A Monte Carlo to Produce Fluorescence Photons

Henrique de Melo Jorge Barbosa, Vitor de Souza and Carola Dobrigkeit
Department of Cosmic Rays, State University at Campinas, Campinas, 13083-970, Brazil

Abstract

This paper will describe a new Monte Carlo program based on CORSIKA which generates fluorescence photons for each charged particle in a shower following the assumption of proportionality to the ionization energy deposit. These photons are tracked down to telescopes allowing us to study the reconstruction of the longitudinal profile and energy of the shower in a realistic way. An example of the agreement between the longitudinal profile of particles in the shower generated by CORSIKA and the longitudinal profile reconstructed using the fluorescence photons is shown. The importance of a detailed method to produce fluorescence photons in a one by one approach is also presented.

1. Introduction

The fluorescence technique has been successfully used to measure extensive air showers by the HiRes Telescopes [1] and more recently by the Auger Observatory [2]. Fluorescence detectors measure extensive air showers counting the photons as a function of depth in the atmosphere to reconstruct the longitudinal development and determine the energy of the primary particle.

The CORSIKA [3] program simulates the development of a shower through the atmosphere and the routines we have implemented in it generate the corresponding fluorescence photons for each one of the charged particles in the shower. This approach is specially important because it generates simultaneously fluorescence photons in a telescope and particles at the observational level.

Simulations of the fluorescence photons in extensive air showers have been done considering a unidimensional shower. The results extracted from the code presented here show the importance of having a full tridimensional simulation.

Besides that we have included in our simulation the possibility of having photons produced by electrons and positrons which fall below the simulation energy cut. These particles are supposed to produce a significant number of photons since the fluorescence yield of a particle is proportional to its ionization loss rate [4].

The influence of the particles below the energy cutoff in the total number

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of photons generated in a shower has been estimated in a indirect way by C. Song et al. [5] to be around 10% if a threshold of 100 keV for particles in the electromagnetic cascade is considered within CORSIKA. We will show this value can be verified using directly the fluorescence photons generated by the simulation we have developed.

2. The Simulation of Fluorescence Photons

We used CORSIKA as the basic framework for the generation of particles in the shower. The detailed simulation of the shower implemented in CORSIKA makes all the information needed to generate fluorescence photons for every charged particle in a shower available. Explicitly, the position of creation and death of the current particle and the energy deposit of this particle in the atmosphere are accessible.

For each charged particle produced inside CORSIKA, a new subroutine that generates the fluorescence light is called. With the initial and final positions $(\vec{x}_i, \vec{x}_f)$ and energies (E_i, E_f) of the particle the subroutine does a Monte Carlo simulation for the production and propagation of fluorescence photons.

However, when the energy of a particle falls below a certain value, it is neglected by CORSIKA and the information needed to create fluorescence photons is not available. For electrons and positrons below the energy cut, we made the hypothesis that they deposit all the available energy as soon as they are discarded by CORSIKA. We also assume that the track length traveled by these particles is given by the Bethe-Block theory [6] and the stopping range is calculated assuming the continuous-slowing-down-approximation.

Since the total path and the energy deposited by particles with energy above the energy cuts and by electrons and positrons with energy below the cutoff are now known, the number of photons produced by these particles per unit path length traveled can be calculated using the fluorescence yield given by Kakimoto et al. [4].

In simulations of high energy EAS one usually adopts a thinning method, in order to reduce the number of particles to be followed/stored. In this procedure a weight W is attributed to each particle. Instead of transferring the weight of the particle directly to the photons it produces, we avoid the necessity of applying an unthinning procedure by producing a number of photons proportional to the weight of the particle.

Finally, since fluorescence emission is isotropic, only a small fraction of these photons is emitted towards the detectors and this fraction depends only on the distance to the detector and on its geometry. Once the user had defined the position and radius of telescopes for which the simulation is done, the average number of photons emitted by a charged particle in the direction of the detectors can be calculated as:

$$\overline{\aleph} = \Delta x \cdot \; yield \; \cdot W \cdot \frac{d\Omega_{tot}}{4\pi} \tag{1}$$

where $d\Omega_{tot}$ is the solid angle subtended by all the detectors and $\Delta x = |\vec{x}_i - \vec{x}_f|$ is the distance traversed by the particle.

In general, we have that $\overline{\aleph} < 1$ because the solid angle subtended by the detectors is small compared to 4π and despite the great amount of photons emitted, the probability that any of them will be directed inside $d\Omega_{tot}$ is very small. According to the physical process involved, the final number of photons (N) emitted by the passage of one given particle can be described by a Poisson distribution with average $\overline{\aleph}$.

Knowing the number of photons to be emitted by the particle, its trajectory is divided in N equal intervals and one photon is emitted from the center of each interval. The emission point is set to the middle of the N_{th} interval and the direction of emission of the photon is drawn inside the solid angle of one of the telescopes. Therefore, we can calculate the point of intersection of the photon's trajectory with the sphere that defines the detector. If such intersection exists, it means that the photon is considered "detected".

3. Results

We have simulated ten showers initiated by protons with primary energy 10^{19} eV falling vertically 15 km away from one telescope of radius 1.1 m. The corresponding fluorescence photons were generated and propagated to the telescope following the procedure described above. The energy cutoff for the electromagnetic particles was set to 100 keV.

A standard reconstruction method [2] was adopted to reconstruct the longitudinal particle profile using the signal measured by the telescope. Figure 1 shows the comparison of the reconstructed profile as determined with the fluorescence photons and the longitudinal development of the particles counted by CORSIKA. The longitudinal profile given by CORSIKA does not take into account particles which have energy below the energy cutoff.

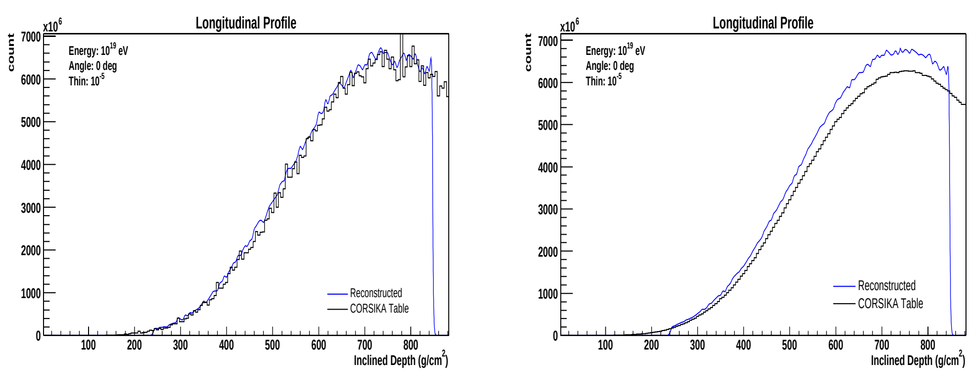

Fig. 1. Average longitudinal particles profiles: (a) Left: Particles above cut; (b) Right: Particles above cut and $e^{\pm}$ below cut.

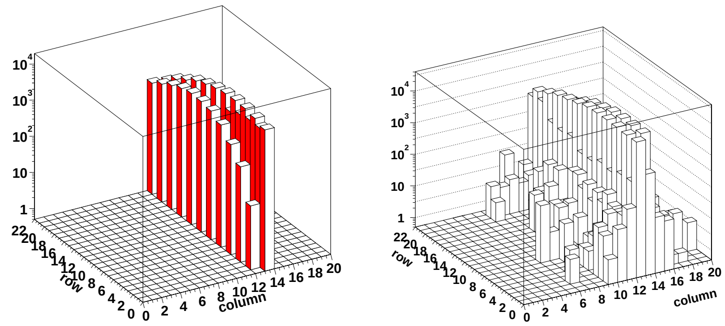

Fig. 2. Photons on a PMT camera. Figures show the difference between a unidimensional and a tridimensional approach.

Figure 1.a shows a reconstructed profile where we have not simulated the particles below the energy cutoff and the agreement with the longitudinal development given by CORSIKA is very good. On the other hand, figure 1.b shows a reconstructed profile where we have simulated the particles below the energy cutoff. In this case, the curves are different by less than 10% corresponding to the contribution of the particles below the energy cut.

Figure 2 shows the signal as seen by the telescope represented over a camera of photomultipliers similar to that of the Auger Observatory. It is noticeable the great number of pixels off the main track hit in the tridimensional simulation when comparing to the unidimensional approximation.

In the same way, we have integrated the reconstructed longitudinal particle profile using the photons detected by the telescope to estimate the primary energy. The energy reconstructed for the ten showers when $e^{\pm}$ below the energy cuts were included and corrections for the "missing energy" were applied was $(9.8 \pm 0.4)\ EeV$.

4. Conclusion

We have shown the procedure implemented to generate fluorescence photons in a tridimensional approach. The method was tested and some results for a specific configuration have been presented. The comparison of simulated and reconstructed longitudinal profiles and energies show the expected results.

Acknowledgments: The authors would like to thank FAPESP, CAPES and CNPq for the financial support. We are also grateful to D. Heck, J. Knapp and M. Risse.

5. References

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