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Simulation of the atmospheric fluorescence from EAS for calculation the photoelectrons at the PMT photocathode of FD

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Abstract. The Linsley standard atmospheric model is used to simulate the atmospheric EAS due to the passage of an UHECR. Adopting the AIRES shower simulation program we derived the longitudinal distribution of electrons and positrons produced. These particles exciting the nitrogen molecules in the atmosphere play a dominant role in the amount of fluorescence light coming from nitrogen de-excitation within the wavelength range of 300 – 400 nm. The fluorescence triggers efficiently the array of photomultiplier tubes (PMT) of the Fluorescence Detector of the Auger Observatory, provided that the signal to noise ratio at each pixel taking part in the trigger decision for counting the photoelectrons is typically greater than 5.

Results of simulation for typical events expected to be registered by the AUGER FD prototypes are presented. The relative counting rate of the PMT array is obtained for a typical shower triggered by a cosmic ray proton for different inclinations. Future perspectives for simulations based on highly resolved spectra of N_2 recorded under variable conditions of temperature and pressure are discussed.

1 Introduction

The detection of the longitudinal evolution of Extensive Air Showers (EAS) in the atmosphere was proposed by Greisen (1960). His model was based at the excitation of atmospheric oxygen and nitrogen molecules by charged particles formed in the atmosphere by the primary high-energy cosmic rays (CR). The produced de-excitation light (fluorescence) could be monitored with installed photomultipliers (PM).The initial energy of the primary beam could be obtained by measuring the intensity of the detected light.

Greisen estimated that the emitted fluorescence was of the order of 4-5 photons per electron per meter of track. Since the relative concentration of nitrogen in the atmosphere is 80% (20% is oxygen), the transmitted light falls generally within the wavelength range of 300-400 nm, characterizing the nitrogen atoms (N_2-fluorescence).

An appropriate array of PM tubes (PMT) viewing the sky could “trace” the track of a CR in the atmosphere as a moving spot and visualize the sky projection of the EAS trajectory.

2 Methodology

Guerard (1998) used for the estimation of the number of photoelectrons that trigger a PMT the following Eq. (1), which in simplified form is given by:

$$S_i = 2.4\, N_e^i \,\frac{A}{4\pi R_p^2}\, \frac{R_p \alpha}{1-\cos\theta_i}\, q_e e^{-\left(\frac{R_p}{\psi \sin^2\theta_i}\right)} \qquad (1)$$

where, S_i is the number of photoelectrons at the PMT cathode,

2.4 (photons m^{-1}), the average number of photons produced per meter and electron,

N_e^i, the number of electrons (positrons) produced at point i (Fig.2),

A, the mirror area (~10 m^2),

R_p, the minimum distance between FD and shower axis,

α, the pixel aperture in degrees (1.5^0),

θ_i, see Fig. 2,

q_e, the photocathode quantum efficiency (0.25),

ψ, the photon attenuation length, 8.4 km, (Giller et al., 1999).

The number of electrons and positrons for each point i, is derived

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from the simulation of EAS by AIRES program (Sciutto, 1999) instead to be calculated by parameterization (Guerard, 1998). Substituting the above values in Eq. (1) we can obtain the number of photoelectrons at the PMTs photocathode as a function of the atmospheric height. Since the fluorescence intensity depends mainly on the energy loss of electrons and positrons per unit path length ($\Delta E/\Delta x$), with knowing it and the nitrogen excitation energy, we can estimate the number of photons per meter produced at different atmospheric depths. This is an independent way to estimate the photons immersed at each point of the shower core. With the AIRES simulation program, we have calculated the longitudinal energy distribution of e^- and e^+ at 500 points along the shower. The shower is created by a vertical primary proton with an energy of 100 EeV. Figure 1 shows the longitudinal development of the energy as a function of atmospheric depth. On the same plot, the ratio $\Delta E/\Delta x$ is shown. At a depth of about 500 gr/cm^2 (at a height of about 5000 meters), the energy of e^- and e^+ reaches its maximum and for lower heights decreases, mainly due to ionization losses. The energy loss per unit path ($\Delta E/\Delta x$), after a short increase decreases and crosses zero becoming negative. If we assume that the energy loss per unit path from its maximum to zero crossing is due to the nitrogen excitation, we could estimate the number of photons produced. Unfortunately, we cannot estimate the photons produced at smaller atmospheric depths (lower than 500 gr/cm^2), because we do not know the amount of energy spent for the production of these photons and for ionizations. For this reason, we used equation (1) and substituted the simulation values in it instead of using $\Delta E/\Delta x$.

3 Simulation of EAS

For simulation of N_e^i (Eq. 1) we used the AIRES simulation program. For each "event" a number of 200 showers are used with a thinning energy of 10^{-5}. 500 bins trace the trajectory of the shower, each of them indicating the number of electrons and positrons created at 500 atmospheric depths in increasing order (from 2.1 – 1034.0 gr/cm^2). For the relation between the atmospheric depth and the altitude we adopted the Linsley standard atmospheric model. The simulation set refers to a primary proton with an energy of 100 EeV and with inclinations 0^0 , 10^0, 20^0, 30^0 , 80^0 and azimuth angle 0^0. The basic parameters are:
Site: Site00
Lat: 0 deg. Long: 0 deg.
Primary particle: Proton.
Primary energy: 100 EeV.
Primary zenith angles: 0 , 10, 20 and 30 deg. (Fig. 2).
Primary azimuth angle: 0.00 deg.
Zero azimuth direction: Local magnetic north.
Thinning energy: 10^{-5} relative.
Injection altitude: 100 km (1.2829219×10^{-3} g/cm^2).
Ground altitude: 297.96 m (1000 g/cm^2).
First obs. level altitude: 43.242 km (1.997288 g/cm^2).
Last obs. level altitude: 314.70 m (998.0040 g/cm^2).
Observing levels and depth step: 500 1.996 g/cm^2.

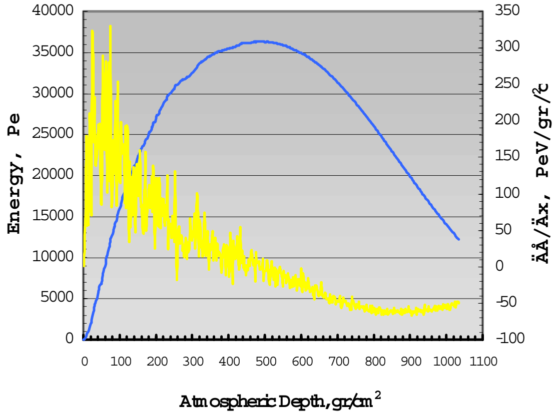

Fig. 1. The simulated longitudinal energy development of e^- and e^+ (smooth curve in blue, left axis) with the $\Delta E/\Delta x$ ratio (rough curve in yellow, right axis).

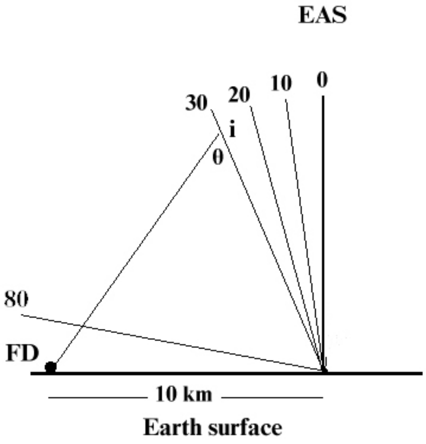

Fig. 2. The relative position of FD with respect to the incident showers at various angles.

Figure 3, shows the number of photoelectrons yield for a vertical and inclined shower. The curves follow the general trend of the number of electrons and positrons derived from the AIRES simulation having a maximum shifted according to the inclination. For a quasi-horizontal shower (80^0), the distribution is restricted to smaller atmospheric altitudes, it has a lower rate (maximum 2000 photoelectrons) and because of this low rate it has more statistical fluctuations. For this particular case the corresponding distribution of electrons and positrons as a function of atmospheric height, derived from simulation of the same primary is shown in Fig. 4 for different altitudes.

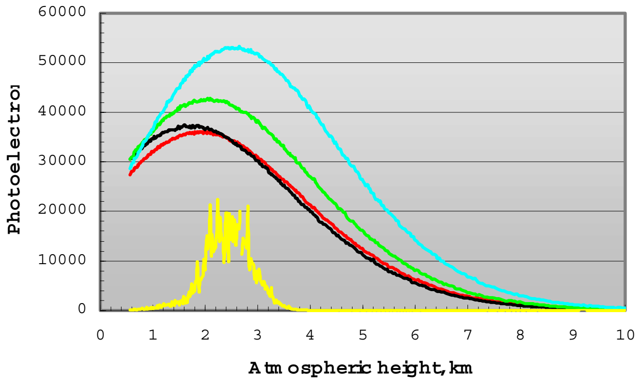

Fig. 3. The number of photoelectrons as a function of atmospheric height for different inclinations of the same EAS. From the upper most to the lowest sequence, curves correspond to 30^0 (blue), 20^0 (green), 10^0 (black), 0^0 (red) and 80^0 (yellow) of inclination. For a better view of plot for 80^0, 10 multiplies the number of photoelectrons.

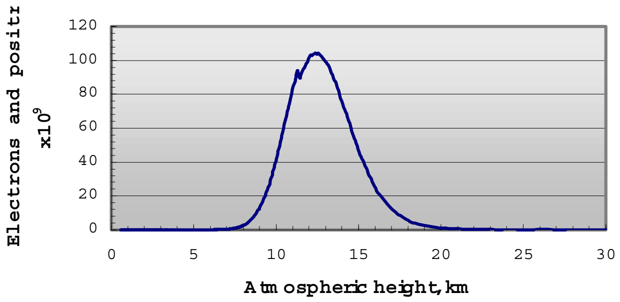

Fig. 4. The distribution of electrons and positrons for a quasi-horizontal shower (80^0 of inclination).

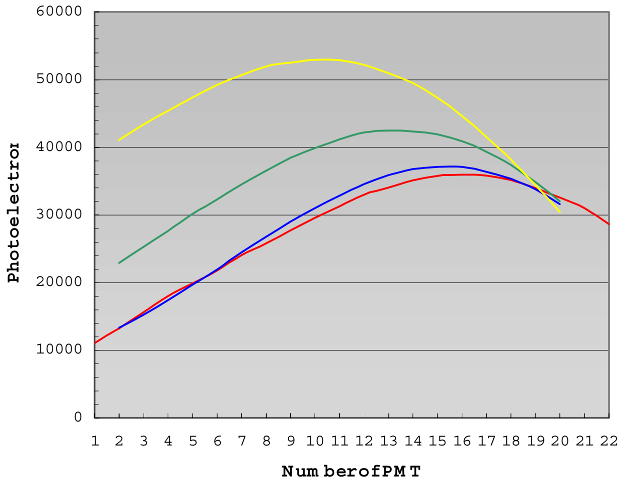

Fig. 5. The number of photoelectrons counted by the PMTs for different inclinations of the shower.

If we take into account the geometry of one FD with an array of PMTs, we can estimate the number of photoelectrons counted for the different inclinations of the shower in Fig. 2. Due to the fact that the tested shower has zero azimuth angle, the activated PMTs lie in the middle of the array on a vertical straight line. The relative signal yields obtained in this line of PMTs are depicted in Fig. 5. For all inclinations the counted photoelectrons increase up to a maximum with increasing the sequence number of PMT. For higher inclinations, the yield of photoelectrons increases and its maximum is shifted toward lower PMT sequence number. For the inclination of 80^0, the yield photoelectrons is extreme low, as can be seen in Fig.3.

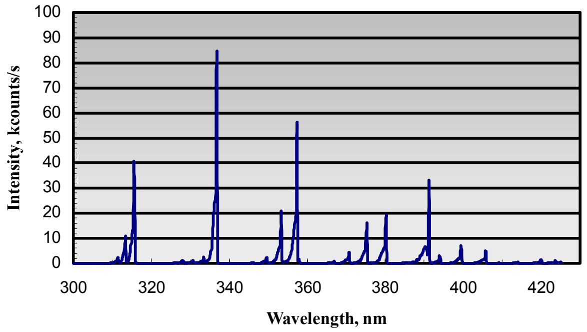

Fig. 6. The spectrum of a low pressure air discharge lamp recorded with an 1-meter focal length monochromator.

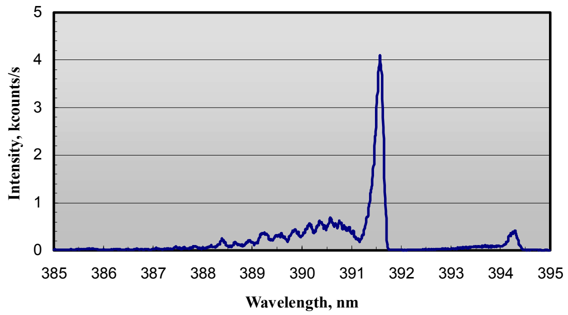

Fig. 7. N_2-spectrum in the region of the 391.4 nm line. Rotational lines of vibrational transitions are also observed (Small bump before the main line).

4 Air fluorescence spectrum

In the following, we present some on-going work, which we plan to incorporate into the simulation procedure. It deals with a more realistic spectrum of air fluorescence, which can be assumed for each atmospheric depth range considered. Since the spectral characteristics of air fluorescence depend on the air pressure and temperature, they they can be experimentally reproduced. Kakimoto (1996) has done this.

We have followed a different procedure in which we get a highly resolved air-fluorescence spectrum from an electrical discharge lamp containing air at low pressure. This spectrum was recorded with an one meter long monochromator. Figures 6 and 7 show the full range of the N_2-fluorescence spectrum and the spectral region around the 391.4 nm line respectively. By changing pressure and temperature of this test lamp, we expect to emulate the typical conditions of air fluorescence as they exist in the atmosphere during an EAS. Then, by segmenting the atmospheric height in, say 20 successive ranges, we could have, for each range, a different corresponding spectrum as input to EAS simulation procedure.

4 Discussion

This preliminary part of the simulation of the atmospheric fluorescence from EAS describes the variation of the photoelectrons registered by the FD as a function of the height of the EAS core. A typical case of an UHECR is simulated, which corresponds to a shower 10 km apart from the FD (Fig. 2).

It would be interesting to explore the possibility in getting a more accurate simulation by incorporating the fluorescence spectrum presented here and the spectral dependence of the quantum efficiency of the PMT. We intend to continue this simulation work adopting a more precise description of the optical components used in the FD. We aim to derive the signal yield distribution of the PMT's of the FD for gamma and iron initiated showers as well as for more distant showers with non zero azimuth angles.

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