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Correlation between cosmic ray flux and electric atmospheric field variations with the ARGO-YBJ experiment

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FOR THE ARGO-YBJ COLLABORATION

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Abstract: ARGO-YBJ is an extensive air shower detector located at Yangbajing (Tibet, China) at 4300 m a.s.l.. It is made by a full coverage carpet plus a guard ring (total surface ~6700 m^2) of Resistive Plate Chambers grouped into 153 units called clusters. The experiment has two different operation modes: in scaler mode the detector records the number of events with particle multiplicity $\geq$1, $\geq$2, $\geq$3, $\geq$4 over each cluster (reaching an energy threshold of a few GeV), while in shower mode the coordinates and arrival time of each particle are recorded for a complete shower reconstruction at an energy threshold of a few hundred GeV.
In this paper the scaler mode counting rate variations during thunderstorms in the summer 2011 and 2012 have been studied. A strong correlation between the counting rate variations and the atmospheric electric field strength has been found.

Keywords: cosmic ray, atmospheric electric field, ARGO-YBJ experiment

1 Introduction

Thunderstorms, usually associated to cumulonimbus clouds, are local convective weather conditions accompanied by thunders, lightnings and often rain. During thunderstorms, the atmospheric electric field (AEF) changes dramatically, and the strength can be up to 100 kV/m and more. Since the high-energy cosmic rays produce a large number of secondary particles through Extensive Air Showers (EASs) in the Earth atmosphere, the study of the interaction between thunderstorms and cosmic rays becomes a significant interdisciplinary frontier problem for practical and theoretical reasons. During thunderstorms, EAS high energy electrons are accelerated by strong AEFs to relativistic energies, producing secondary electrons which in turn create additional secondaries. This multiplication process is referred to as relativistic runaway electron avalanche (RREA) [1, 2]. From the experimental point of view, thunderstorm ground enhancements (TGEs) and terrestrial gamma-ray flashes (TGFs) may be observed.

Indeed a lot of experiments have measured TGEs and TGFs. It has been reported that the single particle counting rate (E>2.5 MeV and E> 25MeV) and EAS rate are significantly increasing in conditions of perturbed weather [3].

In 2002, Alexeenko et al. presented the data on short-term variations of the soft (electrons) and hard (muons) components of cosmic rays separately, and found the intensities being correlated with the near-earth electric field using a second-order polynomial [4].

Tsuchiya et al. [5] made a report on a comprehensive observation of a burstlike γ-ray emission from thunderclouds on the sea of Japan in 2007, which provided the first clear evidence that strong electric fields in thunderclouds can accelerate electrons beyond 10 MeV prior to lightning discharges. In 2009, they ensured the phenomenon of TGE being caused by AEF but not lightning [6].

Using ground-based observations of the thunderstorm-correlated fluxes of high-energy electrons, gamma rays and neutrons, Chilinyarian et al. [7, 8] show the existence of long-lasting particle multiplication and acceleration mechanisms in the thunderstorm atmosphere.

It seems that the results of all the above experiments support the mechanism of RREA. But in 2011, the AGILE Team determined that the TGF emission above 10 MeV has a significant power-law spectral component reaching energies up to 100 MeV [9]. These results challenge the mechanism of RREA.

For this reason more detailed studies about the correlation between cosmic rays and strong AEFs during thunderstorms are necessary. This work is aimed to determine the correlation between cosmic rays and AEF variations using the data of the ARGO-YBJ experiment, and to study the physical mechanism of TGE.

2 The detector

The ARGO-YBJ experiment is an extensive air shower detector located at an altitude of 4300 m a.s.l. at the Yangbajing Cosmic Ray Laboratory. The detector is made by a single layer of Resistive Plate Chambers (RPCs) operated in streamer mode [10] and grouped into 153 units called "clusters". The clusters are disposed in a central full coverage carpet and a sampling guard ring. The detector is connected to two independent data acquisition systems, corresponding to the shower and scaler modes [11].

In scaler mode, the single particle counting rate of each cluster is read every 0.5 s and put in coincidence in a narrow time window (150 ns). Each cluster has 4 channels to record the counting rates corresponding to n$\geq$1, $\geq$2,

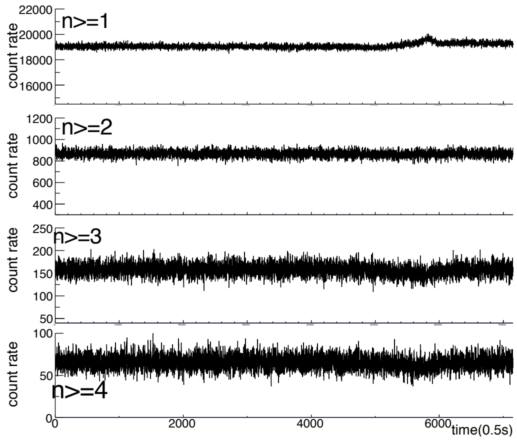

Figure 1: The 0.5 s counting rate variations of cluster No. 130 during one hour on April 26, 2012 for the four scaler channels.

$\geq$3 and $\geq$4 particles. The average counting rates are $\sim$ 40 kHz, 2 kHz, 300 Hz and 120 Hz respectively [12]. Fig. 1 shows the counting rates of a cluster in stable conditions. The counting rates N_i can be obtained from the measured counting rates $N_{\geq i}$ using the relation:

$$N_i = N_{\geq i} - N_{\geq i+1} \qquad \text{for } i = 1,2,3 \qquad (1)$$

In order to make the RPCs running in a steady way, an additional detector control system (DCS) has been installed to monitor the meteorological parameters such as atmospheric pressure, outdoor and indoor temperature, humidity inside the hall and local AEF. Two electric field mills (Boltek EFM-100) are installed on the building roof; the data used in this analysis refer to the EFM in operation since 2005 [13]. At the beginning the selected sensitivity was 1 V/(kV/m) with a maximum range of ± 20kV/m; in 2011 the scale of the EFMs has been expanded to ± 100kV/m. The digital output is connected to the DCS computer (Windows OS) and acquired twice per second. Data are written on a separate file and tagged with the computer time.

A correction of meteorological effects including temperature, pressure and humidity has been done before calculating the percent variations of counting rates [12].

In this presentation the counting rate variations in scaler mode in the summer of 2011 and 2012 and the AEF variations during the thunderstorms will be analyzed and discussed.

3 Data analysis and results

3.1 Thunderstorm events

During summer 2011 and 2012, 24 thunderstorm events were recorded. The variations of scaler counting rates and AEF for two of them are shown in Fig. 2 (thunderstorm event 20120429) and Fig. 3 (thunderstorm event 20120719). In a clear day the magnitude of AEF at Yangbajing maintains a stable value of about 0.2 kV/m, while it changes abruptly during the thunderstorm, with absolute values that can exceed 100 kV/m. In general, in these kinds of events two different behaviours are present: an abrupt positive or negative change in coincidence with the AEF variation, followed by a slow increase lasting a few hours,

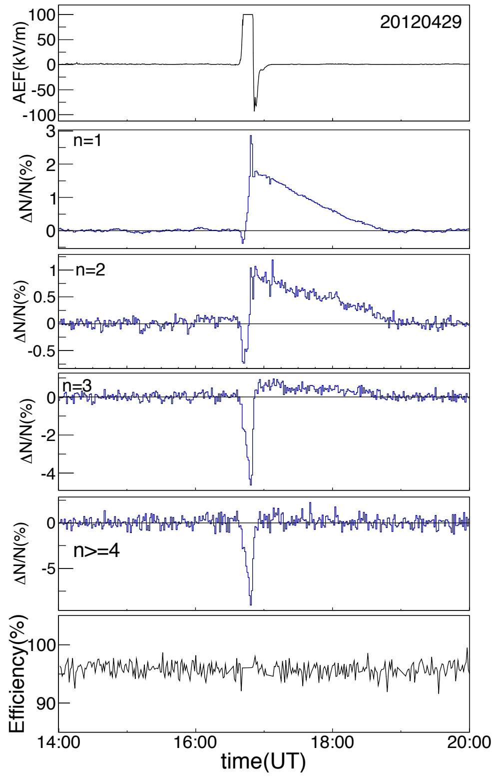

Figure 2: The thunderstorm event (20120429) between 14:00 and 20:00 UT on April 29, 2012. From top to bottom, the AEF value, the percent variations of counting rate for n=1, n=2, n=3, n$\geq$4 and the efficiency of the detectors are shown. The counting rate data from 14:00 to 16:00 and from 19:00 to 20:00 are considered as background, averaged every minute. ΔN represents the difference between the data and the mean value N .

more visible for channels 1 and 2. Notice that there are two peaks in the counting rates for all the channels shown in Fig. 3 corresponding to the rapid change of the AEF.

To investigate a possible instrumental effect, the detector efficiency is continuously monitored by a multi-layer telescope made of five RPCs in operation near the ARGO-YBJ array [14]. According to these data the efficiency of the detector is not affected by the AEF variations (botton panels of Figs. 2 and 3).

To study the temporal behaviour of these phenomena, we define the counting rate increasing (or decreasing) starting time when the ΔN/N is more than 10% of the peak. It can be seen from Fig. 4 that the change of the counting rate is delayed with respect to the beginning time of the AEF change: the counting rate starts to increase (decrease) 10-20 minutes after the AEF change.

Up to now, we have observed two different behaviors of the n=1, 2 counting rate variations: a short duration increase (the peaks of Figs. 2 and 3) and a slow one lasting a few hours with a slow decrease tail. These results are in agreement with ref. [3]. A possible explanation of the latter type could be related to the gamma ray emission from radioactive aerosols carried to ground by the rain, as Radon daughters (that, as it is well known, can act as condensation nuclei for the rain drops) [15]. The first type could be the TGE from RREA.

The counting rate decreases mainly observed for chan-

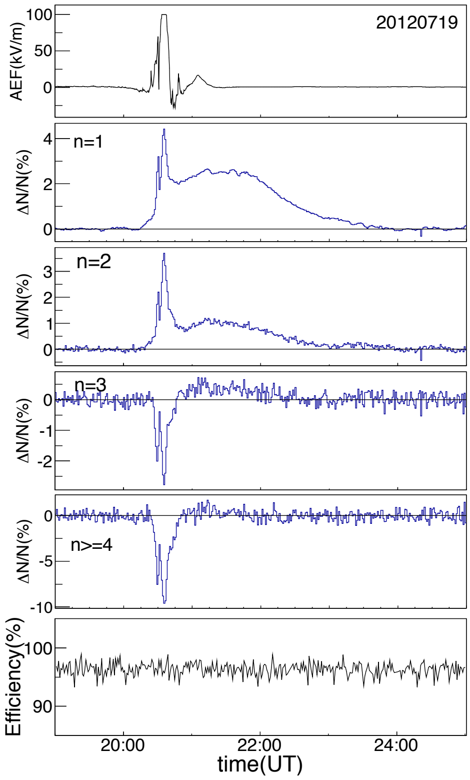

Figure 3: The thunderstorm event (20120719) between 19:00 UT on July 19, 2012 and 01:00 UT on July 20, 2012. From top to bottom, the AEF value, the percent variations of counting rate for n=1, n=2, n=3, n≥4 and the efficiency of the detectors are shown. The counting rate data from 19:00 to 20:00 and from 00:00 to 01:00 are considered as background, averaged every minute. ΔN represents the difference between the data and the mean value N. For n=3 and n≥4, there are two decrease peaks according to the AEF changes.

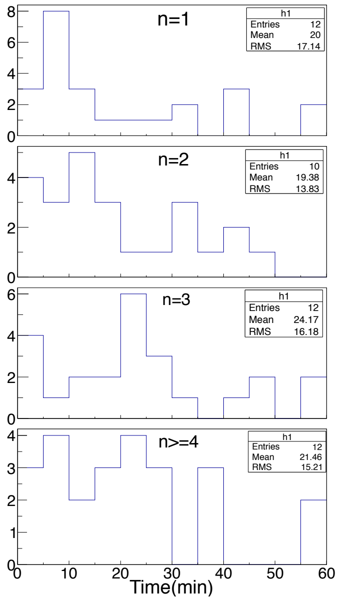

Figure 4: Time delay of the beginning of the counting rate changements with respect to the change of the AEF. From top to bottom, they correspond to n=1, n=2, n=3 and n≥4, respectively.

nel n=3, ≥4 can not be understood by the RREA mechanism. A possible explanation is that secondary EAS particles such as electrons with energy higher than the equilibrium energy [16] lose more energy mainly through bremsstrahlung than getting energy from the AEF during thunderstorms.The energies of n=3, ≥4 recorded particles are higher than the equilibrium energy, so the counting rates decrease with respect to normal weather conditions.

3.2 Regression analysis

All the 24 counting rate data (ΔN/N and the corresponding AEFs) were grouped into 20 bins from -100 kV/m to +100 kV/m. The results of the regression analysis are shown in Fig. 5. For n=1, 2 there is a clear positive correlation with the absolute value of the near-earth electric field, i.e. stronger AEFs produce stronger increase of counting rates. When AEFs are negative, the increase of counting rates become faster than for positive AEFs. For example, when AEF gets -100 kV/m the increase of counting rates is about 3% (n=1) and 2.5% (n=2) while for AEFs equal to +100 kV/m the increase is about 2% and 1.5% for n=1, 2, respectively.

For the n=3, ≥4 there is a clear negative correlation with the absolute value of the near-earth electric field, i.e. stronger AEFs correspond to stronger counting rate decreases. When AEFs are negative, the decrease of counting rates become slower than for positive AEFs. For example, when AEF gets -100kV/m, the decrease of counting rate is about -0.5% (n=3) and -4% (n≥4) while when the AEF gets 100kV/m the decrease is about -2% and -6% for n=3, ≥4, respectively.

4 Summary

The correlation between cosmic ray counting rates for different multiplicities and the AEF variations during thunderstorm have been analyzed using the ARGO-YBJ experiment data in the summer 2011 and 2012.

Two different types of counting rate increases have been observed in our measurements: an increase directly related to the thunderstorm, observed in the data for n=1, 2, lasting about two hours and with a slow decrease tail (type A); a short duration (10-15 minutes) increase, observed also at n=1 and 2, usually superimposed to a slow increase of type A (type B). At the same time, one type of counting rate decrease for n=3, ≥4 has been observed. It lasts tens of minutes, and it is accompanied by a significant increase of type B for n=1, 2. A possible explanation of type A increase could be related to the gamma ray emission from radioactive aerosols carried to ground by the rain, as Radon daughters. And a possible origin of type B increase can be due to the effect of strong AEFs on the propagation of the secondary cosmic rays particles. The decrease of counting rates for n=3, ≥4 may be due to bremsstrahlung of high energy particles.

There are clear positive correlations between the counting rates of n=1, 2 and the near-earth AEF, while there are clear negative correlations between the counting rates of n=3, ≥4 and the near-earth AEF.

A detailed Monte Carlo simulation of EASs develop-

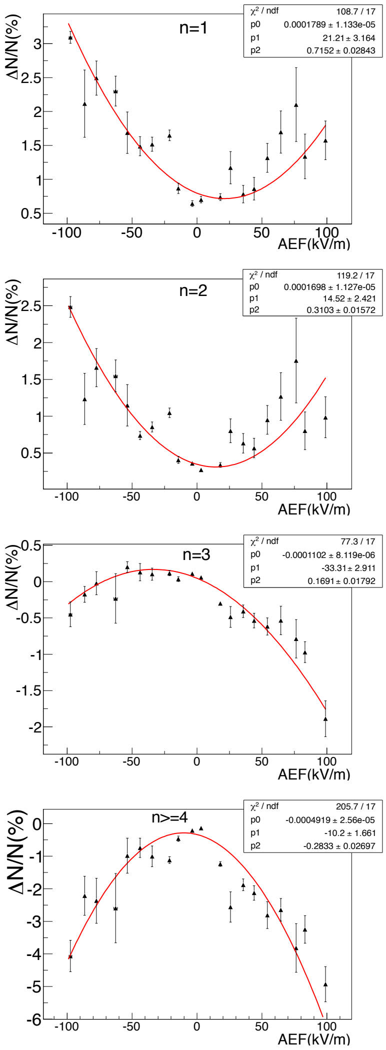

Figure 5: The amplitude of the counting rate relative variation versus the electric field strength. Observations of 24 thunderstorms are included in the analysis. From top to bottom, they correspond respectively to n=1, n=2, n=3 and n$\geq$4.

ment in presence of strong AEFs should be carried out to understand these physical results. Now we are checking the shower mode data of the ARGO-YBJ experiment: the results of this work and of the simulation will be reported afterwards.

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