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Capability of the Scaler System of the Milagro Pond to Observe GRBs

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Abstract: Gamma-ray bursts (GRBs) have been observed up to energies of a few GeV by satellite observatories. In particular, GRB 941017 showed a spectral component extending beyond 200 MeV and distinct from that previously observed at keV energies. Ground-based telescopes have marginally detected very high energy emission (>100 GeV). For instance, the Milagrito observation of GRB 970417a hinted at a distinct higher-energy component inconsistent with an extrapolation of the observed emission at keV-MeV energies. Observations of gamma-ray bursts at GeV energies will bring new insights about different emission mechanisms and serve to constrain current GRB models. Milagro is a wide field (2 sr) high duty cycle ($> 90\%$) ground-based water Cherenkov detector. It triggers mainly on extensive air showers (EAS) in the energy range from 100 GeV to 100 TeV. However, individual photomultiplier tube counting rates (scalers) are sensitive to EAS with energies as low as $\sim$ 1 GeV. In this work, the capabilities of Milagro to detect the high energy component of GRBs using the scalers system are presented and compared with other observatories such as the Pierre Auger observatory's water Cherenkov tanks.

Introduction

Gamma-rays Bursts are the most luminous explosions known in the Universe. They last from a few tenths of a second to hundreds of seconds and they are isotropically distributed on the sky [1]. They have been extensively studied in the 20 KeV to 2 MeV range by satellites [2, 3] and up to several GeV by the EGRET instrument [4]. These studies revealed that there is no cut-off in the GRB spectrum. Furthermore, some models predict TeV emission [5]. Therefore, the spectra of GRBs might extend up to high energies. The high energy component of GRBs can be studied by ground detectors such as the Pierre Auger Observatory or the Milagro detector. The high energy photons (primary particles) that hit the molecules of the upper layers of the atmosphere produce Extensive Air Showers (EAS) that propagate through to the surface of the Earth. As these relativistic charged particles of the EAS pass through purified water, they produce Cherenkov light that can then be detected by the photo-multiplier tubes (PMTs) in these observatories. The number of particles detected by the PMTs is correlated with the energy of the primary particle, while the arrival direction of the primary particle can be determined by the differences of the hit times between PMTs. This method requires a minimum number of PMTs to be hit within a time window of order a nanosecond for the reconstruction to be possible. Primary particles of energy $\sim$ 1 GeV result in very few isolated particles at ground level, they cannot be reconstructed. However, it is possible to gain sensitivity at the price of losing the energy and direction information of the primary particle by using what is known as a "Single Particle Technique" that consists in counting all the hits recorded by the PMTs with scalers [6]. Using this technique, the isolated particles originating from GRB photons at energies as low as 1 GeV can be detected as an excess in the counting rate over the background rate, for sufficiently intense GRBs. This excess can be searched for in coincidence with a satellite detection. Several ground-based experiments have been using this technique to attempt to detect the high energy component of a GRB [7, 8, 9, 10]. In particular, [11], using the Pierre Auger water Cherenkov tanks, concluded that the Pierre Auger Observatory is a competitive instrument for the detection of GRBs at energies from 10 MeV to 10 TeV. It is important to note that evidence of a marginal emission at TeV energies from GRB 970417a was reported by the Milagrito detector [12, 9].

In this work we study the capabilities of the Milagro scaler system to detect the high energy component of GRBs, calculating the minimum fluence expected to be detected.

Milagro Scaler System

Milagro is a ground-based water cherenkov gamma-ray detector, consisting of a large pond of water (60 m wide × 80 m long × 8 m deep) covered with a light-tight cover located at 2630 m above sea level in the Jemez mountains, New Mexico. The pond is instrumented with 723 PMTs divided into two layers under water: The "air shower" layer, at a depth of 1.5 m, with 450 PMTs and the "muon layer" at 6 m, with 273 PMTs used mainly for background rejection of cosmic rays. In order to increase the sensitivity of the experiment, 175 water Cherenkov tanks, each one containing a PMT, were distributed around the Milagro pond.

Milagro can be operated using the individual PMTs (scalers). The scaler system uses a CAMAC data acquisition system to count every single particle (sometimes caused by small showers) that hits the individual PMTs every second at two threshold levels: Low threshold (∼0.25 photoelectrons) and high threshold (∼4 photoelectrons). The PMTs are combined in groups of 8 or 16 PMTs in a logical "or," in order to reduce the number of scaler channels needed to record all the hits. The minimum time separation required to record two hits on different PMTs within the same group is between 20 and 30 ns.

Simulations

In order to determine the capabilities of the Milagro Scaler System to detect GRBs, we simulated 15 million showers with CORSIKA [13, 14]. The showers were produced at fixed energies of 1 GeV, 10 GeV and 100 GeV, with zenith angles from 0 to 10 degrees. The Milagro scaler response to these showers was studied using GEANT4 simulations

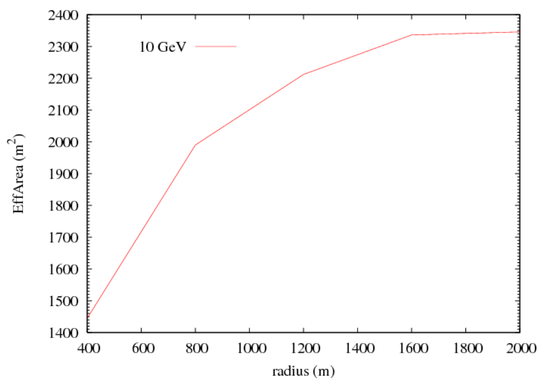

Figure 1: This plot shows the saturation of the effective area beyond a radius r=1600 m for showers created by a 10 GeV photon. This means that it is not necessary to throw showers at a larger radius in order to increase significantly the effective area. Points representing the effective area for radius less than $r = 400$ m, $r = 800$ m, $r = 1200$ m,$r = 1600$ m and $r = 2000$ m are connected by lines.

[15, 14].The shower cores were thrown over an area of radius 2 km, as shown in Fig. 1.

Effective Area and Fluence

Even when the core of a given shower does not hit the physical area (60 m × 80 m) of the Milagro pond, the secondary particles generated in the EAS can still hit it. Therefore, the effective area is given by the area over which the secondary particles produced by a given number of $thrown$ showers over the radius r, hit the PMT with a probability different than zero. Mathematically, the effective area is given by

$$A_{eff} = \left(\frac{hits}{thrown}\right)\pi r^2, \tag{1}$$

According to our simulations, the effective area of the Milagro scaler system for EAS produced by gamma rays at energies between 1 GeV and 100 GeV increases with energy as a power law given by (Figure 2):

$$A_{eff}/m^2 = 39.4(\mathrm{E/GeV})^{1.74} \tag{2}$$

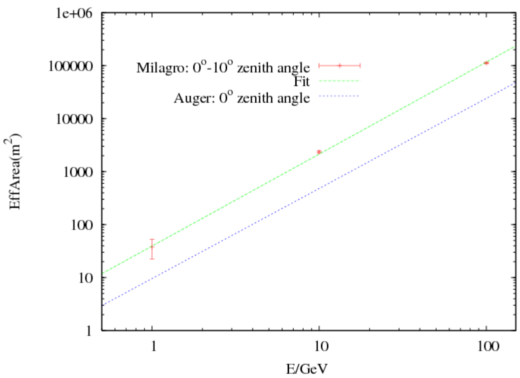

Figure 2: Gamma-ray effective as a function of energy at low threshold trigger for the Milagro scaler System. The green line shows the fitted function to the effective area points (red crosses). The blue line shows the effective area of the Auger tanks, assuming a thrown area of 16000 m^2.

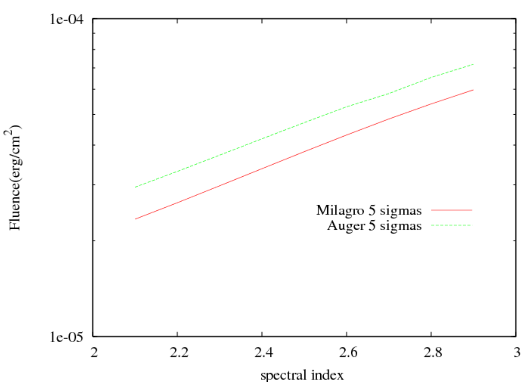

Figure 3: This Figure shows the minimum 1–100 GeV fluence for a 1 second GRB needed in order to be detected by the Milagro scaler system, as a function spectral index. The green line shows the minimum required fluence for Auger in the same energy interval, at 5σ

On the other hand, consider if the differential spectrum of the GRB is given by a power law $\frac{dN}{dE} = K(E/\mathrm{GeV})^{-\alpha}$ between $E_{\min}$ and $E_{\max}$ with spectral index α between 2 and 3, where K is a constant. K can be obtained from the condition to detect a GRB with a statistical significance s :

$$s * \mathrm{noise} = K \int_{E_{\min}}^{E_{\max}} A_{eff} E^{-\alpha} dE \qquad (3)$$

where noise is the expected one standard deviation fluctuation in the air shower low threshold scaler rate. The rate can reveal short and long term trends due to atmospheric conditions and can vary due to noisy channels, so the rate should be corrected to take these factors into account. Here, we took noise to be $\approx$ 15 kHz, which is determined from the sigma of the distribution of the rates in one second time intervals. Due to small showers that produce multiple hits in the PMTs, the sigma is a factor of 3 or 4 larger than the square root of the rate. This effect was also observed in the Milagrito analysis of GRB 970417a [9]

After determining K from Eq. 3, the minimum fluence F, expected to be detected with the Milagro scalers system for 1 s duration GRBs is given by:

$$F = K \int_{E_{\min}}^{E_{\max}} E^{1-\alpha} dE \qquad (4)$$

In this case, Eq. 4 has an analytical solution which is highly dependent on $E_{\min}$ given a fixed $E_{\max}$. For Δt duration, F should be multiplied by $\sqrt{(}\Delta t)$. The fluxes (erg cm^{-2}) detected by BATSE [16] in the range from 25 keV to a few MeV are typically between 3×10^{-8} and 4×10^{-4}. In Fig. 3 we show the Milagro and Auger minimum fluences expected in the range of energies from 1 GeV to 100 GeV for different spectral indices, for 1 s long bursts. For Milagro, the secondary particles were simulated with an incident angle between 0 and 10 degrees and analyzed using the low threshold, 0.25 photo-electrons (pe). The Auger curve was obtained at zenith angle equal to 0 degrees and a trigger threshold of 4 ADC counts ($\sim$ 3 pe) on a single PMT [11].

From Fig. 3, it is expected that some GRBs would be detectable around some few times 10^{-5} to 10^{-4} erg cm^{-2}. Upper limits in the 1–100 GeV energy range for satellite-detected GRBs in the field of view of Milagro for different redshifts are given in [17]. It is important to note that no cuts in energy were assumed, i.e. no attenuation due to the intergalactic infrared emission and cosmic microwave background was considered in these fluence calculations. In order to compare the sensitivity curves obtained here to those obtained for the Pierre Auger Water Cherenkov tanks, we redo the [11] calculations in the range of energies studied here using the results given in [11]. We find that the Auger sensitivity is comparable to the Milagro sensitivity at 5 σ to detect GRBs in the range of energies studied here. At energies below 1 GeV, the probability of a charged particle hitting the PMTs of Milagro is almost zero.

Conclusions

Our results show that when operated in scaler mode, Milagro is a competitive detector to search for emission produced by GRBs in the 1–100 GeV energy range. However, no GRB emission has been detected in the analysis of more than 100 GRBs detected by satellites in the field of view of Milagro since the beginning of 2000 and upper limits in the fluences are reported by [17]. We showed that the Milagro scaler system is about 1.3 times more sensitive to the detection of GRB emission than the whole array of water tanks of the Pierre Auger Observatory from 1 to 100 GeV. Finally HAWC will be more sensitive than Milagro and is expected to detect the high energy component of GRBs using its scaler system.

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