Search for Gamma Ray Bursts and Forbush Decreases in the LAGO Observatory

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Abstract: We describe the LAGO Observatory which consists of arrays of water Cherenkov detectors installed in five different sites in Mexico, Venezuela, Peru, Bolivia and Argentina. The purpose of the LAGO Observatory is to search for Gamma Ray Bursts (GRBs) by using simple counting methods to detect time-correlated excesses in the particle rates measured with the water Cherenkov detectors. We describe in detail specific techniques to monitor the quality and stability of the LAGO detectors and to search for GRBs in the LAGO data. The LAGO Observatory can be used to study solar activity by detecting Forbush decreases. We also describe in detail the algorithms that we use to look for Forbush decreases in the LAGO data and the procedure to correct the particle rates from the LAGO detectors to remove the effects due to variations in atmospheric pressure. Finally we comment on the fluences of gamma rays associated with GRBs as derived from the LAGO data.

Keywords: LAGO Observatory; water Cherenkov detectors; Gamma Ray Burst; Forbush decrease.

1 Introduction

Gamma Ray Bursts (GRB) were discovered in the 1960s by the Vela satellites [1] as a part of a research and development program whose goal was to develop the technology to monitor nuclear tests from space. Ever since, GRBs have become the focus of intensive observational and theoretical research in astrophysics; they are described elsewhere [2] in connection with the LAGO Observatory.

LAGO makes use of the so called single particle technique (SPT) [3] in water Cherenkov detectors (WCDs). When high energy photons from a GRB reach the atmosphere, they produce cosmic ray cascades. The energies are not enough to produce a shower with many particles detectable at ground level (even at high altitudes, only a few reach ground). However, many photons are expected to arrive during the burst, in a short period of time increasing of the measured rate of arrival of secondary cosmic rays on all the detectors. This technique has already been applied at INCA [4] in Bolivia and ARGO [5] in Tibet. A general study of this technique can be found in [6]. The main advantage of WCDs is their sensitivity to photons, which represent up to 90% of the secondary particles at ground level for high energy of the primary photon. This method has been tested on the largest WCD array in operation, the Pierre Auger Observatory [7].

2 Experimental Setups of the LAGO Sites

In order to provide a relevant sensitivity to GRB search, the LAGO sites are located at high altitude, typically above 4500 m.a.s.l., with good infrastructure and easy access. Also low altitude sites can be integrated into LAGO for solar physics studies. At present the LAGO Observatory consists of 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 above the HAWC site. Three 4 m² and two 1 m² WCD have been in operation at the site. Currently, new detectors of 40 m² 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 4m² and one of 1 m². 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 m² WCD taking data since 2010. It is expected to take data for about one year during which higher sites in Peru are investigated.

In the future, new detectors are expected in the north of Chile and Argentina, in Brazil and Guatemala.

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, 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 software.

2.1 New Electronics of the LAGO Water Cherenkov Detectors

We are in the process of implementing new custom-made data acquisition electronics to replace the initial DAQ system borrowed from the Engineering Array of the Pierre Auger Observatory. We use an Spartan 3E Field Programmable Gate Array (FPGA) chip at the heart of the new electronics and digitize the PMT signals with a resolution of 10 bit and a sampling rate of 100 MS/s. We have written the new firmware of the FPGAs using VHDL, and, on the other side, the programs written in various languages (C++, Python, Perl, AWK and bash scripts) for the PC.

3 Data analysis to search for GRBs

Detection of GRBs by the LAGO WCDs may give rise to a high deviation of the sum of counts over a fixed interval with respect to the mean value of this sum over equal intervals measured over the corresponding hour. Therefore, if we introduce the variable \( S_{i,n} \) defined by

\[
S_{i,n} = \sum_{j=(i-1)*n}^{i*n} C_j
\]

where \( C_j \) is the count of PMT pulses on the \( j_{th} \) interval of 5 ms for a given threshold, and \( n \) is a multiple of 5 ms, then we define the excess \( E_n \) by

\[
E_n = \frac{S_n - \overline{S}_n}{\sigma_{S_n}}
\]

where \( \overline{S}_n \) and \( \sigma_{S_n} \) are the mean and standard deviation of the variable defined in Eq. 1 measured over the one-hour time corresponding to a given data file.

A promising strategy to search for GRBs is to look for high deviations of the variable defined by Eq. 2 specially in the highest thresholds where the signal to noise ratio is highest.

Two command-line shell scripts were written to display the variable defined in Eq. 2 for any given channel of the LAGO detectors at any given time. These shell scripts make use of auxiliary programs written in C++, Perl, Python and AWK.

We can use these shell scripts to find out the state of, for instance, channel 1 of the Chacaltaya system at the moment of occurrence of any GRB. For instance GRB100116A triggered the satellite GRB detector at 21:31:00 UTC, with an arrival direction of 15°43' above the horizon of Chacaltaya. By using these shell scripts we can easily create Figure 1 with a default time window of 200 s centered at the given time and a value of \( n = 200 \) for the integration time in Eq. 2.

In a similar way, if we want to find out the state of channel 1 of the Sierra Negra system at the moment of occurrence of GRB080129, which triggered the satellite GRB detector at 06:06:45 UTC with an arrival direction of 58°22' above the horizon of Sierra Negra, we can create Figure 2 displaying the deviations defined in Eq. 2 for channel 11, again with the default time window of 200 s centered at the given time and a value of 200 for the integration time of Eq. 2, corresponding to intervals of 1 s.

If instead of displaying the default width of 100 s around the given time we want to display the data starting at the given time minus let’s say 400 s and ending at the given date plus 400 s, we can easily use the mentioned shell scripts to create Figure 3 with a value of 200 for the integration time of Eq. 2, corresponding to intervals of 1 s.

If now we want to change the default time interval of 1 s in which the deviations from the mean values are calculated (as given by Eq. 2) to let’s say 100 ms, i.e., assuming we want to look for short GRBs, and we want to display a time width of 10 s around the given date, we can use the mentioned shell scripts to create Figure 4 with a value of 20 for the integration time of Eq. 2, corresponding to intervals of 100 ms.
Figure 2: Plot of the variable defined by Eq. 2 for channel no. 11 of one of the Sierra Negra WCDs at the moment of occurrence of GRB080129, which triggered the satellite GRB detector at 06:06:45 UTC, with a time window of 200 s centered at that time. This GRB occurred with an arrival direction of 58°22 above the horizon of Sierra Negra. Each point corresponds to 1 s.

Figure 3: Same as Fig. 1 but using a time window of 800 s centered at the time of occurrence of GRB100116A. Each point corresponds to 1 s.

3.1 Alert Messages for Occurrences of GRBs in the LAGO Field of View

We have also written a bash script to generate e-mail alerts when a GRB is detected by one or more of the various gamma-ray burst detecting satellites (HETE 2, INTEGRAL, Fermi, Swift, Konus-Wind, SuperAGILE, etc.) from the web page in ref[8] which exhibits up to the minute updates. This web page lists more than 880 GRB events from 2004/08/25 up to now. For 2010 alone it lists around 120 GRBs. By using this script one can easily find out that 40 of those GRBs occurred within 60 degrees from the zenith of at least one of the LAGO sites.

It is important to gather the information about GRBs right after their occurrence to do the proper data analysis on the LAGO data and to find out whether any of the LAGO sites detected or not such event. The shell script described below can be installed as part of the cron job scheduling system of a mail server to run every 15 minutes; upon appearance of a new GRB on the web page of ref[8], this script examines whether that GRB occurred within the field of view of any of the LAGO sites and, in case it did, the script sends an e-mail to the LAGO collaborators containing information about that GRB.

4 Search for Forbush Decreases in the LAGO Data

Forbush decreases are rapid variations in the galactic cosmic ray intensity following a coronal mass ejection from the Sun. They occur when the magnetic field of the plasma solar wind sweeps some of the galactic cosmic rays away from Earth. The effect was discovered in 1937 by the American physicist Scott E. Forbush. Forbush also observed that the intensity of cosmic rays reaching Earth was inversely correlated with the 11-year solar cycle of sunspots.

The LAGO sites can detect Forbush decreases and GCR modulation by measuring the low energy flux of secondary cosmic rays with their WCDs. The Pierre Auger Collaboration has been recording single detector rates since 2005 and has demonstrated the capabilities of WCDs for the study of Forbush decreases [9]. Since the time scales of Forbush decreases are much larger than the time scales of GRBs, it is sufficient to take the average of the secondary flux of cosmic rays over several minute intervals. In order to be able to see variations of a few percents in the flux of secondary
Figure 5: Anti-correlation between averaged counting rate and atmospheric pressure for one of the WCDs of Chacaltaya for 10 days from January 15 to January 24, 2010. The left axis shows the particle counting rates averaged over 60 minute intervals and the right axis shows atmospheric pressure in hPa averaged over the same time intervals with the direction reversed. The X axis corresponds to 1 h time intervals.

cosmic rays it is necessary to remove the variations due to atmospheric pressure; a high atmospheric pressure corresponds to a large amount of air above a given WCD with a higher absorption of secondary cosmic rays and therefore a lower counting rate. The anti-correlation of counting rate with pressure has been measured in Chacaltaya and Sierra Negra.

We have also developed several programs, written in bash shell scripts, C++, Python, Perl and AWK, to search for Forbush decreases in the LAGO data. As an illustration, we used one of these scripts to easily obtain the anti-correlation between averaged counting rate and atmospheric pressure for one of the WCDs of Chacaltaya for 10 days from January 15 to January 24, 2010, see Figure 5. On the left axis we show the particle counting rates averaged over 60 minute intervals and the right axis we show atmospheric pressure averaged over the same time intervals with the direction reversed, i.e. increasing from top to bottom. Figure 6 shows the fitted slope \( m = -563 \) to the same data.

5 Conclusions

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 \( 1.6 \times 10^{-6} \) 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 expected in the year 2013.

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References