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Atmospheric multiple scattering of fluorescence light from extensive air showers and effect of the aerosol size on the reconstruction of energy and depth of maximum

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ABSTRACT

The reconstruction of the energy and the depth of maximum X_{max} of an extensive air shower depends on the multiple scattering of fluorescence photons in the atmosphere. In this work, we explain how atmospheric aerosols, and especially their size, scatter the fluorescence photons during their propagation. Using a Monte Carlo simulation for the scattering of light, the dependence on the aerosol conditions of the multiple scattered light contribution to the recorded signal is fully parameterised. A clear dependence on the aerosol size is proposed for the first time. Finally, using this new parameterisation, the effect of atmospheric aerosols on the energy and on the X_{max} reconstructions is presented for a vertical extensive air shower observed by a ground-based detector at 30 km: for typical aerosol conditions, multiple scattering leads to a systematic over-estimation of $5 \pm 1.5\%$ for the energy and 4.0 ± 1.5 g/cm^2 for the X_{max}, where the uncertainties refer to a variation of the aerosol size.

1. Introduction

The detection of ultra-high energy cosmic rays using nitrogen fluorescence emission induced by extensive air showers is a well established technique [1], used previously by the Fly's Eye [2] and HiRes [3] experiments, currently by the Pierre Auger Observatory [4,5] and Telescope Array [6,7], and possibly soon by the JEM-EUSO telescope [8]. Charged particles generated during the development of extensive air showers excite atmospheric nitrogen molecules that emit fluorescence light isotropically in the 300–430 nm range. The energy and geometry of the extensive air shower can then be calculated from information on the amount and time of recorded light signals at the fluorescence detectors (FD). After more than thirty years of development having led to a better understanding of this technique, the current "hybrid" observatories set their energy scale using fluorescence measurements [9,10]. Also, the air-fluorescence technique allows the determination of the depth of maximum of the extensive air shower X_{max} in a direct way, providing an estimation of the UHECR composition [11,12]. For the greatest energies, fluorescence light from an air shower can be recorded at distances up to about 40 km, traversing a large amount of atmosphere before reaching the detector. The effects of the atmosphere on the propagation and attenuation of light must hence be considered carefully. From the production point to the detector, a fluorescence photon can be scattered and/or absorbed by molecules and/or aerosols in the atmosphere. In the case of hazy conditions or fog, the single light scattering approximation – when scattered light cannot be dispersed again to the detector and only direct light is recorded – is not valid anymore. Thus, the multiple light scattering – when photons are scattered several times before being detected – has to be taken into account in the total signal recorded. Whereas the first phenomenon reduces the amount of fluorescence photons arriving at the telescope, the latter increases the total signal recorded and the apparent angular width of the shower track (i.e. the point spread function of the detector). This atmospheric blur occurs especially for long distances to the extensive air shower and total optical depth values greater than unity. Ignoring this contribution to the total light recorded at the fluorescence telescopes would lead to a systematic over-estimation of shower energy and X_{max}. In the case of an isotropic point source – an air shower being usually modelled as a collection of point sources –, it was highlighted that aerosol scattering is the main contribution to atmospheric blur [13–16], resulting especially from aerosol scatter of light at near-forward angles [17,18]. Another radiation is also produced in extensive air showers: the Cherenkov light, emitted mostly at small angles relative to the shower axis. This anisotropic emission produces distributions of scattered light different than in the case

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of fluorescence light. Therefore the work presented in the following can not be applied to the multiple scattering of Cherenkov light.

Three main studies about multiple scattering effect on air shower reconstruction have been done during the last ten years: two of them based on Monte Carlo simulations [19,20], and the last one using only analytical calculations [21]. Contrary to analytical solutions, Monte Carlo simulations allow to follow each photon or photon packet emitted by an air shower and provide their number of scatterings during the propagation, and their arrival direction and time at the detector. All of these works predict the percentage of indirect light recorded at the detector within its time resolution (usually 100 ns) and within a circle of angular radius ζ, for every shower geometry and aerosol conditions. Moreover, these parameterisations are currently used in UHECR observatories to remove the multiple scattered fraction from total signal recorded by the fluorescence telescopes. The multiple scattering of light is affected by the optical thickness of the atmosphere, the aerosol size distribution and the aerosol vertical profile. Whereas the three previous works have studied the effect of the optical thickness, the multiple scattering is also very dependent on the aerosol size distribution, and especially on the corresponding asymmetry parameter of the aerosol scattering phase function [22]. This dependence was recently studied in detail in [23,24] for the case of an isotropic point source. The purpose of this paper is to quantify the dependence of the percentage of indirect light on the aerosol size, and its corresponding effect on the shower energy and $X_{\max}$ reconstructions. Section 2 is a brief introduction of some quantities concerning light scattering, before describing in detail the Monte Carlo simulation developed and adapted for this work. Section 3 gives a general overview of properties of scattered photons recorded at the detector for different atmospheric conditions. Then, in Section 4, we propose an improved parameterisation based on the previous work done in [19], but including this time an explicit dependence on the aerosol size. This result is finally applied to the reconstruction of extensive air showers in the case of a ground-based detector in Section 5: the effect on energy and $X_{\max}$ reconstructions is given for different aerosol conditions and distances to the air shower.

2. Modelling and simulation of scattering in the atmosphere

Throughout this paper, the scatterers in the atmosphere will be modelled as non-absorbing spherical particles of different sizes [25,26]. It is acceptable to approximate the scatterers as being non-absorbing, since absorption (mainly by ozone and dioxide nitrogen) is negligible compared to scattering in the atmosphere in the range of wavelengths 300–430 nm of fluorescent UV light. Scatterers in the atmosphere are usually divided into two main types – aerosols and molecules.

2.1. The density of scatterers in the atmosphere

The attenuation length (or mean free path) Λ associated with a given scatterer is related to its density and is the average distance that a photon travels before being scattered. For a given number of photons N traveling across an infinitesimal distance dl, the amount scattered is given by $\mathrm{d}N^{\mathrm{scat}} = N \times \mathrm{d}l/\Lambda$. Density and Λ are inversely related such that a higher value of Λ is equivalent to a lower density of scatterers in the atmosphere. Molecules and aerosols have different associated densities in the atmosphere and are described respectively by a total attenuation length Λ_{mol} and Λ_{aer}. The value of these total attenuation lengths in the atmosphere can be modelled as horizontally uniform and exponentially increasing with respect to height above ground level h_{agl}. The total attenuation length for each scatterer population is written as

$$\begin{cases} \Lambda_{\mathrm{mol}}(h_{\mathrm{agl}}) = \Lambda^0_{\mathrm{mol}} \exp\left[(h_{\mathrm{agl}} + h_{\mathrm{det}})\Big/H^0_{\mathrm{mol}}\right], \\ \Lambda_{\mathrm{aer}}(h_{\mathrm{agl}}) = \Lambda^0_{\mathrm{aer}} \exp\left[h_{\mathrm{agl}}\Big/H^0_{\mathrm{aer}}\right], \end{cases} \tag{1}$$

where $\left\{\Lambda^0_{\mathrm{aer}},\ \Lambda^0_{\mathrm{mol}}\right\}$ are multiplicative scale factors, $\left\{H^0_{\mathrm{aer}},\ H^0_{\mathrm{mol}}\right\}$ are scale heights associated with aerosols and molecules, respectively, and h_{det} is the altitude difference between ground level and sea level (fixed at 1400 m for the whole study). The *US standard atmospheric model* is used to fix typical values for molecular component: $\Lambda^0_{\mathrm{mol}} = 14.2$ km and $H^0_{\mathrm{mol}} = 8.0$ km [27]. These values are of course slightly variable with weather conditions [28] but the effect of molecule concentration on multiply scattered light is not that of interest in this work. Atmospheric aerosols are found in lower densities than molecules in the atmosphere and are mostly present only in the first few kilometres above ground level. The aerosol population is much more variable in time than the molecular as their presence is dependent on many more factors such as the wind, rain and pollution [29]. However, the model of the exponential distribution is usually used to describe aerosol populations [30]. Only the parameter Λ^0_{aer} will be varied and H^0_{aer} is fixed at 1.5 km for the entirety of this work.

2.2. The different scattering phase functions

A scattering phase function is used to describe the angular distribution of scattered photons. It is typically written as a normalised probability density function expressed in units of probability per unit of solid angle. When integrated over a given solid angle Ω, a scattering phase function gives the probability of a photon being scattered with a direction that is within this solid angle range. Since scattering is always uniform in azimuthal angle ϕ for both aerosols and molecules, the scattering phase function is always written simply as a function of polar scattering angle ψ.

Molecules are governed by Rayleigh scattering which can be derived analytically via the approximation that the electromagnetic field of incident light is constant across the small size of the particle [27]. The molecular phase function is written as

$$P_{\mathrm{mol}}(\psi) = \frac{3}{16\pi}(1 + \cos^2\psi), \tag{2}$$

where ψ is the polar scattering angle and P_{mol} the probability per unit solid angle. The function P_{mol} is symmetric about the point $\pi/2$ and so the probability of a photon scattering in forward or backward directions is always equal for molecules.

Atmospheric aerosols typically come in the form of small particles of dust or droplets found in suspension in the atmosphere. The angular dependence of scattering by these particles is less easily described as the electromagnetic field of incident light can no longer be approximated as constant over the volume of the particle. Mie scattering theory [31] offers a solution in the form of an infinite series for the scattering of non-absorbing spherical objects of any size. Since this infinite series is far too time consuming for the Monte Carlo simulations, a parameterisation named the Double Henyey–Greenstein (DHG) phase function [29,32] is usually used. It is a parameterisation valid for various particle types and different media [33–35]. It is written as

$$P_{\mathrm{aer}}(\psi|g,f) = \frac{1-g^2}{4\pi}\left[\frac{1}{(1+g^2-2g\cos\psi)^{\frac{3}{2}}} + f\left(\frac{3\cos^2\psi - 1}{2(1+g^2)^{\frac{3}{2}}}\right)\right] \tag{3}$$

where g is the asymmetry parameter given by $\cos\psi$ and f the backward scattering correction parameter. g and f vary in the intervals $[-1, 1]$ and $[0, 1]$, respectively. Most of the atmospheric conditions can be probed by varying the value of the asymmetry parameter g: aerosols ($0.2 \leqslant g \leqslant 0.7$), haze ($0.7 \leqslant g \leqslant 0.8$), mist ($0.8 \leqslant g \leqslant 0.85$), fog ($0.85 \leqslant g \leqslant 0.9$) or rain ($0.9 \leqslant g \leqslant 1.0$) [36]. The DHG function