Search for coincidences with astrophysical transients in Pierre Auger Observatory data

David Thomas* for the Pierre Auger Collaboration†

*Colorado State University, Fort Collins CO, USA
†Pierre Auger Observatory, Av. San Martin Norte 304 (5613) Malargüe, Prov. de Mendoza, Argentina

***Abstract*. We analyse extensive air shower data collected by the Pierre Auger Observatory to search for coincidences between the arrival directions of ultra-high energy cosmic rays and the positions of gamma-ray bursts. We also analyse the trigger rate data from individual surface detector stations to search for an increase of the average trigger rate over the entire surface detector array in correlation with gamma-ray bursts.**

***Keywords*: Auger GRB transients**

I. INTRODUCTION

Since their discovery at the end of the 1960s [1], gamma-ray bursts (GRBs) have been of high interest to astrophysics. A GRB is characterised by a sudden emission of gamma rays during a very short period of time, typically lasting between 0.1 and 100 seconds. The equivalent isotropic energy emission during a burst is typically between 10^{51} and 10^{55} ergs. Good source candidates for these bursts are the merger of neutron stars, for short bursts of less than 2 seconds, and core-collapse supernovae type Ib/c, for long bursts. See [2] for a recent review.

A large data set of GRBs was provided by the BATSE instrument on board the Compton Gamma Rays Observatory (1991-2000). More GRBs were then detected by BEPPO-SAX (1997-2002) and HETE (2001-2006). Currently, GRBs are registered by Swift, INTEGRAL, IPN, the Fermi Gamma Ray Telescope. In the last several years, afterglows have been observed allowing us to precisely measure their direction, and giving us a much better understanding of the GRB phenomena. Most observations have however been done below a few GeV of energy, and the highest energy observations have been around 10 GeV [3].

Using the recently completed surface detector array (SD) of the Pierre Auger Observatory [4], [5], an array of more than 1600 water Cherenkov detectors, we look for evidence of GRBs in our data with two separate techniques. For the first study, we use the regular Auger cosmic ray (CR) events to look for an excess of ultra-high energy CRs (UHECRs) in the direction of GRBs. We presented a similar analysis at the last ICRC [6].

In the second study, the "single particle technique" [7] is used with low-level trigger rate data from individual surface detector stations to look for a possible extension of the photon spectrum of GRBs in the 1 GeV – 1 TeV range, which is not well-studied by satellites. When photons in this energy range reach the atmosphere, they produce cosmic ray cascades that can be detected, although the energies are too low to produce a shower detectable at ground level, even at high altitudes. However, a lot of these photons are expected to arrive during a GRB in a short period of time, which would be detectable as an overall increase of the trigger rate in all the detectors [8] in the array.

This technique was first applied in EAS-TOP [7], using scintillators, and subsequently in INCA [9] and ARGO [10], using scintillators and RPCs, respectively. The main advantage to using water Cherenkov detectors [11], [12] is their sensitivity to photons, which represent up to 90% of the secondary particles at ground level for high energy photon initiated showers such as these. This study is also an update to one we presented at the last ICRC [13].

II. SEARCH FOR COINCIDENCE OF UHECRS AND GRBS

For this analysis, we use CR data collected with the Pierre Auger Observatory surface detector. We consider events from 1 January 2004 to 31 March 2009, passing quality criteria discussed elsewhere [14] with zenith angle $\theta < 60°$. We perform no energy cut on the data.

We use a catalogue of 511 GRBs [15] observed with an accuracy better than 1° compiled using data primarily from the Swift mission complemented by measurements from additional GRB observing satellites, including HETE, INTEGRAL, IPN, and Fermi. Out of the total GRB sample, 115 bursts are within the field of view at the time of their bursts, i.e. $\theta_{GRB} < 60°$.

We look for excess CRs in the direction of GRBs by determining the differences in the observation times of the GRBs and the arrival times of CR events that fall within a window of radius ψ around each GRB position. We compare this with the expected rate of events, which is calculated in the same manner, using the declination band of width 2ψ around the GRB (excluding the circular window around the GRB). The expected rate of events is normalized by multiplying by the on-source solid angle of the window divided by the total solid angle (declination band minus the window.)

A value of $\psi = 2°$ corresponds roughly to the angular resolution when all SD events are used. To be consistent with the previous analysis, we also used a window of $\psi = 5°$. The results are presented in Figure 1. There

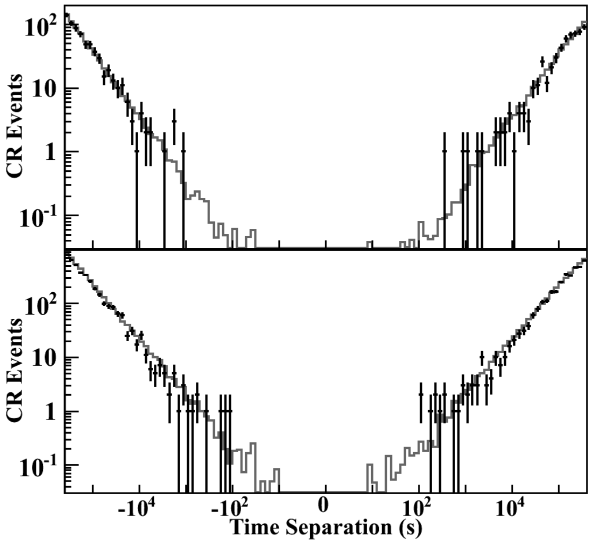

Fig. 1. Number of CR events as a function of the difference between the GRB time and the CR arrival time, for windows of $\psi = 2°$ (top) and $\psi = 5°$ (bottom). Data falling within the windows of radius ψ are indicated by the points. The expected rate of events is indicated by the solid line. For clarity, statistical errors are only shown for the circular windows.

is no evidence for an excess of CRs coming from the direction of GRBs.

III. Single particle technique

A. Scaler data

In addition to the regular data acquisition system used to detect cosmic rays, the surface detectors are equipped with scalers, simple counters that can be set like any other trigger. They record the counting rates of signals more than 3 ADC counts above baseline and less than 20 ADC counts, or approximately between 15 and 100 MeV deposited in the detector. This trigger level has been set to optimise the signal to noise ratio given the expected signal extracted from simulations [16], and the background signal derived from real data histograms. With these cuts, the average scaler rate over the array is of about 2 kHz per detector. Note that the scaler data is completely separate from the regular cosmic ray data, as it only reports trigger rates in individual surface detector stations, and cannot be used to reconstruct cosmic ray events.

To use the scaler data, it must be cleaned. Individual detectors often experience increases in their counting rates due to noisy or unstable baseline, unstable PMTs, or bad calibration. Detectors with less than 500 Hz of scaler counts are discarded. This removes a few badly calibrated detectors. Additionally, for each individual second, only 95% of detectors are kept, removing the 5% with extreme rate counting (2.5% on each side). This removes outliers which could impact the average rate of a specific second, without affecting the GRB detection capability, as GRB would appear as an increase of counting rates in all the detectors.

One then needs to have the array operating properly. Suddenly losing a significant fraction of the array will cause jumps in the scaler rate, as this rate is not uniform over the whole Observatory. Consequently, we only use data periods for which more than 97% of the stations are operating. This keeps 83% of the data. We also require at least 5 continuous minutes with data, to be able to compute reasonable averages and see eventual bursts. This removes 12% of the remaining data set. Some artificial bursts are found in the cleaned scaler data set due to lightning strikes. Therefore, we do not use the data taken during lightning storms, removing 4% of the data. This scaler data cleaning process is different from the one used in the analysis of the modulation of solar CRs [17] due to the difference in time scales.

B. $\sigma - \delta$ method

To search for bursts, the average rate for each second as well as a longer term average rate are computed. As a burst would produce a similar increase in all stations, a good estimator of the average rate for each second, r, is the median of the rates of all the stations. It is much less sensitive to misbehaving detectors than the arithmetic average. Then, to estimate a long term average R, a $\sigma - \delta$ method is used with $\sigma = 0$ and $\delta = 0.1$ Hz, meaning that every second the average rate R is moved by 0.1 Hz towards the current rate r. After 30 seconds of data, this average converges to the expected average value, and one can compute the variation Δ of the rate r of a specific second using:

$$\Delta = \frac{r - R}{\sqrt{r/N}}$$

where N is the number of active detectors at that second.

The Δ parameter can be used directly to search for bursts, and its histogram can be seen in Figure 2. The underlying Gaussian has a width of 1.4. It would have a width of 1 if the arriving flux of particle was poissonian, the fluctuations of each detector were independent, the baselines of the detectors were not fluctuating, and the $\sigma - \delta$ method gave the true average at each moment. One sigma of deviation corresponds roughly to 1.5 particles per detector, i.e. a flux at ground level of 0.15 $m^{-2}\,s^{-1}$.

C. Search for self-triggered bursts

Once all the cuts defined above have been applied, a total of 70% of the data period (21 September 2005 - 31 March 2009) is available for a search for bursts. The resulting Δ histogram is shown in Figure 2.

Only three candidate bursts are observed significantly outside of the Gaussian distribution. To be related to a GRB, the increase of the rate should be uniformly distributed over all the detectors. One can therefore check that each individual detector has on average an increase at the moment of the burst with respect of the previous seconds. The observed outliers do not present such a feature, as only a fraction of the array sees a significant excess. We show in Figure 3 the histogram

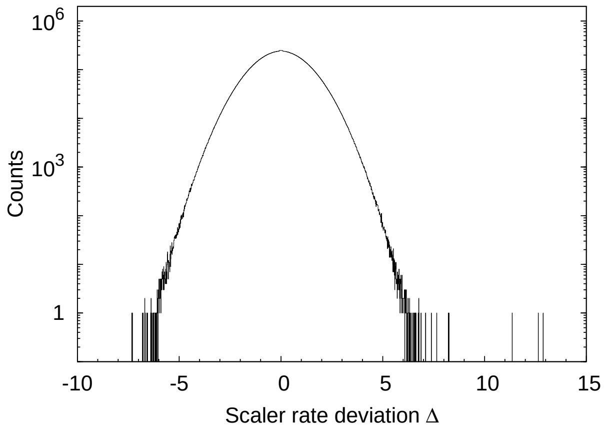

Fig. 2. Histogram of the deviations Δ of the scaler counting rates. The distribution is Gaussian with a width of 1.4. Three candidate bursts are present above 10σ which we looked at more closely to determine if they are due to GRBs.

of the difference of the scaler rate from the average over the previous seconds for one of these candidate bursts. Most of the rate increase is attributable to a small portion of the array. The excess is therefore artificial and must be due to lightning. All other candidate bursts display this same attribute.

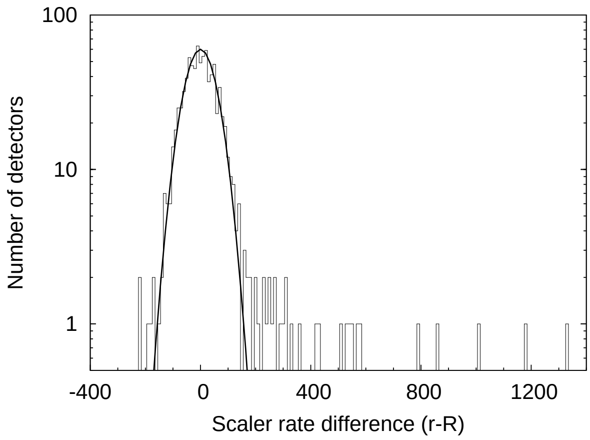

Fig. 3. Histogram of the difference of scaler rates from the average over the previous seconds for one of the three candidate bursts. The scaler rate increase is due to an increase in the rate for a small fraction of the array. Thus, this candidate burst is due to lightning. The other candidate bursts display this same characteristic.

D. *Search for satellite-triggered bursts*

In the period studied, 129 bursts detected by satellites occurred in the field of view of Auger ($\theta_{GRB} < 90°$). For all these bursts, the scaler data were checked within 100 seconds of the burst for a one second excess. No excesses were found and the resulting 5 σ fluence limits were computed assuming a GRB spectra $dN/dE \propto E^{-2}$ in the 1 GeV – 1 TeV energy range (as in [9]). The limits are reported in Figure 4.

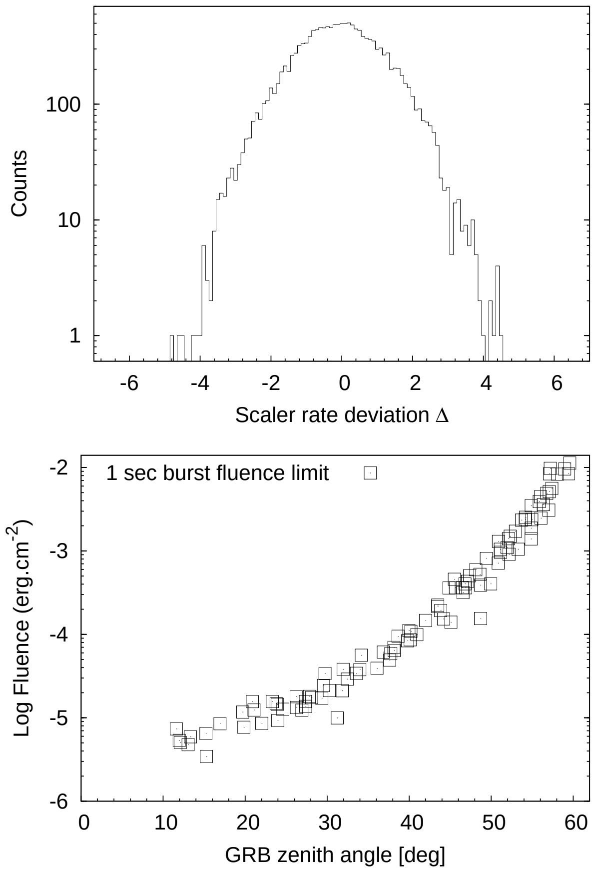

Fig. 4. Top: histogram of the deviations Δ of the scaler counting rates within 100 seconds of the bursts reported by satellites. No significant excess is observed. Bottom: 5-σ fluence limits in the 1 GeV – 1 TeV energy range from Auger for these bursts, for a single second burst, assuming a spectral index of -2.

IV. Conclusion

We have used the cosmic ray data from the surface detector of the Pierre Auger Observatory to search for cosmic rays that correlate with the time and position of GRBs. No such correlations were found.

As a separate analysis, we used the scaler data to look for increases in the average trigger rate of the surface detectors, which would indicate the occurrence of a GRB. No burst with characteristics similar to those expected for GRBs was observed.

Fluence limits of up to $3.4 \times 10^{-6}\,\mathrm{erg\,cm^{-2}}$ (depending on the burst zenith and duration), were deduced for the 1 GeV – 1 TeV energy range. Note that models do not generally favor fluences above $10^{-6}\,\mathrm{erg\,cm^{-2}}$ in the energy range considered [18], [19]. To reach such a sensitivity, a detector is needed that covers a significant surface at higher altitude. Such a detector could be an extension of the LAGO project [20] that has been taking data since 2007.

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