*SF2A 2008*
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# ATMOSPHERIC EFFECTS ON EXTENSIVE AIR SHOWERS OBSERVED WITH THE SURFACE DETECTOR OF THE PIERRE AUGER OBSERVATORY

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**Abstract.** Atmospheric parameters, such as pressure ($P$), temperature ($T$) and density ($\rho \propto P/T$), affect the development of extensive air showers (EAS) initiated by energetic cosmic rays (CRs). We have studied the impact of atmospheric variations on EAS by means of the surface detector of the Pierre Auger Observatory, analyzing the dependence on $P$ and $\rho$ of the counting rate of events. We show that the observed behaviour is explained by a model including $P$ and $\rho$ and validated with full EAS simulations.

## 1 Introduction

The properties of the primary CRs have to be inferred from EAS, which are typically sampled by an array of detectors at ground level. As the atmosphere is the medium in which the shower evolves, its state affects the shower development. Changes in the atmosphere are expected to have an effect also on the measured signal. We have studied the atmospheric effects on EAS by means of the surface detector (SD) of the Pierre Auger Observatory (Abraham et al. 2004) designed to study CRs from $\approx 10^{18}$ eV up to the highest energies. The signals in the detectors are fitted in each event to find the signal at a 1000 m core distance, S(1000), which is used to estimate the primary energy. The atmosphere is continuously monitored by meteorological stations at the detector site and balloon-borne sensors provide measurements of $T$ and $P$ as a function of the height $h$.

## 2 Atmospheric effects on EAS

An increase (decrease) of $P$, which measures the vertical air column density above ground, corresponds to an increased (decreased) matter overburden and implies that the shower is in a more (less) advanced stage when it reaches the ground level. On the other side, a decrease (increase) of $\rho$ increases (decreases) the Molière radius $r_M$ and thus broadens (narrows) the lateral extent of the EAS. The impact on S(1000) can then be modelized using a Gaisser-Hillas and a Nishimura-Kamata-Greisen profile, which describe the longitudinal and the lateral distribution of the electromagnetic component of the EAS, respectively. In fact, the relevant value of $r_M$ is the one corresponding to the air density $\rho^*$ two radiation lengths ($X_0$) above ground (Greisen 1963) in the direction of the incoming shower. On time scales of one day or more, the temperature gradient ($\mathrm{d}T/\mathrm{d}h$) in the lowest layers of the atmosphere is constant. Therefore the variation of $\rho^*$ on temporal scales of one day essentially follows that of $\rho$. An additional effect is related to the diurnal variations of $\mathrm{d}T/\mathrm{d}h$. During the day the surface of the Earth is heated, producing a steeper $\mathrm{d}T/\mathrm{d}h$ whereas during the night $\mathrm{d}T/\mathrm{d}h$ becomes smaller. As a result, the amplitude of the diurnal variation in $T$ is smaller at 2 $X_0$ above ground than at ground level. It is then useful to separate the daily modulation from the longer term one introducing the average daily density $\rho_d$ and the instantaneous departure from it, $\rho - \rho_d$. The energy reconstructed with no correction is $E_r \propto [\mathrm{S}(1000)]^B$ where $B \approx 1$ (Abraham et al. 2008). The primary energy $E_0(\theta, P, \rho)$ that would have been obtained for the same shower at the reference pressure $P_0$ and density $\rho_0$ is related to $E_r$ as: $E_0 = E_r\,[1 - \alpha_P(P - P_0) - \alpha_\rho(\rho_d - \rho_0) - \beta_\rho(\rho - \rho_d)]^B$ where the coefficients $\alpha_{P,\rho}$ and $\beta_\rho$ depend on the zenith angle $\theta$. Assuming that the cosmic ray spectrum is a pure power law $\mathrm{d}J/\mathrm{d}E \propto E^{-\gamma}$, the rate $R(\theta, P, \rho)$ of events at a given zenith angle is:

$$R = R_0\,[1 + a_P(P - P_0) + a_\rho(\rho_d - \rho_0) + b_\rho(\rho - \rho_d)] \tag{2.1}$$

with $R_0 = R(\theta, P_0, \rho_0)$ and coefficients $a_{P,\rho} = (B\gamma - 1)\alpha_{P,\rho}$ and $b_\rho = (B\gamma - 1)\beta_\rho$.

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## 3 Modulation of the measured rate of events

To study the modulation of the events rate with the ground weather parameters we use the data taken from 1 January 2005 to 31 December 2007 that have $\theta < 60°$. The value of the air density $\rho$ at ground is deduced from $P$ and $T$ measured at the meteorogical stations. Rather than using the raw number of triggering events, we measured the rate as a function of time, to account for temporal variation of the active detection area. Assuming that the rate of events computed each hour follows a Poisson distribution, a maximum likelihood fit gives the estimated values of the coefficients in eq.(2.1). The result is shown in Fig. 1.

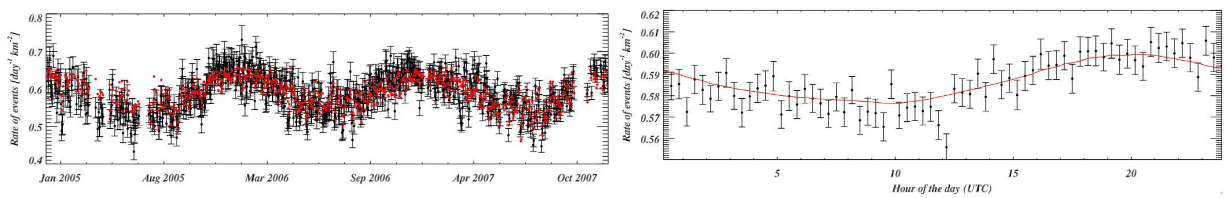


**Fig. 1.** Left: daily modulation of the measured (black points) and fitted (red points) rate of events. Right: diurnal modulation (black) and fitted (red) events rate.

## 4 Comparison of the experimental results with model and simulations

We now compare the atmospheric coefficients derived from data and simulations with those expected from the model (Fig. 2). The Corsika code with the QGSjetII model for high energy hadronic interaction, was used to simulate a set of proton showers at $10^{18.5}$, $10^{19}$ and $10^{19.5}$ eV in 5 different atmospheres and at various $\theta$. The atmospheric profiles used are a parametrisation of the seasonal averages of several radio soundings carried out at the detector site, but, being averages on large time scales, do not account for the diurnal variations of $T$.

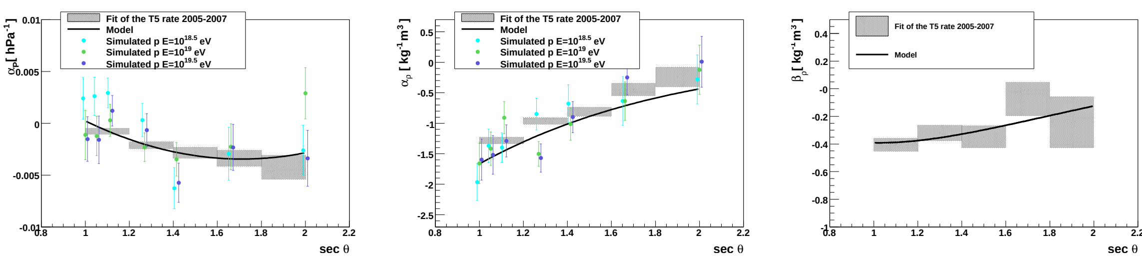


**Fig. 2.** Comparison of the $\alpha_P$ (left), $\alpha_\rho$ (center) and $\beta_\rho$ (right) coefficients, as a function of $\sec\theta$ obtained from data (grey shaded rectangle), simulations (bullets) and model (continuous line).

## 5 Conclusion

We have studied the effect of atmospheric variations on EAS using 3 years of data collected by the SD of the Pierre Auger Obsrvatory. We observe a significant modulation of the event rate, both on seasonal scale ($\sim 10\%$) and on shorter time scale ($\sim 2\%$ on average during a day). This modulation is due to the impact of the density and pressure changes on the EAS development, and in turn on S(1000). Comparing the coefficients deduced from data, shower simulations in different atmospheric profiles and expectations from the model, a remarkable agreement is obtained, not only for the overall size of the effect but also for the $\theta$ dependence.

## References

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