Measurement of Low Energy Cosmic Radiation with the Water Cherenkov Detector Array of the Pierre Auger Observatory

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Abstract: The flux of secondary cosmic ray particles recorded in the 1660 water Cherenkov detectors of the Pierre Auger Observatory is continuously monitored and analysed for calibration purposes. It is possible to study the flux of primary cosmic rays within the GeV to TeV energy range using calibration histograms of the total energy deposited in the detectors, or data from low threshold scaler counters, which are publicly available. The observed flux is affected by several factors, such as solar activity, the directional properties of Galactic cosmic rays, and local meteorological conditions. The measured secondary flux (of the order of $10^8$ counts per minute) can provide important data on these factors by virtue of the high counting rates which are possible due to the large collecting area of the whole array. Current results of the analysis of each of these factors are presented.

Keywords: Pierre Auger Observatory, low energy cosmic rays, solar activity

1 Introduction

The flux of low energy Galactic cosmic rays (GCRs) is modulated by transient solar eruptions and by changes of the global structure and polarity of the magnetic field in the heliosphere. Variations in the intensity of secondary cosmic rays observed at the surface of the Earth also provide valuable information about the transport of particles in the inner and outer heliosphere, as well as about particles coming into the solar system from the local interstellar medium [1].

The flux of GCRs shows a long-term modulation associated with the solar cycle and short-term variations produced by the passage near the Earth of solar ejecta (i.e., the interplanetary manifestation of a coronal mass ejection, ICME), known as Forbush decreases (Fds) [1]. When observed with neutron monitors and with muon detectors, these Fds exhibit an asymmetrical structure: a characteristic fast decrease of the cosmic ray flux with a time-scale of some hours, and a smooth recovery with a timescale of several days. In some cases, Fds can show complex structures [2] due to the interaction of ICMEs with fast streams of plasma or with other ICMEs during their propagation through the interplanetary space [3]. In this article we present measurements of low energy cosmic radiation, in the range from GeV to several TeV, performed with the Pierre Auger Observatory. In section 2 we describe the water Cherenkov detectors of the Pierre Auger Observatory and their calibration with background muons. In sections 3 and 4 we describe the scaler mode for measuring the flux of low energy radiation and how the calibration histograms can be used to study the dependence of the intensity on energy, while in section 5 the detector response is evaluated. We present conclusions in section 6.

2 The Pierre Auger Observatory

The Pierre Auger Observatory [4], located at Malargüe, Argentina (69.3°W, 35.3°S, 1400 m a.s.l.), was designed for the study of cosmic rays of the highest energies. It combines two complementary techniques for the detection of the secondary particles in extensive atmospheric showers (EAS), produced by the interaction of cosmic rays with the atmosphere. In this hybrid design, two types of detectors register EAS: the fluorescence detector (FD) consists of twenty-seven telescopes located at four sites for the observation of ultraviolet fluorescence radiation produced by the shower, and the surface detector array (SD) measures the lateral distribution of secondary particles at ground level. The SD consists of an arrangement of 1660 water Cherenkov detectors. The detectors of the main array are placed in a triangular grid with a spacing of 1500 m, distributed over an area of 3000 km². It has an operation duty cycle of nearly 100%. Each water Cherenkov detector consists of a tank containing 12 m³ of high-purity water with an area of 10 m², providing the full array with a total detec-
tor area of about 16,600 m². Cherenkov radiation is generated by the passage of charged, ultra-relativistic EAS particles through the water in the detector. While each detector works as a calorimeter for $e^\pm$ and photons (which create $e^\pm$ pairs in water), typical muons possess enough energy to go through the full detector, and their Cherenkov emission is proportional to their track length within the water volume.

Three 9° Photons photomultiplier tubes (PMTs) collect the Cherenkov light in each detector and their signals are processed with a sampling rate of 40 MHz by six 10-bit flash analog-to-digital converters (FADC). Each detector is an autonomous station linked to the central data acquisition system (CDAS) in Malargüe through a dedicated radio network with a bandwidth of 1200 bps per station.

As detailed in [5], the detector is self-calibrated by measuring the pulse signals produced by the particles interacting in the water volume and by building one-minute histograms of their total charge. Since the total signal from a muon depends mainly on its track length, muons produce a characteristic peak. The position of the peak corresponds to (1.03 ± 0.02) times the total signal deposited by a vertical and central through-going muon [6]. Since the energy loss for energetic muons is $dE/dX \approx 2 \text{MeV} \text{g}^{-1} \text{cm}^2$, it is possible to calibrate the charge histograms, originally in arbitrary units of FADC counts, in units of energy deposited within the water volume, $E_d$. Figure 1 shows a typical charge histogram, with deposited energy measured in MeV.

![Figure 1: Charge histogram of the signals recorded by one PMT of a water Cherenkov detector of the SD, in bins of energy $E_d$. Both indicated energy regions ($15 \leq (E_d/\text{MeV}) < \infty$ for Period I, and $15 \leq (E_d/\text{MeV}) \leq 100$ for Period II) correspond to the counting interval of the scaler mode of the SD, as described in section 3.](image)

Each time the SD detects an EAS, the current one-minute histograms of all nearby detectors with significant signal are sent to CDAS for their storage in order to be used for an off-line calibration of the stations. In this way, on average 10 one-minute histograms of the flux of secondary particles at ground level are registered every minute.

3 The Scaler Mode

In March 2005, a new detection mode known as “single particle technique” was implemented in all the detectors of the SD at the Pierre Auger Observatory. This mode consists in the recording of low threshold rates (scalers) for the surface detectors of the array. It is intended for measurements of low energy radiation, long term stability and monitoring studies, and the search of transient events such as gamma ray bursts or Forbush decreases [7].

Two different configurations of the scaler mode were implemented at Auger, in different time periods. In Period I, from 01 Mar 2005 to 20 Sep 2005, the scaler mode counted the total number of signals per second in each detector above a threshold of 3 FADC counts above the baseline (corresponding to $E_d \sim 15 \text{MeV}$), with a typical rate of about 380 counts s$^{-1}$ m$^{-2}$. In Period II, starting at the end of Sep 2005, an upper bound of 20 FADC counts ($E_d \sim 100 \text{MeV}$) was introduced in order to diminish the sensitivity of the scalers to muon signals. This produced a reduction of the counting rate to about 200 counts s$^{-1}$ m$^{-2}$.

The main characteristics of the scaler rates for both periods are summarised in table 1. As both periods include the construction phase of the Observatory, the total detector collecting area ranged from 6,660 m² at the beginning of 2005 to 16,600 m² after its completion in 2008, with counting rates of $\sim 2 \times 10^8 \text{counts min}^{-1}$ for the full SD.

The flux of low energy particles at ground level, produced by the interaction of primary cosmic rays at the top of the atmosphere, is intrinsically non-constant. It is furthermore modulated by several atmospheric factors, such as atmospheric pressure. As expected, a strong anti-correlation is observed between the scaler rate and atmospheric pressure, corresponding to $(-2.7 \pm 0.2) \%$ per hPa for Period I, and $(-3.6 \pm 0.2) \%$ per hPa for Period II [7].

A comparison of the pressure-corrected Auger scaler rate with data from the close-by Los Cerrillos Observatory 6NM64 neutron monitor [8] (Chile, 33.3° S, 70.4° W, 10.8 GV cut-off rigidity) is shown in figure 2. Peaking at 15 May 2005 08:05 UTC, Auger scalers show a decrease of 2.9% with respect to the reference rate for May 2005. The fit of an exponential function for the recovery phase gives a time constant of 2.21 ± 0.18(stat) days. A decrease of 4.8% is found in the Los Cerrillos neutron rate, with a time constant of $3.52 \pm 0.12\text{(stat)}$ days. The observatories possess a similar cut-off rigidity. The differences in the observed time constants result from the higher energy threshold of the Auger detectors compared to neutron monitors.

Instead of using averaged scaler rates for the whole array, it is also possible to study the scaler rate of individual stations, in order to study the propagation of some phenomena across the Auger SD, like the crossing of a storm over the 3000 km² of the SD (see [9]). The flux of secondary particles changes as the pressure front moves from the SW towards the NE border of the SD. Additional analyses to study the influence of the variation of electric fields on the flux of EAS particles are currently being carried out.
Table 1: Count rates for Auger scalers in both periods as defined in section 3. The collecting area range is due to the installation of new detectors in the SD, up to its completion in 2008.

<table>
<thead>
<tr>
<th>Period</th>
<th>Energy range [MeV]</th>
<th>Average scaler rate [counts s⁻¹ m⁻²]</th>
<th>Total collection area [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I: 01 Mar 2005 - 20 Sep 2005</td>
<td>$E \gtrsim 15$</td>
<td>$\sim 380$</td>
<td>6 660 - 8 420</td>
</tr>
<tr>
<td>II: After 20 Sep 2005</td>
<td>$15 \lesssim E \lesssim 100$</td>
<td>$\sim 200$</td>
<td>8 420 - 16 600</td>
</tr>
</tbody>
</table>

It has been suggested that an increment in the flux of low energy cosmic rays could be expected as a precursor to the occurrence of a major earthquake, and some low significance correlations have been found with low altitude spacecraft measurements [10]. At 27 Feb 2010 06h34 UTC an 8.8 magnitude earthquake occurred in Chile, with the epicentre located at 35.9° S, 72.7° W in the Bio-Bio Region, 300 km SW from the Auger Observatory. The averaged scaler rate for the whole array and also for individual stations showed a $24 \sigma$ decrease beginning (90 ± 2) seconds after the earthquake. This delay is compatible with the propagation of seismic S-waves over that distance. The scaler rate from 6h15 to 6h45 UTC is shown in figure 3.

Figure 2: Ten seconds average of the Auger scaler rate for the 27 Feb 2010 Chile major 8.8 magnitude earthquake. A strong $24 \sigma$ decrease is found $90 \pm 2$ (stat) seconds afterwards, compatible with the time delay expected for seismic S-waves traversing the distance from the epicentre to the Auger Observatory.

4 The Histogram Mode

Except for a strong Forbush decrease observed on 13 Dec 2006, no other significant activity in the heliosphere was recorded in the period 2006–2009. This period was therefore selected to study the influence of atmospheric conditions on the charge histograms. A subset of detectors of the complete array was selected and, for each PMT of each of those stations, a fit of the correlation of the observed rate of particles in each 20 MeV bin of deposited energy with atmospheric pressure was performed, and the fitted parameters were averaged over the selected sub array.

The scaler rate in the “single particle technique” mode is related to the integral of the calibration histogram between two limits defined by the lower and upper scaler trigger bounds (see figure 1). By integrating the calibration histograms with other bounds, it is possible to obtain a rate related to the flux of secondary particles in a specific range of deposited energy. As shown by simulations (see section 5), this flux is related to the number of incident primary cosmic rays of different energies.

The pressure corrected histogram data of the sub array detectors for the 15 May 2005 Fd are shown in figure 4. Six-hour averages in five 20 MeV deposition energy bands of the charge histogram are shown, centred at 140 MeV, 240 MeV, 480 MeV, 840 MeV and 1 GeV. Since a vertical and central through-going muon deposits $\sim 240$ MeV in the water volume, the integrated counting rate of this band is strongly related to the counting of muons at ground level. The Fd is clearly visible in all the energy bands.
Figure 4: May 2005 Forbush decrease observed by the Pierre Auger Observatory. Each curve shows, as a function of time, the integral of the pressure corrected charge histogram over a 20 MeV bin of deposited energy \( E_d \), centred at 140 MeV, 240 MeV, 480 MeV, 840 MeV and 1 GeV. Each energy band was offset by a value of 3%, 1.5%, 0%, −1.5%, and −3% resp.

5 Detector response

To determine the energies of primary GCRs to which the Auger Observatory low energy modes are sensitive, a set of low energy EAS simulations was performed using CORSIKA 6.980[11] with QGSJET-II model for the high energy hadronic interactions and GHEISHA low energy interaction routines. The flux of primaries at the top of the atmosphere for all nuclei in the range \( 1 \leq Z_p \leq 26 \) (1 ≤ \( A_p \) ≤ 56) was assumed to be a power law of the form \( j(E_p) = j_0(E_p/\text{GeV})^{-\gamma} \). The values for \( j_0 \) and the spectral index \( \gamma \) were obtained from[12], from the measured spectra in the range \((10 \times Z_p) < (E_p/\text{GeV}) < 10^6\), and for \( 0^\circ \leq \theta_p \leq 88^\circ \) in zenith angle. The detector response was simulated using a simple simulator developed within the Auger data analysis framework. Results are shown in figure 5, where the fraction of the observed contribution for four primary GCR energy bands is plotted as a function of the energy deposition within the detector volume. Different regimes are visible in the figure: while for \( E_d \sim 240\text{ MeV} \), the typical deposited energies for single muons, the contribution is dominated by primaries of \( E_p < 350 \text{ GeV} \), at \( E_d \gtrsim 600 \text{ MeV} \) the contribution becomes dominated by GCRs of higher energies.

6 Conclusions

The study of variations in the galactic cosmic ray flux is important because it carries information about the local interstellar and interplanetary media, and about the physical mechanisms involved in the interaction between charged particles and plasma in the heliosphere.

In this work, measurements of low energy cosmic radiation in the GeV–TeV range using the surface detector array of the Pierre Auger Observatory are described. The capabilities of water Cherenkov detectors for the study of transient solar events at the Earth surface has been demonstrated using the scaler data.

The scaler mode is now complemented by the analysis of the calibration charge histograms, which enable the study of the time evolution of transient solar events at the same rigidity cut-off for different bands of deposited energy.

The full scaler data set, averaged every 15 minutes for the whole surface detector array, is publicly available and can be downloaded from the Pierre Auger Observatory Public Event Display web site[13]. A user-friendly web interface has been set up to handle, visualise and download the data.

References