Relevance of the fluorescence radiation in VHE gamma ray observations with the Cherenkov technique

D. Morcuende*, J. Rosado*, J.L. Contreras*, F. Arqueres

*High Energy Physics Group GAE and UPARCOS. Facultad de Ciencias Físicas. Universidad Complutense de Madrid. E-28040 Madrid, Spain.

Abstract

Atmospheric fluorescence is usually neglected in the reconstruction of the signals registered by Cherenkov telescopes, both IACTs and wide-angle detector arrays. In this paper we quantify the fluorescence contribution to the total light recorded in typical observational configurations. To this end we have implemented the production and tracking of fluorescence light in the CORSIKA code. Both the Cherenkov and fluorescence light distributions on ground (2200 m a.s.l.) have been simulated for γ-ray showers in a wide energy range (10^{-1} – 10^{7} TeV). The relative fluorescence contribution has been evaluated as a function of the shower energy and zenith angle. Our results indicate that at about 1000 m from the shower impact point more than a 5% of the IACT signals come from atmospheric fluorescence. The contamination at these core distances can be much larger for arrays of wide-angle detectors working in the PeV range.

Keywords: Monte Carlo simulations, Air-fluorescence, Cherenkov telescopes, IACT technique, gamma rays

1. Introduction

The charged particles of extensive air showers (EASs) generate light due to two physical processes; namely, the Cherenkov effect and the fluorescence emission. The detection of the atmospheric Cherenkov radiation is the basis of several observational techniques, the imaging atmospheric Cherenkov telescopes (IACTs) being the most powerful one for very high-energy (VHE) γ-ray astronomy. On the other hand, the observation of atmospheric fluorescence with optical telescopes has been used since many years to measure the longitudinal development of EASs in the ultra-high-energy (UHE) range (> 10^{15} eV).

The Cherenkov and fluorescence photons emitted from any point in an EAS are indistinguishable at the telescope level because they arrive simultaneously and within the same wavelength range of around 300 – 450 nm. However, the angular distributions of both components are quite different. The Cherenkov radiation is peaked at a small angle of ~ 1° around the shower axis, forming on ground the so-called Cherenkov light pool. On the contrary, the fluorescence emission is isotropic. As a consequence, the signal of a telescope pointing towards the shower axis is dominated by the Cherenkov component, while the signal of a telescope recording the shower conversely is dominated by the fluorescence one. Another difference between both processes is that fluorescence emission is less efficient than Cherenkov production. For instance, a 1 GeV electron in 1 m of atmosphere near ground generates about 30 Cherenkov photons but only about 4 fluorescence photons.

In the IACT technique, several telescopes with a field of view (FoV) of some degrees point at a given γ-ray source from different positions. Fast Cherenkov pulses are recorded to image the EASs stereoscopically (e.g., see [1]). We single out the Cherenkov Telescope Array (CTA), which is the next-generation IACT observatory currently entering into its construction phase and designed to cover the wide energy range from 20 GeV to 300 TeV [2,3]. The atmospheric Cherenkov light can also be registered by arrays of wide-angle Cherenkov detectors (WACD). Each unit usually consists of one or more photomultipliers that collect the light through a Winston cone and the fluorescence contribution to the signals recorded by both imaging and non-imaging γ-ray telescopes is assumed to be negligible.

Fluorescence telescopes are non-steerable devices with a wide FoV that register transversely the track of the shower in the atmosphere within a typical time window of microseconds. Although the signal is dominated by the fluorescence component, a non-negligible amount of Cherenkov light gets into the telescope and it has to be included as a relevant ingredient in the reconstruction algorithm [7]. The fluorescence technique is being successfully employed by the Pierre Auger Observatory [8] and the Telescope Array project [9]. Besides, the LHAASO project has designed flexible and mobile telescopes that can be operated in both Cherenkov and fluorescence modes [10].

A detailed Monte Carlo (MC) simulation of the development of EASs is a key tool in this field. Notably CORSIKA [11] has been extensively used since the late 90’s for this purpose. Cherenkov telescopes need detailed simulations of the
Cherenkov radiation generated by the shower. To this end, the Cherenkov production was implemented in CORSIKA for the simulation of the HEGRA AIROBICC detector [12] and later on upgraded by K. Bernlöh [13]. The simulation of the fluorescence telescope signals is customarily based on the generation of both Cherenkov and fluorescence photons from a one-dimensional shower profile obtained by either an analytical EAS model or a MC code like CORSIKA (see, e.g., [14]).

In a previous work [15], we made a preliminary implementation of the fluorescence emission in CORSIKA, following a procedure similar to that used by V. de Souza et al. [16]. We showed that the fluorescence contribution to the signals of Cherenkov telescopes might be non-negligible in some particular cases. In this paper we present an updated implementation of the fluorescence emission and systematic MC results to quantify this fluorescence contamination in ground-based Cherenkov telescopes in detail.

The paper is structured as follows. In section 2 the atmospheric fluorescence in EASs and the used parameterization are described. In section 3 we detail the implementation of the fluorescence emission in CORSIKA. The MC production and the tools used to extract the relevant information are described in section 4. In section 5 the results on fluorescence contamination in both IACTs and WACDs are shown for typical observational conditions. Also a cross-check of our MC predictions with a numerical algorithm is presented. In section 6, foreseen improvements of our fluorescence implementation in CORSIKA as well as other potential applications in γ-ray astronomy and cosmic rays physics are discussed. Finally, in section 7 we present the conclusions of this work.

2. Atmospheric fluorescence in extensive air showers

Atmospheric fluorescence [17] is produced by the de-excitation of molecules previously excited or ionized by charged particles of an EAS [17]. In the near UV, molecular nitrogen is mainly responsible for this light emission, which is dominated by the so-called Second Positive system (2P) of N2 (C1Πu \( \rightarrow \) B1Πg) and the First Negative system (1N) of N2 (B2Σu+ \( \rightarrow \) X2Σg−). Each one consists in a number of molecular bands according to the vibrational quantum numbers \( v' \), \( v \) of the upper and lower electronic states of the transition, respectively. A small contribution from the Gaydon-Herman system of N2 is also present [18]. Shower electrons and positrons are mostly responsible for this light emission, which is dominated by the collisional quenching (i.e., when \( P \rightarrow 0 \)). The parameter \( P' \) is defined as the pressure for which the probability of radiative de-excitation equals that of collisional quenching and depends on temperature \( T \) and humidity \( h \).

Alternatively, the fluorescence yield for any molecular band can be expressed relative to the absolute yield measured for a reference band in dry air at a given pressure \( P_0 \) and temperature \( T_0 \) as

\[
Y_\lambda(P, T, h) = Y_{337}(P_0, T_0) I_0(P_0, T_0) \frac{1 + P_0/P'_{337}(T_0)}{1 + P/P'_{337}(T, h)},
\]

where \( Y_{337} \) is the fluorescence yield in the absence of collisional quenching (i.e., when \( P \rightarrow 0 \)). The parameter \( P'_{337} \) is defined as the pressure for which the probability of radiative de-excitation equals that of collisional quenching and depends on temperature \( T \) and humidity \( h \).

3. Implementation of fluorescence in CORSIKA

Firstly, in subsection 3.1 the details of particle transportation relevant for fluorescence and Cherenkov emission as well as the main features of the Cherenkov implementation in CORSIKA are summarized. Later on, our implementation of the fluorescence production is described in subsection 3.2.

3.1. Particle transportation and Cherenkov radiation

CORSIKA handles the transport of all particles generated from the very first interaction of the incoming particle down to the observation level. They are tracked while their energy is above a certain threshold, which is set by the user for each
particle type. In addition, particles going upwards are discarded from being tracked\(^2\) when a particle is propagated between two interaction points, its spatial and time coordinates are updated. For charged particles, the ionization energy loss, the multiple scattering and the bending of the trajectory in the Earth’s magnetic field are also evaluated. Once the type of inelastic interaction or decay that the particle undergoes is determined, the outgoing particles are tracked, provided that they survive the above-mentioned energy and angular cuts.

The Cherenkov radiation production within a predefined wavelength interval is evaluated each time a charged particle fulfilling the Cherenkov condition undergoes a transportation step. The step is subdivided into smaller sub-steps of equal length and a bunch of photons, treated as a whole, is generated at the midpoint of each sub-step. The number of sub-steps of a given transportation step is chosen such that the number of photons in any bunch\(^3\) is always less than a certain bunch size set by the user. For each bunch, the number of photons and their emission angle relative to the particle direction are determined by the refractive index at the corresponding height and the velocity of the particle, which is calculated taking into account the continuous energy loss along its trajectory. The azimuthal emission angle of the bunch around the particle direction is taken at random. Finally the bunch is transported to ground level and its information (i.e., number of photons, spatial and time coordinates at observation level, arrival direction and height of emission) is written to a file as long as it reaches the detector area defined by the user. This procedure reduces significantly the computation and storage needs, while includes statistical fluctuations in the spatial distribution of bunches on ground.

Optionally, CORSIKA can assign a specific wavelength to each bunch to evaluate both the refraction and the absorption of the atmosphere as well as the photon detection efficiency of the telescopes. However, this option needs substantial computational resources and is not activated in the default settings of CORSIKA.

### 3.2. Air-fluorescence emission

The fluorescence emission was implemented in the CORSIKA v7.6300 code. We followed the same scheme of photon bunches used in the simulation of the Cherenkov light production described above. Every time a charged particle deposits energy in the atmosphere, bunches of fluorescence photons are generated. The amount of fluorescence light is evaluated within a wavelength interval set by the user. In the workflow of CORSIKA the energy deposition takes place under two different circumstances that are described next, together with the procedure to build-up the bunches.

In the first place, when a particle is transported between two interaction points, it deposits an amount of energy equal to the continuous ionization energy loss. Most of the charged particles of an EAS are electrons and positrons having transportation steps shorter than 20 m, for which the atmospheric characteristics can be assumed to be constant. In this case, the number of fluorescence photons in the whole step is randomly calculated from a Poisson distribution with mean equal to the photon yield calculated as described in section\(^2\) taking the atmospheric parameters at the step midpoint\(^4\). Then, photons are equally distributed in bunches, each one generated in a sub-step in the same way as for the Cherenkov light production. However the maximum fluorescence bunchsize is defined independently to allow for a different granularity of these two processes. Each bunch is emitted at a random direction, but restricted to downward angles to save computing time.

For transportation steps larger than 20 m (mostly taken by muons), we first split the total path into steps of 20 m or less and then apply the above treatment for every newly defined step. The energy deposit of the original step is distributed proportionally to the thicknesses of the new ones.

The other circumstance when energy is deposited is that a particle does not survive the angular or energy cuts. Note that, as opposed to the Cherenkov light production, this has to be considered for the fluorescence production, because this process has no sizable energy threshold and is isotropic. The energy deposit is assumed to occur at the point where CORSIKA stops tracking the particle, and it depends on the type of particle. Photons, electrons and other stable particles deposit their kinetic energy. For positrons, the annotated energy deposit includes additionally the energy corresponding to two electron masses released as annihilation photons, which are not tracked. For muons and other unstable particles, the energy deposit is the total particle energy minus the mean energy fraction carried by neutrinos, which are supposed to deposit no energy in the atmosphere.

Each time CORSIKA applies the angular or energy cuts to a particle, bunches of fluorescence photons are emitted at random directions from the point where the energy is deposited. The distribution of photons in bunches is done taking into account the fluorescence bunchsize, as explained before.

Some remaining small contributions due to a variety of hadronic interactions producing subthreshold secondary particles are not included yet, but they were checked to be less than 1% of the total energy deposited by electromagnetic showers and less than 3% for EASs induced by TeV protons.

In the same way as for the Cherenkov radiation, only bunches reaching the predefined detector area are stored. The information of both Cherenkov and fluorescence bunches are written to the same standard output file. We made use of the sign bit of the variable that stores the number of photons to differentiate between the two types of bunches.

The current implementation of the fluorescence emission has two main limitations. First, the wavelength-dependent atmospheric absorption and detector efficiency are not evaluated for

\(^2\)The transportation of upward-going particles may be activated in CORSIKA, but this option is not included in the default settings, as it is irrelevant for the determination of the Cherenkov light at ground level.

\(^3\)In general, this is a fractional number.

\(^4\)The standard atmospheric parameterization in CORSIKA only has information on the air density and the mass overburden as a function of height. Therefore, pressure and temperature were calculated under the assumption of an ideal gas under a gravitational acceleration of 9.81 m/s\(^2\). Humidity effects were neglected.
fluorescence bunches. Second, it is still not compatible with the IACT option of CORSIKA, which provides an advanced output for Cherenkov telescopes [13]. Both limitations will be addressed in the future.

4. Monte Carlo simulations

The implementation presented in the previous section has been applied to simulate the fluorescence light at conditions relevant for Cherenkov telescopes, with the aim of studying the importance of the fluorescence contamination. Next, we describe the used CORSIKA setup and input parameters as well as the tools that we developed to analyze the simulation data.

In this work we used the high- and low-energy hadronic interaction models of QGSJET–01C and GHEISHA 2002d, respectively. The CERENKOV option, needed for the simulation of Cherenkov radiation, was used in combination with the EGS4 package that allows the full Monte Carlo treatment of the electromagnetic component. The energy thresholds were set to 0.3 GeV for hadrons, 0.1 GeV for muons and 0.02 GeV for the electromagnetic component.

The detector was defined as a 5 \times 5 \text{ km}^2 square. As a representative case, we set the observation altitude at 2200 m a.s.l., which is the one of the Roque de los Muchachos Observatory, island of La Palma. The geomagnetic field corresponding to this location was introduced. The US Standard atmospheric profile was selected. According to CORSIKA coordinate system, the x axis points to the magnetic North and the y axis towards the West direction.

The maximum bunchsize for Cherenkov and fluorescence light emission was set to 10 and 5, respectively. In this way we compensated the more efficient production of Cherenkov photons with respect to that of fluorescence and the isotropic emission of the latter. The wavelength range of the simulated photons was 300 – 450 nm for both light components.

The MC production carried out for this work consists in γ-ray showers within a large energy range (100 GeV to 1 PeV) with zenith angles θ between 0° and 60°. To get a good statistics of the photon density distributions on ground, the number of events was scaled with the shower energy (e.g., 1000 showers of 10 TeV and 100 showers of 100 TeV for each θ value). Simulated showers were forced to impact at the center of the detector area so that arrival coordinates of bunches are given relative to the shower core at observation level. Inclined showers were assumed to go always from North to South, as depicted in figure 1.

Dedicated Python-based scripts were developed to read the output files containing the bunch information and calculate the spatial distributions of Cherenkov and fluorescence photons on ground. For this purpose, the detector area of 5 \times 5 \text{ km}^2 was discretized into a dense grid and the number of photons in each grid element was counted, i.e., summing over all the bunches impinging on it. Cuts on the arrival angle of the bunches were implemented in such a way that the pointing direction and FoV of a Cherenkov telescope can be simulated (see figure 1). No cut in the arrival time of bunches was applied for this work, although it can be easily implemented for further studies of the time profile of the recorded signals.

5. Results

In subsection 5.1, the spatial distribution of both Cherenkov and fluorescence light components on ground are compared with the assistance of some illustrative examples. Afterwards, we present the results of a systematic study on the fluorescence contamination in Cherenkov telescopes as a function of the primary γ-ray energy (subsection 5.2) and zenith angle (subsection 5.3). For the IACT technique, the impact of the observation offset angle is analyzed in subsection 5.4. Finally, in subsection 5.5 our implementation of the fluorescence emission is cross-checked against the predictions from a numerical algorithm.

5.1. General features of the light distribution on ground

As an illustrative case, the spatial distribution of both Cherenkov and fluorescence photon densities averaged over 1000 vertical 10 TeV γ-ray showers is shown in figure 2. For this example, no angular cuts have been applied. Both distributions have azimuthal symmetry around the shower core position, as the effect from the geomagnetic field is very small. Thus, we averaged the Cherenkov and fluorescence photon densities over azimuth angle to obtain the corresponding radial profiles (figure 3). Cherenkov light concentrates on the pool region, which extends up to a radial distance of \sim 120 m in this case, while the photon density sharply drops outside this region. On the other hand, the fluorescence photon density decreases much less steeply with increasing core distance due to the isotropic nature of the fluorescence emission. In fact, the fluorescence photon density becomes even greater than the Cherenkov one at very large core distance.

In a general case of inclined showers, the photon density distributions on ground do not have azimuthal symmetry. For simplicity, we calculated the photon density profiles only along the x axis. Therefore, we restricted the detection area to a strip of

\footnotetext[5]{The extension of the Cherenkov light pool on ground depends on the shower inclination, but it is almost independent of the primary γ-ray energy.}
10 m width along this axis and defined bins of $10 \times 10 \text{ m}^2$ within this strip (see figure 1). Examples of these photon density profiles for 100 TeV showers with $\theta = 20^\circ$ averaged over 100 MC events are shown in the upper panels of figures 2 and 4. Two distinct observational techniques are contemplated. Figure 4 illustrates the case of WACDs pointing to the zenith, like those of [4, 5, 6]. Here, the dashed lines represent the light profiles without any angular cut, while the solid lines correspond to the profiles obtained by imposing the realistic condition that photons arrive with a zenith angle lower than 60° (i.e., within a FoV of 0.85 sr around the vertical direction). As a consequence of the directional emission of Cherenkov photons, almost all of them fulfill this condition as long as the detector is not too far away from the shower impact point. The fraction of fluorescence photons collected by the detector is around 70% for positive $x$ values. On the other hand, this fraction is significantly lower along the negative $x$ axis, because the lower portion of the shower is outside the FoV when observing from that side, as illustrated in figure 1. For a typical detector area of the order of 0.1 m$^2$, the trigger level is around $10^3$ photons per square meter [6]. This translates into a maximum acceptable $x$ value of a few hundreds of meters for this shower energy, although core distances up to 1000 m can be of interest in the PeV energy range.

The scenario shown in figure 5 is that of IACTs with a FoV of 10° (solid lines) or 20° (dashed lines) assuming on-axis observation (see subsection 5.4 for a discussion about off-axis effects). Narrower FoVs, e.g., 5°, are only used in the low-energy range ($< 1$ TeV) and with small impact parameters for which the fluorescence contamination is negligible. The photon density was calculated for a horizontal surface element regardless of the inclination of the telescope. Core distances greater than 1000 m were not considered in the IACT case either, because the light intensity collected by a telescope positioned at such
a distance would be extremely low and it would only image the uppermost portion of the shower. Notice that, although the lateral distributions exhibit a strong mirror symmetry, the light density decreases slightly more steeply along the negative $x$ axis, since light travels a longer distance to reach ground.

The narrow FoV of an IACT severely limits the fraction of both Cherenkov and fluorescence photons detected at a given core distance. The narrower the FoV, the smaller the portion of the shower development within it. On the other hand, since the missed portion of the shower is the lowest one (see figure 1), only photons with large emission angle relative to the shower axis are lost. Therefore, the reduction in fraction of detected photons is more important for the fluorescence component due to its isotropic nature.

In this work, we define the fluorescence contamination $R_{FC}$ as the ratio of the fluorescence over Cherenkov light densities. This quantity is represented as a function of $x$ for the corresponding studied cases in the lower panels of figures 4 and 5. The parameter $R_{FC}$ is very small ($< 1\%$) inside the Cherenkov light pool, while it grows roughly exponentially outside this region. At a core distance of around 1000 m, it will be very significant, i.e., $\sim 5\%$ for an IACT and even larger than 10\% for a WACD. A detailed quantification of $R_{FC}$ as a function of the observation conditions is given in the next subsections.

As mentioned above, no cut in the arrival photon times has been applied in this work. Nevertheless, we made some tests to check that the effect of using a finite time window has a negligible effect on the calculated $R_{FC}$ values, since both light components have similar time distributions. For example, for 100 TeV showers with $\theta = 20^\circ$ and a telescope FoV of $10^\circ$, imposing a time window of 100 ns reduces $R_{FC}$ from 6\% to 5\% at $x = 1000$ m.

5.2. Energy dependence

The total number of charged particles in an EAS as well as the energy deposited by them scale approximately with the energy of the primary particle. Therefore, the total amount of Cherenkov and fluorescence light scales with energy too. However, the spatial distributions of both light components on ground also depend on the longitudinal development of the shower. The higher the shower energy, the deeper into the atmosphere it develops and the more steeply these light distributions decrease with core distance. This effect is stronger in the fluorescence component than in the Cherenkov one, since the latter is concentrated within the pool. As a consequence, the fluorescence contamination should in principle increase with increasing energy. On the other hand, a finite FoV has an opposite effect because it reduces the fluorescence contamination, as explained before. This reduction is more important as the energy increases, because the deeper into the atmosphere the shower develops, the larger the fraction of the shower development outside the telescope FoV.

The dependence of the fluorescence contamination on the primary $\gamma$-ray energy for wide-angle detectors (60\° FoV in the vertical direction) is shown in figure 6 for showers with $\theta = 20^\circ$ and at the characteristic core distances of 500, 750 and 1000 m. $R_{FC}$ is found to grow approximately as $E^0.22$ for positive $x$ values (solid lines), reaching up to $R_{FC} \approx 1$ at 1000 m for 1 PeV showers. The contamination is less significant and weaker dependent on energy for negative $x$ values (dashed lines), because the impact of the FoV is more important in this region, as shown in figure 4 and compensates the above-mentioned effect of the deeper shower development.

Figure 7 shows the results for IACTs with a FoV of 10\°, observing 20\° inclined showers on axis. For this FoV, $R_{FC}$ becomes non-negligible ($> 1\%$) at a distance larger than 500 m and is found to be nearly independent of energy at all core distances (the asymmetry between positive and negative $x$ values is very small). Although we report results for a wide range of shower energies, it should be stressed that, outside the Cherenkov light pool, the photon density for showers with energy lower than 1 TeV is comparable to typical night sky back-
ground values, thus the fluorescence contamination is only relevant for higher-energy showers when observed from large core distance.

5.3. Dependence on shower zenith angle

The angular dependence of the fluorescence contamination for 100 TeV γ-ray showers is shown in figures 8 and 9 for the two techniques studied in this work. The behavior shown in these figures can be understood in terms of two effects of the shower inclination on the spatial light distributions. In the first place, the size of the Cherenkov light pool on ground is nearly proportional to sec² θ along the x axis and to sec θ along the y axis, that is, in the coordinate system x’ ≡ x cos² θ, y’ ≡ y cos θ, it is delimited by a circle of radius r’ ≈ 120 m at 2200 m a.s.l. Therefore, R_FC will be modulated by the modified coordinates (x’, y’) rather than by (x, y). In the second place, an inclined shower develops higher in the atmosphere because, for a given atmospheric thickness transversed, the corresponding vertical depth is smaller by a factor cos θ. As a consequence of both effects, R_FC generally decreases with θ for a given x value.

For WACDs and positive x values, this decrease in R_FC is partly compensated by the fact that the detector observes the shower development at lower altitudes and with larger angle as θ increases. The opposite happens for negative x values, resulting in a steeper decrease of the fluorescence contamination with θ.

In the IACT case, the asymmetry between positive and negative x values is very small and the narrow FoV compensates the effects due to variations in the shower development, as explained in the previous subsection. In fact, for a fixed modified radial distance r’, R_FC is found to be nearly independent of both the shower energy and θ. For example, for an IACT with a FoV of 10° pointing to a certain γ-ray source, R_FC will be around 3% for any incoming shower that impacts at r’ = 750 m. Note however that, for a very large zenith angle of 60°, this would involve a core distance of 3000 m along the x axis or 1500 m along the y axis, which is unreachable for the IACT technique. As a simple recipe, a good estimation of R_FC at an arbitrary position (x, y), γ-ray energy and zenith angle θ can be obtained from the result given in figure 5 for 20° inclined showers at an equivalent core distance

\[ x_{eq} \equiv r' \sec^2 20° = 1.13 \sqrt{(x \cos^2 \theta)^2 + (y \cos \theta)^2}. \] (3)

5.4. Fluorescence contamination in off-axis observations

Quite often IACTs do not point exactly in the direction of the γ-ray source, but observe the incoming showers with an off-axis angle φ of up to a few degrees. This is the case of sky surveys (e.g., [21]), observation of extended sources, etc. We show here that the fluorescence contamination may be larger for off-axis observations.

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6 This can be justified assuming that the Cherenkov light beam can be approximated by an inclined cone with the vertex at a fixed height regardless of the angle of inclination.

7 Note that for θ > 30° and positive x values, the detector would operate in fluorescence mode, as it would observe the shower transversely.
As a representative case, the lateral light profiles for the sample of 100 TeV showers with $\theta = 20^\circ$ and FoV of $10^\circ$ (figure 5) have been recalculated for several off-axis angles $\phi$. The results on the fluorescence contamination are presented in figure 10. For simplicity, we assumed that both the shower axis and the main optic axis of the telescope are on the XZ plane ($\phi$ is the angle between them). Positive $\phi$ values indicate the case in which the two axes intersect at a point above ground level, i.e., a convergent observation. This is equivalent to augmenting the telescope FoV in an on-axis observation, because it increases the observed fraction of the shower development. Therefore, the $R_{FC}$ value increases with $\phi$. On the other hand, the negative $\phi$ values in the figure represent a divergent observation. For large core distances of interest for this work, this situation would correspond to a telescope that only catch the uppermost portion of the shower, collecting an amount of Cherenkov light insufficient to record a useful image.

In the general case that the telescope axis is outside the XZ plane, the fluorescence contamination for small $\phi$ angles is expected to be moderately larger with respect to the on-axis observation. It should be noted, however, that IACTs with a FoV larger than $10^\circ$ (e.g., LHAASO-WFCTA [10]), may have a very relevant fluorescence contamination in case they can observe with $\phi > 5^\circ$.

5.5. Cross-check with a numerical algorithm

Our implementation of the fluorescence production in CORSIKA has been tested against a numerical algorithm [22, 15] developed for that purpose. This algorithm does not include statistical fluctuations in the photon production and assumes a one-dimension shower development.

The cross-check between the simulation results and these numerical calculations has been carried out with vertical $\gamma$-ray showers of 100 TeV and assuming a FoV of $10^\circ$ around the vertical direction. Simulation results were averaged over 100 showers. The longitudinal profile of energy deposit used in the numerical algorithm was the averaged one from the same MC sample.

The comparison of radial distributions of fluorescence photons evaluated by both procedures is shown in figure 11. As can be seen, the numerical calculations (dotted line) overestimate the fluorescence photon density at very small core distance, while underestimate it at very large $r$ values. These discrepancies can be attributed to the linear-shower approximation applied in our algorithm. To prove this, such approximation was replicated in CORSIKA by modifying the output so that the arrival bunch positions on ground were calculated as if they were generated at the shower axis. The results are represented by solid lines in the plot, showing an excellent agreement with those of the numerical algorithm.

6. Future work

We aim to include the implementation of fluorescence emission in the official version of CORSIKA software. To that end, there are still some upgrades to be done as explained at the end of section 3. This tool is operative for both electromagnetic and hadronic showers. Thus, it would allow $\gamma$-ray and cosmic-ray communities to simulate both the Cherenkov and fluorescence light contributions to the recorded signals taking into account all the particularities of their instruments (e.g., the detection efficiency, the ray-tracing in the telescope, the time evolution of signals and the setting trigger conditions). Also it will be possible to account for the atmospheric conditions. This may be specially interesting when both light components are comparable.

The numerical algorithm used to validate our implementation of fluorescence in CORSIKA can also evaluate the Cherenkov light production from EASs. All the details of this complementary tool, previously outlined in [22, 15], will be published.
soon. It provides quick but reasonable predictions on the detected light intensity at arbitrary conditions and shower energies, even including some effects that may be costly to simulate. In particular, we used it to estimate the fluorescence contamination when including the wavelength-dependent atmospheric absorption and the detection efficiency of a typical Čerenkov telescope. We found that the $R_{\text{FC}}$ values given in section 5 may be reduced by a factor of $\sim 0.8$ after correcting for these effects.

In a previous work [23], we used the above numerical algorithm to give, for the first time, preliminary results on the capability of a large array of IACTs, like those of the CTA Observatory, to detect EASs using the fluorescence technique. This operation mode would benefit from stereoscopic observations with a potentially large effective area, and it could be used simultaneously to regular observations with the Čerenkov technique. A single IACT with a typical FoV of $10^\circ$ can track about 5 km of the longitudinal development of a shower when observed transversely from a distance greater than 30 km. This might allow the detection of UHE cosmic rays as long as signals can be recorded within a time window of tens of microseconds. For smaller shower-to-telescope distances (hence, smaller shower energies), the fraction of shower development observed would be insufficient for a full reconstruction. Nevertheless, this technique could still be used if several telescopes track different parts of the shower development, with the advantage that, in contrast to the fluorescence telescopes, their higher angular resolution may provide additional information on the shower lateral development. We are upgrading our numerical algorithm to include realistic trigger conditions of telescopes taking into account the lateral shower development, among other things. This work will be published in a paper in preparation.

7. Conclusions

We have implemented the atmospheric fluorescence emission in the CORSIKA code in a similar way to the Čerenkov light production. Updated air fluorescence data and models were used for this purpose. With the assistance of this tool we have quantified the fluorescence contribution to the signals recorded by ground-based air-Čerenkov telescopes, which is so far ignored in the reconstruction of EASs.

As a consequence of the very different angular distributions of these two light components, the Čerenkov one dominates within the light pool. In addition, the fluorescence contribution is strongly suppressed in telescopes with a narrow FoV, like IACTs. However, the fluorescence contamination is $\sim 1\%$ at a core distance of 500 m and significant ($>5\%$) at 1000 m. Thus ignoring this effect would have an impact on a VHE γ-ray observation carried out by arrays of IACTs that collect measurable signals at large core distances (e.g., CTA). It has been found that the fluorescence contamination in IACTs is nearly independent of the shower energy and weakly dependent on the zenith angle for a fixed distance relative to the Čerenkov light pool. As a consequence, for very inclined showers ($\theta > 50^\circ$), this is negligible at a core distance smaller than 1000 m. We also found that off-axis observations lead to an increase in the fluorescence contamination.

According to our simulations, arrays of WACDs are strongly affected by the fluorescence contamination, in particular, for the highest energy showers. In the PeV region, the signals of counters located 1000 m from the shower core can contain up to 45% of fluorescence (i.e., $R_{\text{FC}} = 0.8$).

As a future work, we plan to include our implementation of fluorescence emission in the official version of the CORSIKA code, making it available for the detailed simulation of IACTs and arrays of WACDs working at conditions where fluorescence contamination is expected to be non-negligible. In addition, this tool will allow us to pursue a detailed study on the feasibility of using an array of IACTs in fluorescence mode.

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