Radio-detection of cosmic ray air showers by the RAuger experiment, a fully autonomous and self-triggered system installed at the Pierre Auger Observatory

The Pierre Auger collaboration

Abstract

RAuger is a radio experiment consituted of three fully autonomous and self-triggered radio-stations installed at the center of the Pierre Auger Observatory's Surface Detector (SD). It aims at the radio detection of the electric field emitted by the secondary charged particles of the atmospherical shower initiated by ultra-high energy cosmic rays. Installed in November 2006, we recorded the first atmospherical showers in coincidence with the Pierre Auger SD in July 2007. Up to now, 65 such coincidences have been obtained. The skymap in local coordinates (zenith angle, azimuth) of these events presents a strong azimuthal asymetry in agreement with what was observed in the Northern hemisphere by the CODALEMA experiment (the asymetry is simply switched by 180° in azimuth). We also recorded a threefold coincidence making possible a complete reconstruction: both the radio reconstructed shower axis and the shower energy are in perfect agreement with the Auger estimations.

1. Introduction

Encouraged by the results obtained by the CODALEMA [1] and the LOPES [2] experiments, part of the cosmic ray radio detection community installed some experiments to detect cosmic rays among the Pierre Auger observatory. RAuger is one of these experiments and we describe in this paper some of its results. The radio detection technique is very interesting because it has a 100 % duty cycle with a reduced cost as compared to a typical surface particle detector or fluorescence detector. It has been demonstrated that the technique is well suited for cosmic ray detection in terms of angular resolution on the shower axis direction and in terms of radio signal, highly correlated to the primary cosmic ray energy. Moreover, the radio signal is expected to be sensitive to the longitudinal development [3] of the shower making the observed electric field also correlated to the nature of the primary cosmic ray which is of great importance to understand the acceleration mechanisms at the sources of high energy cosmic rays. The electric field generated by the secondary charged particles of the atmospherical shower is detected in the frequency band [1-100] MHz. The particularity of RAuger is to use a simple analog threshold trigger on the East-West component of the electric field so that the detection of cosmic rays is completely independent of any external trigger. In this paper, we first describe the Pierre Auger observatory and the RAuger experiment. Then we explain how the identification of cosmic rays is done and we present the sky distribution of the events and the reconstruction of the threefold event.

2. The Pierre Auger observatory

The southern part of the Pierre Auger observatory is installed in Malargüe, Mendoza, Argentina. It is an hybrid detector made of one particle detector (the surface detector, SD) and four fluorescence telescopes (the fluorescence detector, FD) [4]. The RAuger experiment, installed at the center of the SD, is far from the FD and no coincidence is expected with it so that we will not describe the FD in the following.

The covered area is 3 000 km^2 with 1 600 regularly spaced particle Cherenkov water tanks. The tanks are distributed on a triangular grid with 1.5 km edge. Each tank is a plastic cylinder of 3.6 m diameter and 1.2 m height filled with 12 m^3 of purified water. The top of the tank is equipped with three photomultiplier tubes (PMTs) in optical contact with the water. The PMT signals are digitalized by a 40 MHz ADC. The tanks are calibrated in real time in units of vertical equivalent muons (VEM) corresponding to the signal produced by a single muon entering the tank vertically at the center of the top side. The tank sends its data to the Central Data Acquisition System (CDAS), in Malargüe, using a radio link. All the electronics is powered by solar panels. The tank trigger (the level 2 trigger, T2) is decided when one of the two following criteria is met: the signal is above 1.75 VEM in at least one bin of the ADC trace or the signal is above 0.2 VEM in 13 bins in a time window of 3 μs, corresponding to 120 bins. The trigger timing is ensured by a GPS receiver. The CDAS receives the T2 times of all the tanks and computes a level 3 trigger (T3) based on compacity (in space and time) of the T2s. The T3 rate

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with the complete array is about 3 events per minute with about 1 event per minute being an actual shower, above 3×10^{17} eV.

3. The RAuger experimental setup

3.1. Hardware and self-trigger

The RAuger experiment is constituted by three prototype radio-stations A1, A2 and A3, working in a fully autonomous mode. Each station is independent in terms of power supply, trigger, data acquisition and transmission. The detailed characteristics of the setup is described in [5]. The three antennas are in the center of the Auger SD and form an small equilateral triangle of area 0.016 km^2 which represents 0.85 % of the Auger SD elementary triangle area. At the center of the RAuger triangle, an additonnal SD tank (named Apolinario) has been installed in order to locally increase the Auger T3 rate by locally decreasing the energy threshold. The layout of the 3 radio-stations is presented in Figure 1.

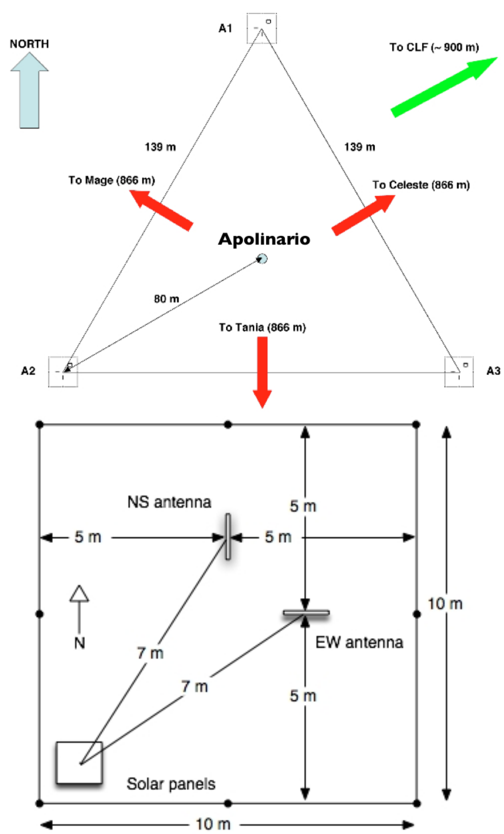

Figure 1: *Top: setup of the 3 radio-stations A1, A2 and A3 around Apolinario. Mage, Celeste and Tania are the three neighbouring standard Auger SD tanks. Bottom: sketch of an individual station with the 2 cross-polarization dipolar antennas NS (North-South) and EW (East-West).*

For each radio station, radio events are detected by two dipolar antennas in the North-South (NS) and East-West (EW) polarizations. The first channel is the full-band EW signal between 100 kHz and 100 MHz. The second channel records the full band NS signal. A 100 MHz filter has been inserted on the acquisition line to remove high frequency, very powerful TV transmitter carriers previously observed above 200 MHz and that could add a strong noise on the signal. The trigger decision is taken on the EW signal after filtering in the [50-70] MHz frequency band. This filtered signal is sent to a voltage comparator (threshold) to build the trigger in order to start the acquisition of the wave form, recorded over 5 μs at 500 MHz by a 8 bits ADC. The threshold level cannot be changed neither remotely neither by software in these first generation radio station prototypes. The absolute time tagging of the trigger is done in the same way as the Auger SD tanks; we are using the same GPS module. The acquisition is vetoed until the event is read from the scope. Data are then transmitted via a high gain WiFi link to our central PC Radio Data Acquisition System (RDAS) located at a distance of 800 m. The maximum trigger rate is around 0.37 events.s^{-1} due to a dead time of $\sim$ 2.7 s which corresponds to the time needed to read an event on the scope and to send it to the RDAS.

The RDAS receives the data from the three stations but no higher level trigger is decided, we record every event detected by the radio stations. The events are stored locally and sent to France and the analysis is done offline on the three data streams.

4. Identification of atmospherical showers

We record an event when the detected electric field in the frequency band [50,70] MHz is above a pre-defined threshold. These transients can have various origins: anthropic noise, close and distant thunderstorms and atmospherical showers. Moreover, the sensitivity of the dipolar antennas used in RAuger is varying according to the local weather conditions and the time of the day (day/night effect) so that the daily trigger rate is highly variable. Nevertheless, it is easy to identify actual cosmic ray events thanks to the low value of the maximum trigger rate (0.37 events.s^{-1}) which almost guarantees that the number of fortuitous coincidences between RAuger and Auger is negligible. We are searching for coincidences with Auger by an offline comparison of the radio trigger times of each antenna to the arrival time of the Auger events reported to Apolinario's location. If these time differences are smaller than 1 μs, we verify that the radio trigger time is compatible with the passage of the shower front given by the shower geometry. A pessimistic over-estimation of the instantaneous fortuitous coincidence rate gives a number below 10^{-10} s^{-1} (assuming the worst situation where the radio trigger rate is close to saturation) so that the expected number of fortuitous coincidence with Auger SD in a large time window of 20 μs to be safe is of the order of 0.016 integrated over the time range of the RAuger experiment (~ 2.6 years) and considering a daily flux of 1.4 cosmic rays having an axis distance to Apolinario below 1 km (we are not sensitive to more distant showers with these early prototypes).

Since July 2007, we regularly obtain unambiguous self-triggered events in coincidence with Auger, all of them except one involving one or two of the three radio-stations. The correlation between the expected time difference (given the Auger SD shower geometry) with the observed time difference for each pair of time values antenna/Apolinario is excellent. The slope of the line fit is equal to one as presented in Fig. 2.

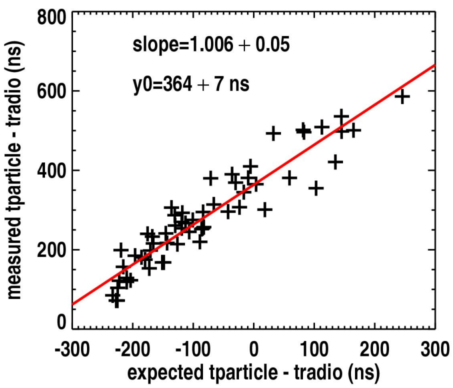

Figure 2: *Correlation between the measured time difference between a coincident antenna and Apolinario and the expected time difference given the shower geometry.*

Since May 2008, A1 is the only radio station having a stable behaviour leading to the detection of coincidences with Auger (the time interval distribution of these events is Poissonian with a time constant of 12 days). But in November 2009, we discovered and fixed several problems on both A2 and A3 so that we got a threefold coincidence with Auger SD ten days after the correction of the problems. This event is described in section 6. Unfortunately, the antennas A2 and A3 had some failures again quickly after this threefold coincidence.

5. Arrival direction of the cosmic showers detected by RAuger

In the CODALEMA experiment in Nançay, France [1] where the same EW dipolar antennas are used, we demonstrated that the arrival directions of the cosmic rays are correctly described by an electric field emission mechanism of the form $\vec{E} \propto \vec{n} \times \vec{B}$ where $\vec{E}$ is the electric field, $\vec{n}$ is the shower axis direction and $\vec{B}$ is the geomagnetic field in Nançay. This geomagnetic model permits to predict an event density map (under the hypothesis that the probability to trigger is proportionnal to the amplitude of the electric field in the given polarization) and to compare it to the observed density map. This comparison is very satisfactory on the CODALEMA data [6]. It is also possible to compute the predicted event density map for the Malargüe site. The simplest case to consider here is to use an isotropic incoming cosmic ray distribution ($\mathrm{d}N/\mathrm{d}\Omega \propto \sin\theta\cos\theta$) multiplied by the EW projection of $\vec{n} \times \vec{B}$ (since we are triggered by the EW polarization). The corresponding density map, smoothed with a 10° Gaussian beam is presented in Figure 3 (top) together with the observed skymap with the 65 coincident events (bottom).

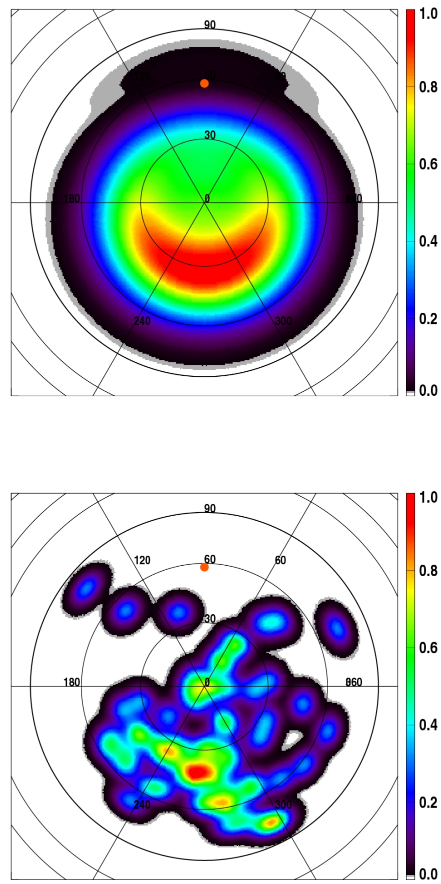

Figure 3: *Top: predicted density skymap with the geomagnetic model. Bottom: skymap in local coordinates of the 65 events in coincidence with Auger. The red dot indicates the position of the geomagnetic field in Malargüe. Both skymaps are smoothed by a 10° gaussian beam. The zenith is at the center and the azimuths are oriented as in a compass.*

6. A fully reconstructed threefold coincidence

We recorded a threefold coincidence with Auger SD some days after a major repair on antennas A2 and A3. The event occurred on Monday 30$^{\mathrm{th}}$ November 2009. It is a five-tanks event, including the additionnal tank Apolinario. The axis is in the direction $(\theta, \phi) =$

$(51.0^\circ \pm 0.5^\circ, -150.4^\circ \pm 0.5^\circ)$[1] and the energy of the event is estimated at 1.43 EeV according to the Auger reconstruction. Figure 4 shows the geometry of the event with respect to the RAuger experiment and the neighbouring Auger SD tanks. Apolinario is at the center of the triangle A1-A2-A3.

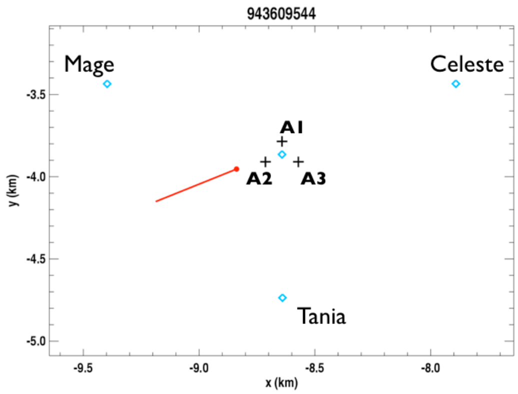

Figure 4: *Geometry of the event (using the shower parameters estimated by the Auger SD reconstruction). The Auger tanks are represented by the diamonds and the three radio stations around Apolinario by the crosses (A1 is at North, A2 South-West and A3 South-East). The red line shows the arrival direction in the horizontal plane and the red point is the shower core as reconstructed by Auger.*

Using the core position given by the Auger reconstruction, the shower axis of the event is at 163 m, 80 m and 183 m from A1, A2 and A3 respectively. Using the individual trigger times of each of the three antennas and knowing their ground positions, we compute the arrival direction of the shower front and the values are $(\theta = 51.3^\circ \pm 0.4^\circ, \phi = -150.2^\circ \pm 0.1^\circ)$ for RAuger and $(51.0^\circ \pm 0.5^\circ, -150.4^\circ \pm 0.5^\circ)$ for Auger. The 3D angular difference between the direction estimated by the radio stations and the direction estimated by Auger SD is $\delta\alpha = 0.38^\circ$ showing that the two directions are perfectly compatible since the Auger angular resolution for this type of event is greater than 1° [7].

Concerning the observed signal, fitting a simple exponential decrease of the electric field E^{EW} with the axis distance d of the form $E^{\mathrm{EW}}(d) = E_0^{\mathrm{EW}}\, e^{-d/d_0}$ in the East-West polarization leads to $E_0^{\mathrm{EW}} \sim 900\ \mu\mathrm{V/m}$ and $d_0 \sim 265$ m in the 50-70 MHz frequency band. Using the CODALEMA parameterization of the correlation between the electric field in the East-West polarization on the shower axis E_0^{EW} and the primary cosmic ray energy E_{CIC} (with the constant intensity cut CIC hypothesis) $E_0^{\mathrm{EW}} = 10^{-15.9}|(\vec{n} \times \vec{B})_{\mathrm{EW}}|\, E_{\mathrm{CIC}}^{1.05}$ (see [8, 9]), it corresponds to an energy in the range $[1.2 - 1.3]$ EeV according to the chosen parameterization, which is very close to the Auger SD value of 1.43 EeV.

[1]For the azimuths, 0° is East, 90° is North.

7. Conclusion

The RAuger experiment detects high energy cosmic rays at the center of the Pierre Auger observatory with three self-triggered and fully autonomous radio stations. The skymap in local coordinates of the 65 events in coincidence with Auger presents a strong excess of events coming from the South in accordance with the skymap predicted by the geomagnetic model proposed by CODALEMA. Among these events, one of them is a threefold coindicence (the three radio stations saw it) and the axis direction and the estimated energy is in perfect agreement with the Auger reconstruction.

References

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