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THE LARGE APERTURE GAMMA RAY OBSERVATORY AS AN OBSERVATIONAL ALTERNATIVE AT HIGH ALTITUDE

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RESUMEN

A pesar de que las observaciones por satélite han permitido develar algunos misterios sobre el origen y localización de rayos cósmicos a bajas energías, hay preguntas aún no resueltas en los rangos más altos de energías (>1 GeV). El flujo de partículas a altas energías es muy bajo, necesitando de grandes áreas de medición, por lo que la detección de partículas secundarias en observatorios sobre la superficie terrestre representa una solución viable. Aunque el Observatorio Pierre Auger tiene esa capacidad, dados sus 16000 m^2 de detectores, su baja altura sobre el nivel del mar reduce en gran medida su capacidad de detección. El proyecto LAGO es una alternativa de observación aceptable, que intenta superar ésta limitación. Este proyecto, iniciado en el 2005, sitúa detectores Cherenkov de agua a gran altura. Los sitios de observación han sido seleccionados siguiendo algunos requisitos básicos, a saber: altitud, infraestructura académica y técnica, existencia de un grupo de investigación responsable del montaje y mantenimiento de los detectores así como de la visualización, análisis, divulgación y preservación de los datos. Este artículo presenta el estado general de los observatorios de Sierra Negra-México, Chacaltaya-Bolivia, Marcapomacocha-Perú, Mérida-Venezuela y Bucaramanga-Colombia.

ABSTRACT

Although satellite observations have revealed some mysteries about the origin and location of cosmic rays at low energies, questions remain to be resolved in higher energy ranges (>1 GeV). However, the flow of particles at high energies is very low, large sensitive areas are necessary, so that the detection of secondary particles from observatories on the surface of the earth is a technically viable solution. While the Pierre Auger Observatory has such capacity given its 16000 m^2 of detectors, low height above sea level greatly reduces its detection capability. The Large Aperture Gamma Ray Observatory (LAGO) is an observational alternative that attempts to overcome this limitation. This project was started in 2005, placing water Cherenkov Detectors at high altitude. Observation sites have been selected with some basic requirements: altitude, academic and technical infrastructure, existence of a research group responsible for assembly and maintenance of the detectors and the analysis, visualization, divulgation and data storage. This paper presents the general status of the observatories of Sierra Negra-México, Chacaltaya-Bolívia, Marcapomacocha-Perú, Mérida-Venezuela and Bucaramanga-Colombia.

Key Words: gamma rays: observations — instrumentation: detectors

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1. INTRODUCTION: THE LAGO PROJECT

Since their discovery at the end of the 60's by the US military satellites VELA (Klebesabel et al. 1973), Gamma Ray Bursts (GRB) have been of high interest to astrophysicists. A GRB is characterized 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) for 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

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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 (Morelo et al. 1984) where the detectors are used to count individual particles. 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 (Morelo et al. 1984) in Italy, INCA (Cabrera et al. 1999) in Bolivia and ARGO (Bacci et al. 1999) in Tibet. A general study of this technique can be found in (Vernetto 2000). It has not been applied in the past 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 (Bertou & Allard 2005).

This method has been implemented since March 2005 in the Pierre Auger Observatory (Thomas 2009). The Pierre Auger Observatory (Abraham et al. 2004) 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.

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.

Fig. 1. Current LAGO sites.

2. PRESENT STATUS

2.1. *LAGO Sites*

In order to provide a relevant sensitivity to GRB search, a candidate site must be at high altitude, typically above 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 (see Figure 1) with detectors in operation:

• Sierra Negra, Mexico, 4550 m.a.s.l.: this is the first LAGO site, in operation since 2007. It is nearby the Large Millimetric Telescope (LMT) and above the HAWC 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:

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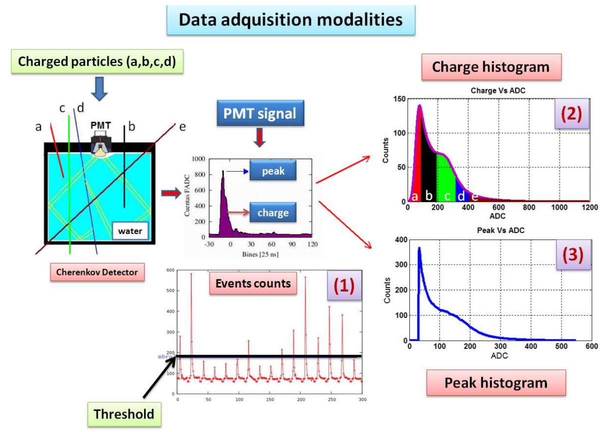

Fig. 2. High energy charged particles (a, b, c, d, e) produce Cherenkov Radiation in the water. The Cherenkov ligth fills the entire volume of water due to diffuse reflection on the tyvek. A light portion is collected by the PMT. The signal can be acdquiered as single events (1), charge (2) or peak histogram (3).

- at the Centro Atómico Bariloche in Argentina, a prototype is used for calibration and software tests since 2006;
- in Caracas and Mérida, Venezuela, Bucaramanga, Colombia, Lima and Cuzco, Perú, 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 cable car reopens, the Pico Espejo site will be instrumented.

2.2. *Experimental Setup*

All WCD share similar characteristics (see Figure 2). 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 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 (Bertou et al. 2006) 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.

3. ONGOING RESEARCH

3.1. *GRB Data analysis*

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) 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

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of view of both sites. The data were then averaged in bins of 100 ms and looked for excesses (4σ with σ being the square root of the average rate over 200 seconds before the burst) in coincidence in at least 2 detectors. Thus, 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 (De Castro 2009).

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 (Bertou 2010).

3.2. *`LAGOVirtual` for Data storage, access and sharing*

Nowadays the cost, sophistication and rapid advance of new experiments makes it essential that previous results remain accessible for accountability, re-analysis, and training of future generations. These needs have prompted the Open Data Movements (Arzberger et al. 2004; Sabourin & Dumouchel 2007; Xu 2007).

The LAGO Collaboration has developed a prototype of data repository, `LAGOvirtual` (Camacho et al. 2009) where the data are classified mainly into three types: instrument calibration data, data sets captured by the WCD instruments and simulated data. In the future we want the members of the collaboration use this repository also to preserve papers, thesis, Labs Notes and/or any documents related with the project. Each data file is tagged by a metadata set specifically adapted to LAGO. The existence and implementation of a scientific metadata standard model will allow an uniform access to data for all the members of LAGO colaboration, interoperability between scientific information systems, and will also contribute to data preservation and its usability in time. The metadata model we propose for `LAGOvirtual` is an adaptation of the model raised for the Council for the Central Laboratory of the Research Councils (CCLRC).

Metadata standardization allows the definition of common terminologies specifying entry, validation, access, integration and synthesis in automation, and ensures complete and accurate documentation of data-set content. Structures (classes) are composed of metadata items associated with descriptive semantic definitions for some of the possible data attributes. The incorporation of metadata demands an investment of time and effort, but ensures their relevance to future generations (Borgman et al. 2007).

The prototype of the data repository for the LAGO collaboration is implemented by adapting the system DSpace (DSpace), an open source software that enables open sharing of many types of content, generally used for institutional repositories. Dspace can expose the data and metadata through the Open Archives Initiatives Protocol for Metadata Harvesting (OAIPMH). This protocol is used by external systems to collect the data and metadata and create services of aggregated value like meta-searchers. Also offers the data through Really Simple Syndication channels, RSS, which is available at all levels in the structure of the repository. These channels are a simple mechanism to show contents recently submitted.

3.3. *Solar Program*

The LAGO solar program was started in 2010, and aims at using LAGO WCD for the study of galactic cosmic rays (GCR) modulation. GCR flux is modulated by 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 can be determined.

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 (Augusto et al. 2010), 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.

3.4. *Vertical Muon Flux and Seismic Precursors*

The purpose in this experiment is to utilize WCD used by LAGO to study the vertical muon flux, before, during and after a seismic event in Mérida-Venezuela. There is experimental evidence, but no general consensus, that variations of electromagnetic activity before an earthquake occur (Lockner et al.

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1983; Vallianatos et al. 2004; Herraiz et al. 2000; Frid et al. 2003; Uyeda et al. 2009). The progressive accumulation of mechanical energy in the fracture site, also promotes a progressive variation in the electric and magnetic properties of the rock (Parrot 1990; Hadjicontis& Mavromatou 1994; Stravrakas et al. 2008), therefore, before the seismic event, which represents the rock fracture, one should observe a significant variation in the "leakage" of the geomagnetic field, affecting the vertical flow of high-energy charged particles near the event sites (Aleksandrin et al. 2003).

Among the factors that influence the cosmic flux variation in the atmosphere, the climatological variables and solar activity are the most important (Lockner et al. 1983; Usoskin et al. 2008), hence the need to eliminate these spurious contributions. Using the LAGO electronic we can easily isolate from a charge histogram the muon vertical contribution (see Figure 2). We improve the isolation by means of a lateral filter, consisting of a 22-meters-deep and 40-cm-thick reinforced concrete, from a structure already present in the building of the Science Faculty of Universidad de los Andes, Mérida-Venezuela (see Figure 3). A charge histogram at 0 and 22 mt is shown in Figure 3. Figure 4 shows the flux's vertical component, monitored every 5 minutes from Jun 2009 to January 2011, along with local seismicity at 50 km from detector. Of particular interest is the muon flux behavior before, during and after the seismic event (4.2 M) occurred on February 6, 2009, 30 km from the detector. This event was the principal in a seismic storm belong to the same seismic focus and registered it in the time interval between January 15 to February 8, 2009. Other case was observed one month before the seismic events (4.0 M) occurred on 28 November 2010. The muon flux decrease showing an anomalous behavior, that disappears after the event (see Figure 4). It is clear that more data has to be taken, but no other important seismic events (> 4.0 M) have occurred during the period studied. A similar experimental setup has been recently installed by LAGO-Colombia in Bucaramanga, a region of prominent seismic activity, and is currently taking data.

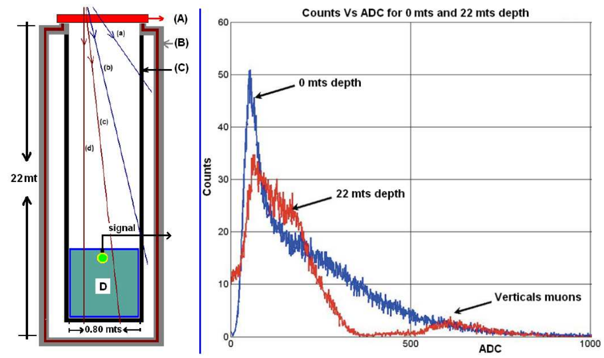

Fig. 3. In order to isolate the vertical muon flux, a WCD (D) has been installed at 22 mt depth within a reinforced (B and C) column of concrete (left). Low energy direct vertical particle has been removed with an iron filter 10 cm thick (A). A charge histogram at 0 and 22 mt depth illustrates the muon component (right).

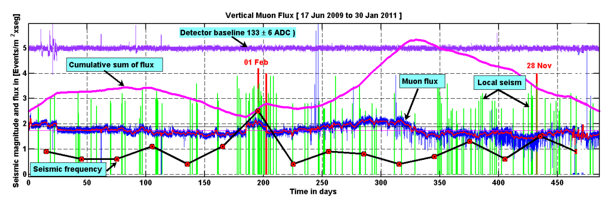

Fig. 4. Vertical muon flux from 17 jun 2009 to 30 January 2011. Cumulative sum of vertical muon flux events and seismic frequency are shown. Local seisms are selected at distances < 50 km from detector.

4. REMARKS AND CONCLUSION

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 0.5–100 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.

The use of high energy vertical muons flux, from cosmic radiation may represent a possibility to measure the global geomagnetic field variations on large terrestrial areas. This methodology can be an indirect way to measure changes in the mechanical stress on rocks, before, during and after a seismic events, in order to establish a possible way to early warning earthquakes.

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