Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 319–322

ID 302

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Weather induced effects on extensive air showers observed with the surface detector of the Pierre Auger Observatory

CARLA BLEVE[1], FOR THE PIERRE AUGER COLLABORATION[2]
[1]*School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT, United Kingdom*
[2]*Observatorio Pierre Auger, Av. San Martín Norte 304, (5613) Malargüe, Mendoza, Argentina*
C.Bleve@leeds.ac.uk

Abstract: The rate of events measured with the surface detector of the Pierre Auger Observatory is found to be modulated by the weather conditions. This effect is due to the increasing amount of matter traversed by a shower as the ground pressure increases and to the inverse proportionality of the Molière radius to the air density near ground. Air-shower simulations with different realistic profiles of the atmosphere support this interpretation of the observed effects.

Introduction

The surface detector (SD) of the Auger Southern Observatory, located in Malargüe, Argentina, is designed for the detection of ultra high energy cosmic rays through the measurement of the signal induced by the shower particles reaching the observation level ($\sim$ 880 g cm^{-2}) in an array of water-Cherenkov tanks arranged in a triangular grid with 1500 m spacing.

The regular data taking of the SD started in January 2004, with the array continuosly growing from 100 stations up to the current 1200. To check the detector stability we monitored the shower counting rate, finding that it is modulated by weather effects. This dependence is expected since changes in the atmospheric density profile due to weather variations influence the development of the air shower and in turn the amplitude of the signal measured at ground. As a consequence, a study of the detector stability has to account for the rate dependence on the atmospheric conditions. Moreover, since the SD estimate of the energy of the primary particle is based on $S(1000)$, the signal measured at 1000 m from the shower axis, we are interested in the dependence of $S(1000)$ on the atmospheric conditions. This requires a continuous monitoring of the weather and a good knowledge of the relationship between $S(1000)$ and the measured weather parameters. The former is provided by a meteorological station, at the centre of the SD array, that records the weather parameters every 5 min, allowing the correlation of the modulation of observed quantities, such as the rate of events, with the measured ground temperature T and pressure P.

Weather effects on EAS

The expected effects related to the change of weather conditions are essentially two:

(i) an increase in the ground pressure P corresponds to an increased slant depth X and implies that the shower is older when it reaches the ground level. The longitudinal development of the electromagnetic component of the shower at 1 km from the core can be parameterised as a Gaisser-Hillas profile, $N_{em}(E,X) \propto X^{\hat{X}_m/\Lambda}\exp[(\hat{X}_m - X)/\Lambda]$, where $\hat{X}_m$ is the average maximum of the shower at 1 km from the core ($\simeq$ 200 g cm^{-2} deeper than at the core) and $\Lambda \simeq 70$ g cm^{-2} is an effective hadronic attenuation length. Then, under a pressure change, the electromagnetic component S_{em} of $S(1000)$ changes by

$$\frac{\mathrm{d}\ln S_{em}}{\mathrm{d}P} = -\left[1 - \frac{\hat{X}_m}{X}\right]\frac{\sec\theta}{\Lambda}, \qquad (1)$$

where $\mathrm{d}X = \mathrm{d}P\sec\theta$ was used. Since for the energies of interest, $E > 10^{18}$ eV, the maximum of

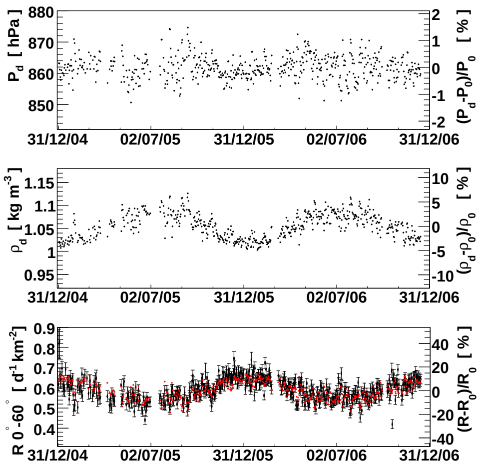

Figure 1: Daily averages of ground pressure (top), density (middle) and event rate (bottom, black). Since the pressure is stable, the prominent effect on the rate modulation is due to the density (temperature) variation. The red points in the bottom plot show the results of the fit.

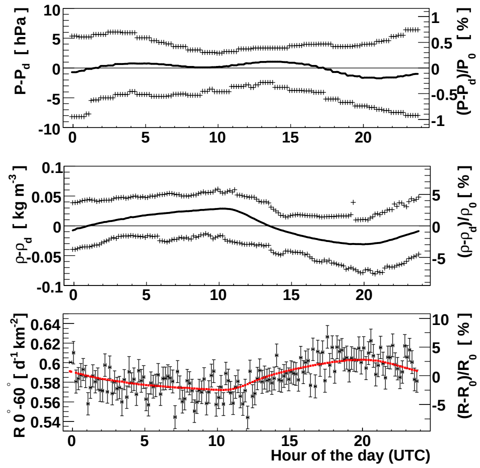

Figure 2: Variation of P (top) and ρ (middle) during the day: the values averaged over 2005 and 2006 (lines) are shown together with the maximum variation values during the 2 years considered (crosses). Bottom: the result of the fit (red) reproduces very well the average diurnal modulation of the measured rate (black). The local time is UTC - 3 h

vertical showers is close to ground, this effect is expected to be more pronounced for inclined showers.
(ii) an increase in the air density reduces the Molière radius r_M (proportional to $1/\rho$) and hence the lateral extent of the electromagnetic component of the shower. The lateral distribution of the electromagnetic component can be approximately described with an NKG profile, which for large radius r from the core behaves as $N_{em}(r) \propto r_M^{-2}(r/r_M)^{-\alpha}$, where $\alpha \simeq 4$ and $r_M \simeq 83\ \mathrm{m}/(\rho/\ \mathrm{kg\ m^{-3}})$. Hence, under a density change

$$\frac{\mathrm{d}\ \ln S_{em}}{\mathrm{d}\rho} \simeq \frac{(2-\alpha)}{\rho}. \qquad (2)$$

The effective value of r_M is that corresponding to the air density ρ^* two cascade units above ground [1] ($\sim 700\ \mathrm{m}\cos\theta$ at the Auger site, with θ being the zenith angle). Since the ground T, P are the only available observables, we have to express ρ^* in terms of the density ρ measured at ground.

On time scales of one day or more, the temperature gradient in the lowest layers of the atmosphere (the planetary boundary layer) can be described by an average value of $6.5°\mathrm{C\ km^{-1}}$; therefore the variation of ρ^* is the same as that of ρ. An additional effect is related to the diurnal variations of the gradient that is smaller before sunrise, at which time even T inversions are common, and larger in the early afternoon hours. As a result, the amplitude of diurnal variations in T (and ρ) is smaller at 2 cu than at ground level by a factor $\simeq 0.5$. We define the average daily densities ρ_d and ρ_d^* and the reference values (averaged over 2 years of measurements) $\rho_0 = 1.055$ kg m^{-3} and $P_0 = 861.9$ hPa, ρ_0^* denotes the reference density at 2 cu above ground. The energy reconstructed with no correction for weather effects is $E_r \propto [S(1000)]^B$, where $B = 1.13 \pm 0.02$ [2]. Hence we can parameterise the relation between the shower energy $E_0(\theta, P, \rho)$ at the reference weather conditions and the reconstructed one E_r as:

$$\begin{aligned} E_0 &= E_r\{1-\alpha_P(P-P_0)-\alpha_\rho(\rho^*-\rho_0^*)\}^B \\ &= E_r\{1-\alpha_P(P-P_0)- \\ &\quad \alpha_\rho(\rho_d-\rho_0)-\beta_\rho(\rho-\rho_d)\}^B \end{aligned} \qquad (3)$$

where the coefficients $\alpha_{\rho,P}$ and β_ρ depend on the zenith angle θ.
Assuming that the cosmic ray spectrum is a pure power law $\mathrm{d}J/\mathrm{d}E \propto E^{-\gamma}$, it is easy to show that the rate $R(\theta, P, \rho)$ of events at a given zenith angle θ can be expressed as:

$$\begin{aligned} R &= R_0\{1 + a_P(P - P_0) + \\ &\quad a_\rho(\rho_d - \rho_0) + b_\rho(\rho - \rho_d)\} \end{aligned} \tag{4}$$

with $R_0 = R(\theta, P_0, \rho_0)$ and coefficients $a_{\rho,P} = (B\gamma - 1)\alpha_{\rho,P}$ and $b_\rho = (B\gamma - 1)\beta_\rho$, the latter describing the diurnal modulation of the rate with the density.

Modulation of the measured rates of events

To study the modulation of the event rate with the ground weather parameters, we use the data taken from 1 January 2005 to 31 December 2006 that have a zenith angle $\theta < 60°$. The data selection criterion is the same as applied for the SD spectrum [2]. The value of the air density ρ at ground is deduced from P and T measured at the central meteorological station. Rather than using the raw number of triggering events, we compute the rates, as a function of time, to account for the temporal variation of the active detection area due mainly to the deployment of new stations and occasionally to stations experiencing a temporary failure [3]. The modulation of the rate during the year, and as a function of the hour of the day, follows the changes in density and pressure (Figs. 1 and 2). A characteristic of the Malargüe site is the stability of pressure (less than ± 2% variation), while ρ_d changes up to a maximum of ± 6% during the year with an additional diurnal variation of density of ± 2% on average, with maximum values of $^{+6}_{-8}$% during the two years considered. Assuming that the rates computed each hour follow a Poisson distribution, a maximum likelihood fit gives the estimated values of the coefficients in eq. (4) averaged over the event distribution in the zenith range $0° - 60°$:

$$\begin{aligned} a_P &= (-0.0009 \pm 0.0005)\ \mathrm{hPa}^{-1} \\ a_\rho &= (-2.68 \pm 0.07)\ \mathrm{kg}^{-1}\ \mathrm{m}^3 \\ b_\rho &= (-0.85 \pm 0.07)\ \mathrm{kg}^{-1}\ \mathrm{m}^3. \end{aligned} \tag{5}$$

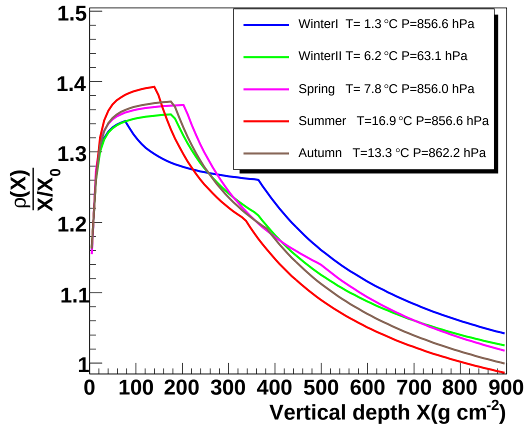

Figure 3: Seasonal atmospheric profiles derived from the parameterisation of radio soundings performed in Malargüe and used in simulations. The density profiles are divided by the profile of an isothermal atmosphere (with X_0 = 900 g cm^{-2}) to enhance the differences. The corresponding values of P and T are given in the box.

Comparison of the experimental results with model and simulations

To test the validity of our interpretation, we compare the coefficients obtained from the fit of data with results from full shower simulations and the predictions on theoretical grounds.
The Corsika code [4] with the QGSjetII model [5] for high energy hadronic interactions, was used to simulate a set of proton showers at 10^{19} eV in 5 different atmospheres and at various zenith angles. The atmospheric profiles used (Fig. 3) are a parameterisation of the seasonal averages of several radio soundings carried out at the detector site [6] and provide a sample of realistic conditions above the Auger SD array, but, being averages on large time scales, do not account for the diurnal variation of the temperature in the lower atmosphere. The expected signal $S(1000)$ is estimated through the simplified assumptions that e^+, e^- and photons deposit all their energy in the surface detector, while for muons we take the minimum between the kinetic energy and 240 MeV (the energy deposited by a vertical muon crossing a SD tank). As expected, the simulated signal depends on the ground density and pressure according to the expression in

eq. (3) (with $\rho - \rho_d = 0$) with coefficients α_ρ and α_P shown in Fig. 4 for all zenith angles between $0°$ and $60°$. The large uncertainties are due to the limited number of atmospheric profiles used.
For the theoretical expectations, we consider the variation of the total signal, given by the sum of the electromagnetic and muonic component. The coefficients $\alpha_{\rho,P}$ in (3) result from the variation of both components: $\alpha_{\rho,P} = F_{em}\alpha^{em}_{\rho,P} + (1 - F_{em})\alpha^{\mu}_{\rho,P}$, where F_{em} is the electromagnetic fraction at 1 km. The dependence of S_{em} on ρ and P is discussed in section 2. For a quantitative prediction we adopt in eq. (1) $\hat{X}_m = 950$ g cm^{-2}, typical of 10 EeV proton showers, and $X = 880 \sec\theta$ g cm^{-2}. For the electromagnetic fraction F_{em} we use a fit to the results of shower simulations with 10 EeV protons ($F_{em} \simeq 0.7$ near the vertical and decreasing with θ to reach ~ 0.2 at $60°$). We assume a negligible correlation of S_μ with pressure and a constant value $\alpha^\mu_\rho = -0.26\,\mathrm{kg}^{-1}\,\mathrm{m}^3$ for the dependence on density (suggested by the results of simulations). In Fig. 4 we compare the coefficients obtained by fitting the data in five zenith ranges. The procedure to obtain $a_{\rho,P}$ is the same described in section 3, then we derive the signal coefficients $\alpha_{\rho,P}$ dividing by $(B\gamma - 1) = 2$. Their values are in good agreement with both the model predictions and the results from simulations.

Conclusions

The modulation of the event rates measured by the Auger SD can be explained by known effects on the shower development, both on seasonal and diurnal scales. At the Auger site the dominant effect is related to the density (temperature) variation. The systematic error, when determining the energy of a single shower in the zenith range $0° - 60°$, amounts to a maximum of $\sim 10\%$ (for extreme values of ground pressure and temperature). The quantitative agreement of the theoretical model with simulations and data, suggests that it can be used to correct the SD energy reconstruction for weather induced effects.

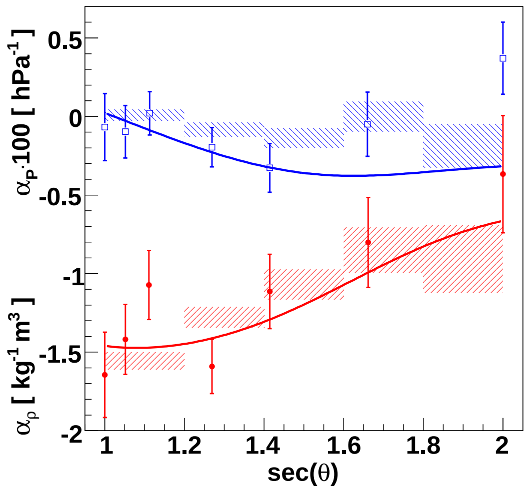

Figure 4: Comparison of the signal coefficients α_ρ (squares) and α_P (circles) obtained from the fit of simulated signal for 10^{19} eV proton showers, fit of the measured rates (shaded rectangles), and values obtained with the theoretical model described in the text (lines). The value of X_m = 750 g cm^{-2}, used in the model, corresponds to 10 EeV showers according to the measured elongation rate [7].

References

[1] K. Greisen, Progress in Cosmic Ray Physics III, J. G. Wilson (Interscience, New York), 1956.

[2] M. R. P. A. Collaboration], These proceedings #0313.

[3] T. S. P. A. Collaboration], These proceedings #0299.

[4] D. H. et al., Report FZKA 6019, 1998.

[5] S. S. Ostapchenko, Nucl. Phys. B (Proc. Suppl.) 151 (2006) 143 and 147.

[6] B. K. et al, Astropart. Phys. 22 (2004) 249.

[7] M. U. P. A. Collaboration], These proceedings #0594.