by the extragalactic background light (EBL) model of Gilmore [24]), then HAWC would detect 200 γ-rays [22].

With the same EBL mode and the same zenith angle as HAWC calculation, we find that if the spectrum just extends to 23 GeV, CGAO can reach a 5σ detection. If the spectrum extends to 50 GeV, 166 γ-rays (31σ significance) would be detected by CGAO. If spectrum extends to 125 GeV, 666 γ-rays (126σ significance) would be detected by CGAO. From the significance value, we can conclude that the sensitivity of CGAO is nearly 6 times better than HAWC above 10 GeV, for short GRBs (one seconds) such as GRB090510. The simulated light curve of GRB090510 detected by CGAO assuming the spectrum extend to 125 GeV is shown in Figure 4.

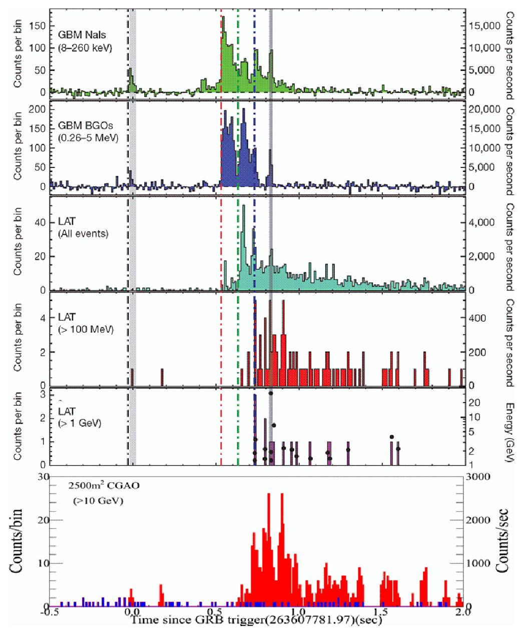

Figure 4: Light curves of GRB 090510. The first to fifth panels are the light curves detected by Fermi-GBM and Fermi-LAT at different energies [4]. The sixth panel is the simulated light curve could be detected by CGAO assuming the spectrum extended to 125 GeV and the zenith angle of 20^o. The blue histogram is CRs background and the red one is γ-rays signal.

3 Discussion

A suitable site should have proper supporting infrastructure, such as road and electric power supply, good weather condition etc. Except Sheta, there are some other site candidates above 5000 m elevation in Tibet, such as Kamba La, Dajia Lake, Everest base camp and Mopuyong Lake. The elevations and atmospheric pressures of these candidates are listed in Table 1.

Except scintillator counter, WCD is considered too. WCD is also a mature technique that is widely used in astrophysical experiment. The advantage of WCD is the low threshold and high detection efficiency of secondary γ-ray photons. The cost of WCD is also much lower than scintillator counter. With the same budget, the area can be significantly larger. However, in order to construct a WCD array the site altitude is preferred to be lower than 6000 m. Another problem of WCD is that the water may freeze in the winter and the PMTs will be broken. The expected performance of CGAO using WCD is under study.

An challenging idea is to setup a PMT array directly in a high altitude, clean lake. The depth and interval of upward-looking PMTs are just about several meters, which need to

Site Name	Elevation	Atmospheric Pressure
Sheta	6100 m	477 g/cm^2
Kamba La	5450 m	520 g/cm^2
Dajia Lake	5200 m	538 g/cm^2
Everest base camp	5200 m	538 g/cm^2
Mopuyong Lake	5010 m	553 g/cm^2

Table 1: Candidate sites of CGAO in Tibet

be optimized with Monte Carlo study. To obtain a stable data quality, we may need to monitor the water depth at all times and adjust automatically the PMTs. A key problem of this kind of design is how to shield the light. The advantage of this kind of detector is that it can avoid the freezing problem and cheaper. There are 17 lakes above 5000 m elevation in Tibet. Dajia Lake (with very convenient transportation) and Mopuyong Lake (with very convenient transportation and existing electric power supply), are probably very good candidate sites.

Logistics is very important too. The site should be accessible so that it will be very convenient if we can use truck to transport the heavy equipment, e.g. detectors, DAQ system and power equipment. It is also necessary to provide pressurized environments for the habitation and laboratories (data collection, equipment repair, etc.) for people in residence. Outdoor activities such as setting up, adjusting, and maintaining the detector system, might require supplemental oxygen. The transport of personnel would be preferable to use a helicopter. An appropriative helicopter can be offered as the price become cheaper and cheaper.

4 Summary

A full-coverage air shower array aiming to observe GRBs at tens of GeV is proposed at 6000 m elevation in Tibet. The candidate sites, detector selection and logistics are discussed. Preliminary performance is presented. It is expected to significantly improve the understanding of GRBs, the related astrophysics and basic physics, if such an experiment can become a reality.

References

[1] Pe'er, A., et al. and Waxman, E., Astrophys. J., 613, 448(2004)
[2] Rm'em Sari, et al., Astrophys. J., 548, 787(2001)
[3] Zhang, B. B., et al., Astrophys. J., 730, 141 (2011)
[4] Abdo, A. A., et al. 2009, Nature, 462, 331
[5] Abdo, A. A., et al., Astrophys. J., 723, 1082 (2010)
[6] K. Hurley, et al., Nature, 372, 652(1994)
[7] N. Omodei et al., The Fermi-LAT GRB Catalog, 2011 Fermi Symposium, 9-12 May 2011, Rome, Italy
[8] Amenomon, A., et al., Astron. Astrophys. 311, 919(1996)
[9] Aielli, G., et al. 2009, ApJ, 699, 1281
[10] Abdo, A. A., et al. 2007, ApJ, 666, 361
[11] Bertou, X. 2008, International Cosmic Ray Conference, 4, 441
[12] Horan, D., et al. 2007, ApJ, 655, 396
[13] Garczarczyk, M., et al. 2010, American Institute of Physics Conference Series, 1279, 312
[14] Aharonian, F., et al. 2009, Astron. Astrophys., 495, 505
[15] Atkins, G., et al., Astrophys. J., 533, L119(2000)
[16] Allard, D., et al. 2009, arXiv:0906.0814
[17] Jones, L. 1999, International Cosmic Ray Conference, 2, 524
[18] DANZENLUOBU et al., , ICRC 2011, ID 1348
[19] Amenomori M, et al., ApJ, 678,L53-L56 (2008).
[20] Zhaoyang Feng et al., , ICRC 2011, ID 1058
[21] Atwood, W. B., et al. 2009, ApJ, 697, 1071
[22] Brenda Dingus, talk at Multi-Messenger Astronomy of Cosmic Rays Conference, KIAA, Beijing April 11-14, 2011
[23] Fermi LAT, T., & GBM Collaborations 2010, arXiv:1005.2141
[24] Gilmore, R. C., Madau, P., Primack, J. R., Somerville, R. S., & Haardt, F. 2009, Mon. Not. R. Astron. Soc., 399, 1694