PROCEEDINGS OF SCIENCE

The Large Aperture GRB Observatory

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The Large Aperture GRB Observatory is an international project started in 2005 aiming at a better understanding of Gamma Ray Bursts (GRB) by constraining their emission at high energies, above 1 GeV, where the fluxes are low and direct measurement by satellites are difficult. This goal can be achieved by operating Water Cherenkov Detectors (WCD) at high altitude sites in order to detect air showers produced by high energy photons. In order to be efficient in the 1 GeV - 1 TeV energy range, the one probably most relevant for GRB physics, background rates are measured by scalers and GRB are searched by the Geiger technique.

As of 2010, WCD are in operation in Sierra Negra (Mexico, 4650 m a.s.l.), Chacaltaya (Bolivia, 5200 m a.s.l.), Marcapomacocha (Peru, 4450 m a.s.l.), and other sites are planned in Venezuela (Pico Espejo, 4750 m a.s.l.), Argentina, Brazil, Chile, Colombia, and Guatemala. Most of the new sites will not be at high enough altitudes to detect GRB, but will provide valuable measurement of secondaries at ground level, relevant for solar and Heliospheric physics.

4th School on Cosmic Rays and Astrophysics,
August 25- September 04, 2010
Sao Paulo Brazil

PoS(CRA School)036

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1. Gamma Ray Bursts

Since their discovery at the end of the 60's by the US military satellites VELA[1], the Gamma Ray Bursts (GRB) have been of high interest to astrophysicists. A GRB is characterised by a sudden emission of gamma rays during a very short period of time (between 0.1 and 100 seconds). The luminosity reached during this flare, assuming the emission is isotropic, is typically between 10^{51} and 10^{55} ergs. The astrophysical source of these bursts is still not totally clear but good candidates are coalescence of compact objects (neutron stars) fort short bursts (less than 2 seconds), and supernovae produced by very massive stars (hypernovae) for the long bursts (more than 2 seconds). Mechanisms based on internal shocks of relativistic winds in beamed relativistic shocks give good agreement between theory and observations.

A first large data set of GRB was provided by the BATSE instrument on board the Compton Gamma Rays Observatory (1991-2000). From this data set the two types of GRB (short and long) were identified, and the isotropy of GRB was verified. However, a deficit of faint GRB was observed pointing to a non uniformity of sources. Detection of GRB by BEPPO-SAX (1997-2002) allowed the determination of their distance by measuring their afterglow in optical wavelength. They were found to be of cosmological origins, and their fluence was determined. Current measurements (mainly by Swift and Fermi) provide more information on short GRB afterglows and high energy photon fluences.

However, when the photon fluxes reach the level of a few photons per square meter, satellites observations are no longer possible, and one has to design ground based experiments. A classical method to use is called the "single particle technique"[2], where the detectors are used to count individual particles. As this is in some sense similar to using the detectors in Geiger mode, this technique will be referred to in this paper as the "Geiger technique", which we believe is more descriptive and easier to grasp for physicists not used to the single particle technique.

When high energy photons from a GRB reach the atmosphere, they produce a cosmic ray cascade with secondaries at ground level that can be detected. The energies are usually too low to produce many particles detectable in coincidence at ground level (even at high altitudes). However, as a lot of these photons are expected to arrive during the burst, some of them could produce a shower which would give one or a few hits in a ground based detector, on a time scale of one second. One would therefore see an increase of the background rate on all the detectors of a ground array on this time scale. This technique has already been applied in EAS-TOP[2] in Italy, INCA[3] in Bolivia and ARGO[4] in Tibet. A general study of this technique can be found in [5]. It had not in the past been applied to arrays of Water Cherenkov Detector (WCD). The main advantage of using the water Cherenkov technique over the usual scintillator/RPC detectors is the WCD sensitivity to photons, which represent up to 90% of the particles at ground level for high energy photon initiated showers. This significantly increases the efficiency of detection, as reported in [6].

This method has been implemented since March 2005 in the Pierre Auger Observatory[7]. The Pierre Auger Observatory[8] is the largest cosmic ray observatory in operation. It is composed among other detectors by 1600 WCD located in Malargüe, in Argentina. Despite its low altitude (1440 m a.s.l.), its large collecting surface (16000 m^2) and sensitivity to secondary photons makes it a possible competitor to higher altitude experiments. However, its operation as the largest UHECR observatory limits its performances as a GRB detector, as its WCD are calibrated to detect high energy showers.

The Large Aperture GRB Observatory (LAGO) has been a spin-off from the Pierre Auger Observatory, aiming at reaching a similar sensibility to GRB with the Geiger technique by operating WCD similar to the Auger ones but at high altitude mountain sites and with an optimized calibration and DAQ for the Geiger technique. It started in 2005 as a collaboration between groups from Argentina, Bolivia and Mexico and has in 2010 extended to Venezuela, Peru and Colombia. Brazil, Chile and Guatemala are likely to join the LAGO collaboration in 2011.

2. The Geiger Technique

Ground arrays of detectors are usually used in coincidence to detect Extensive Air Showers (EAS) and determine the arrival direction of the primary, its energy and its nature. This however is only possible when many secondaries reach ground level, and the energy threshold is usually above 10^{12} eV, depending on the detector and its altitude. The likely most interesting energy range for new GRB observation is the 1 GeV-1 TeV range where the maximum photon production energy is expected. At 1 TeV, there is little expectation to detect any signal from GRB, and the EAS technique is therefore of little use.

The Geiger technique consists in using the detector in what one could call a Geiger mode, counting particles in each detector without looking for space or time coincidence. In this context, one expects one or a few particles to enter one detector for some of the primary photons of a GRB. However, the large flux of primaries over the full area of the ground array allows a significant increase in this background measurement during the time of the burst. No direction and energy reconstruction is possible at the level of individual photons, as they are not detected individually. Only the global increase is a sign for a GRB. This methods provides a very low threshold (as low as a few GeV, depending on the detector and its altitude), an estimation of the total energy of the burst above the threshold energy, and the timing structure of the high energy component of the GRB. This information is of significant interest when compared to complementary measurements at lower energies, as satellites can provide the arrival direction, and, most of the time, optical observations can provide the GRB redshift.

A good Geiger mode particle detector therefore needs to be located at high altitude (for a low threshold and to benefit from particle multiplication in the EAS cascades), have as large an area as possible, and ideally detect all the secondaries. The detector threshold to detect particles should be set as low as possible. The counting periods should be short, at the millisecond scale, in order to allow the best exploitation of the data, since most of the information will be in the time profile of detected secondaries. Finally, the detector should have an uptime as close as possible to 100%, as the threshold obtained for a reasonably sized detector are too high to detect most GRB, and only a closeby GRB occurring in the field of view of the detector, close to the vertical, where the atmospheric absorption is minimal, can be expected to be detected. In this rare event type of physics, together with a high uptime it is essential to have a good background rejection to be sure no spurious noise can be interpreted as a GRB.

3. LAGO Sites and experimental setup

In order to provide a relevant sensitivity to GRB search, a candidate site must be at high altitude, above typically 4500 m a.s.l.. A good infrastructure and easy access are obviously serious factors to consider when choosing a site. If high altitude sites are not available, a low altitude site can be used to operate the detector for solar physics studies.

The LAGO project has three sites with detectors in operation:

- Sierra Negra, Mexico, 4550 m a.s.l.: this is the first LAGO site, in operation since 2007. It is closeby the Large Millimetric Telescope (LMT) and above the Hawk site. Three 4 m^2 and two 1 m^2 WCD have been in operation at the site. Currently, new detectors of 40 m^2 are being considered.
- Chacaltaya, Bolivia, 5250 m a.s.l.: this is the highest site of LAGO as well as the one with the best infrastructure. Three WCD are in operation, two of 4 m^2 and one of 1 m^2. The detectors are housed in the Chacaltaya Cosmic Ray Observatory. They have been taking data since 2008.
- Marcapomacocha, Peru, 4450 m a.s.l.: this is the last LAGO site to be in operation, with one 2 m^2 WCD taking data since 2010. It is expected to take data for about one year during which higher sites in Peru are investigated.

Various other WCD are installed or being installed:

- at the Centro Atómico Bariloche in Argentina, a prototype is used for calibration and software tests since 2006;
- in Torino, Italy, a prototype has been used to check the increase in signal produced by the addition of wavelength shifter (Amino-G) in the water volume;
- in Caracas and Mérida, Venezuela, Bucaramanga, Colombia, Lima and Cuzco, Peru, prototypes are taking data at the universities;
- at Pico Espejo, in Mérida, Venezuela, three 4 m^2 WCD have been installed at 4750 m a.s.l.. Unfortunately, the Mérida cablecar which allowed to reach the detectors had a failure and was shut down in 2008.

In the future, new detectors are expected in the north of Chile and Argentina, in Brazil and Guatemala. Many high altitude sites are available in Peru and are being surveyed. Whenever the Mérida cablecar reopens, the Pico Espejo site will be instrumented.

All WCD share similar characteristics. They are filled with high quality purified water up to a level of 1.2 to 1.5 m, ensuring a full efficiency for photon detection through pair production in the water volume. The water is contained in a reflective and diffusive bag, made either of Tyvek™ or Banner, to achieve optimal uniformity of the detector response, independently on the direction and entry point of the particle in the detector. The water volume is overlooked by a single photomultiplier tube, usually of 8". The signal is digitized and readout by prototype electronics from the Engineering phase of the Pierre Auger Observatory, with custom made programming

Figure 1: Top left: picture of the LAGO collaboration at Chacaltaya (2006). Top right: WCD at Sierra Negra (blue and silver covered detectors), with the LMT in the background. Bottom left: WCD received on top of Pico Espejo. Bottom right: picture of the LAGO collaboration at Marcapomacocha (2010).

both of the DAQ CPU and of the low level FPGA trigger. New electronics is being developed for LAGO and the complete replacement of the currently used electronics is foreseen for 2011.

The FPGA have been programmed to provide every 5 ms 4 scalers per channel. The thresholds are set depending on the PMTs characteristics (gain and noise). At Sierra Negra, they are set to about 15, 150 and 600 MeV deposited in the WCD, while a special scaler counts undershoots. At Chacaltaya, where higher gain phototubes are available, they are set to $1/2$, 5 and 20 photoelectrons (about 2, 25 and 100 MeV deposited), with the same undershoot counter. The undershoot counter allows detecting High Frequency noise pick up on the cables. This is necessary to discriminate HF noise produced in electric storms from bursts of particles.

Monitoring and calibrating a WCD at high altitude is a more complex task than at sea level. The characteristic hump left by muons in a WCD (such as the one used for calibrating the Pierre Auger Observatory WCDs, see [9]) is smeared by the large background of electrons, positrons and photons. While the muon hump is almost indistinguishable on a pulse amplitude histogram, a characteristic shoulder can be seen on a charge histogram, shown on figure 2. One can therefore use this break point to intercalibrate detectors. The rate obtained for values above the break point (about 600 Hz.m^{-2} in Sierra Negra for example) is compatible with a muonic origin. It is important to note that as we are going to work in amplitude (scalers), we need to correct for different charge to amplitude ratio from different detectors. We therefore determine the average charge to peak ratio for each detector at the level of the break, and use this ratio to fix a threshold in amplitude equivalent to one muon for each WCD.

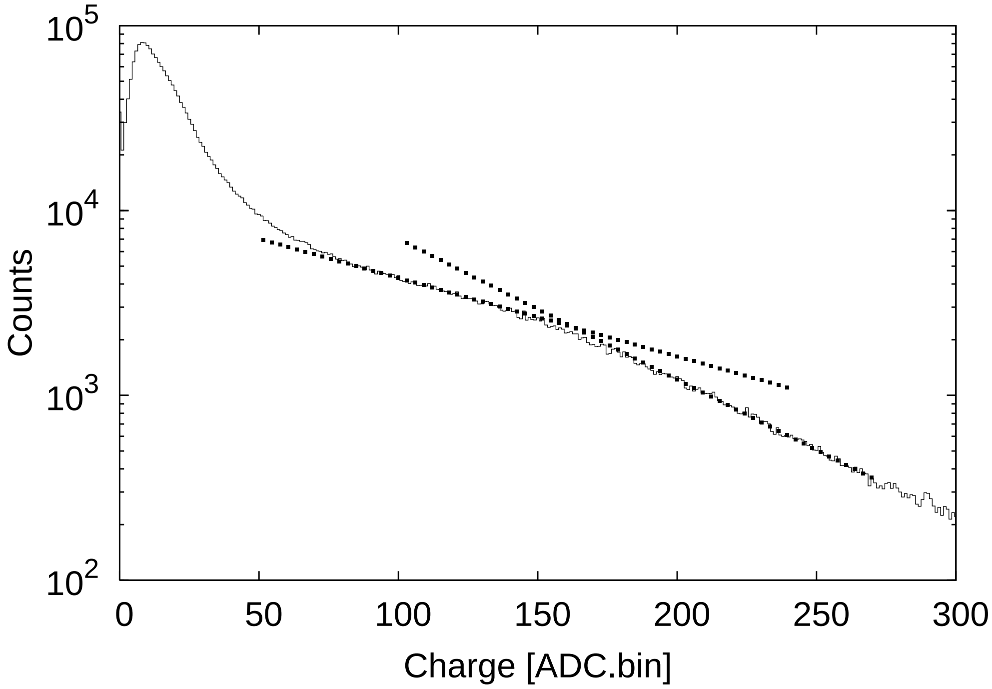

Figure 2: Charge histogram for one minute of data of a 4 m^2 detector at Sierra Negra. While there is no characteristic muon peak at this altitude, a change in the slope can be determined and used for calibration. The intersection of the two fitted dotted lines is used to determine a calibration reference point.

4. Data analysis

4.1 Search for satellite triggered bursts

A first way to find the high energy component of GRB using ground based WCD is to look at their signal when a GRB is reported by a satellite. A search for signal within 100 seconds of a GRB reported by a satellite was performed on data taken from early 2007 to April 2009. The Gamma-Ray Burst Online Index (GRBOX [10]) was used to extract bursts data and those happening for each site with an apparent zenith angle lower than 60 degrees were selected. A site is requested to have at least 2 detectors in operation at that moment, removing noisy detectors. 21 bursts for Chacaltaya and 20 for Sierra Negra passed these criteria, with one burst occurring in the field of view of both sites. The data were then averaged in bins of 100 ms and looked for excesses (4 σ with σ being the square root of the average rate over 200 seconds before the burst) in coincidence in at least 2 detectors. 2 bursts candidates for Chacaltaya and 2 candidates for Sierra Negra were selected by this method. These were individually checked and found consistent with statistical fluctuations. The highest signal in a 100 ms bin was then taken in order to set a limit to the fluence between 0.5 GeV and 100 GeV assuming a spectral slope of -2.2, with a formula based on simulations[11]. The fluence limits obtained are summarized in figure 3. The lowest limit obtained is 1.6×10^{-6} erg.cm^{-2} for GRB 080904.

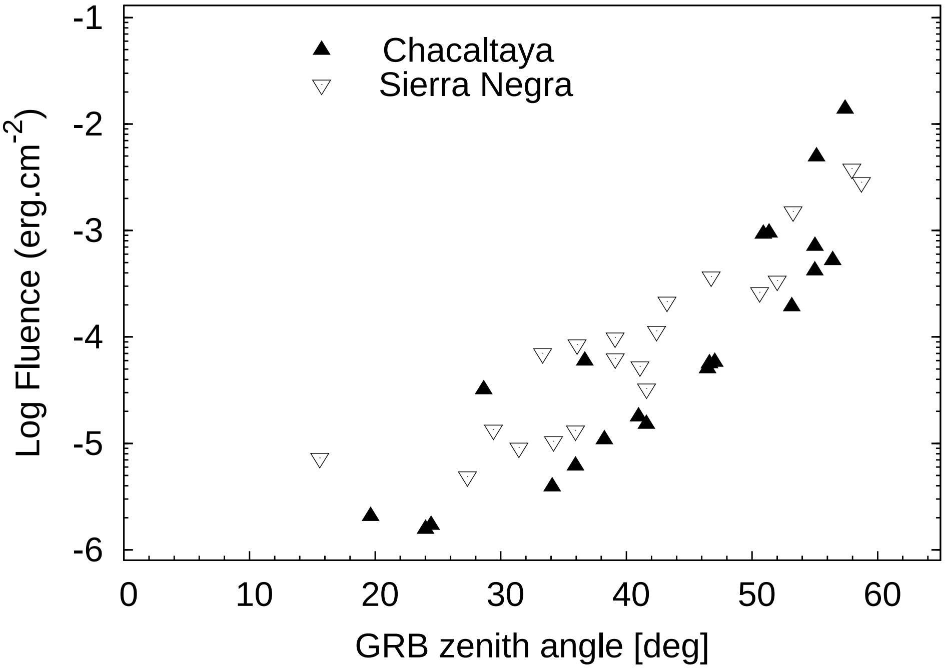

Figure 3: Fluence limits in the 0.5 GeV - 100 GeV range for the 41 bursts in the field of view of LAGO in the 2007 - April 2009 period, assuming a a spectral slope of -2.2. Filled up-triangles are bursts occurring in Chacaltaya field of view. Empty down-triangles are bursts in Sierra Negra field of view.

4.2 Search for self-triggered bursts

Bursts can furthermore be searched independently of satellite data. However, should such a burst be found it would be very difficult to attribute it to a cosmic event and reject any possible instrument noise, unless a correlation is found between sites. The current large angular separation between the two sites of LAGO makes such a coincidence unlikely. New sites in between (Venezuela, Peru, Colombia) will greatly increase this possibility.

Nevertheless, an algorithm to search for potential bursts while rejecting known noises has been developed and applied to the current data. Data are averaged in 100 ms bins and a running average is obtained by a sigma-delta method, modifying the estimated average by 0.001 Hz every time bin in the direction of the rate of this bin. The second scaler of each channel is used as the first one was found to be noisy on some detectors. The fluctuations of each detector are assumed to be the square root of the estimated average. The distribution of the fluctuation obtained by this method can be seen on figure 4. It is a Gaussian with width 1.18, due to correlated noise and to the method used to get the moving average.

A candidate burst is defined as an event where two detectors in coincidence see a 5 sigma fluctuation (equivalent to 5.9 of our estimated fluctuation) at least twice in a 5 minute window. 16 candidate bursts are found in Chacaltaya, probably produced by electronic noise as signals are also

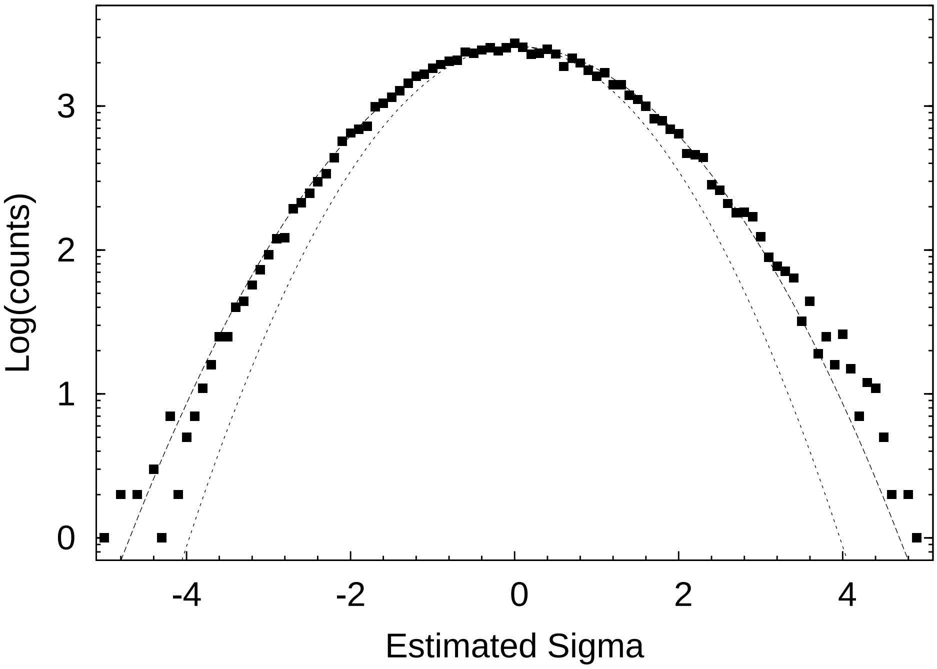

Figure 4: Distribution of the estimated fluctuations by the sigma-delta method, with the underlying Gaussian of 1.18σ width. A one σ Gaussian is also drawn for comparison.

found on a disconnected channel (it is unlikely that these are true signals produced for example by crosstalk as a GRB should manifest as many small signals and not by large PMT signals which are the ones likely to produce electronic crosstalk). These candidate bursts are likely HF noise produced by storms.

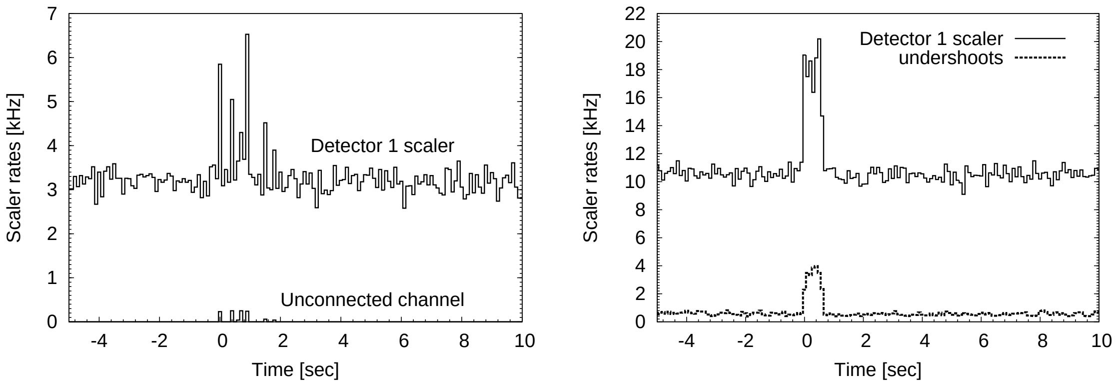

Figure 5: Example of noisy counting rates for Chacaltaya (left) and Sierra Negra (right). One channel is shown, together with an unconnected channel (left) or the undershoot counter (right). In both cases, signals in the other counter indicate the burst is due to noise.

The same analysis on the Sierra Negra data set provides a large set of 230 candidate bursts. While the Chacaltaya detectors are installed inside a building under a thin roof, the Sierra Negra ones are less protected and suffer more directly from the harsh weather conditions of the site. Furthermore, Sierra Negra is quite isolated (together with the close-by Pico de Orizaba) in a vast plain while Chacaltaya is in a mountain range. Finally, the hurricane season in Mexico is worse than the Bolivian summer rains, explaining these many triggers. All bursts are rejected as HF noise candidates, either using a disconnected channel or using the undershoot counter scaler. Examples of these noisy events are given in figure 5.

5. LAGO Solar program

WCD used in Geiger mode are a natural detector for measuring low energy primary cosmic ray flux. Given the geomagnetic cutoff at the latitude of all LAGO sites, no solar cosmic ray can be seen, and the flux of secondaries at ground level should be directly related to the $\approx$10 GeV flux of galactic cosmic rays (GCR).

This flux is modulated by the solar activity, and is therefore an indirect indicator of this activity. Both long term variations (typically the 11 and 22 years solar cycles) and short term variations (Forbush decreases, where a coronal mass ejection reaches the Earth and acts as a shield to GCR, reducing the GCR flux by a few percent in a few hours, and lasting a few days) can be determined by WCD in Geiger mode. Furthermore, the timescales being much larger than the ones used for GRB, no statistical issues are expected. One has however to pay specific attention to systematics, than can easily mask the few percents of modulation effects. Reports on a ground level enhancement of secondaries produced by a solar flare were reported by the Ice Cube collaboration[12]. The Pierre Auger Collaboration has been recording single detector rates since 2005 and has presented the capabilities of WCD for the study of GCR modulation[13].

The LAGO solar program was started in 2010, and aims at using LAGO WCD for the study of GCR modulation. In order to do such studies, it is sufficient to use 5 minutes averages of the counting rates. One then has to correct for pressure effects, as a high pressure corresponds to a large amount of air above the WCD, hence a higher absorption of cosmic ray cascades, and therefore a lower counting rate. The anticorrelation of counting rate with pressure has been measured in Chacaltaya and is reported in [14], together with some measurement of the GCR at the LAGO site.

The increasing solar activity registered since end of 2009 points to a maximum of activity around 2013. LAGO will have many detectors in operation at that time to provide relevant GCR measurements at different geomagnetic cutoffs.

6. Conclusions and prospects

WCD used in Geiger mode are efficient detectors sensitive to the high energy photon flux of GRB, due to their ability to count secondary photons converting to an electron-positron pair in their water volume. When located in high altitude mountain sites, they can be a complementary method of observation of GRB, as their efficiency starts at high energies, where the flux of primaries is too low for satellite to perform observation.

The LAGO project is an international effort of many groups in different countries to operate a network of WCD in high altitude sites in Latin America. Data taking has started in 2007, and no

GRB has been observed to date. Limits on 40 GRBs were set, with the most stringent one being 1.6×10^{-6} erg.cm^{-2} for GRB 080904 in the 0.5 GeV - 100 GeV energy range.

LAGO data can also be used to monitor the solar activity through its modulation effect on galactic cosmic rays. A monitoring program has started in order to provide a network of observation during the current solar cycle, in particular during next maximum of activity in 2013.

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