Extensive Air Shower Light Composition

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Abstract

Presented in this paper are simple studies of the amount of extensive air shower (EAS) light received by the fluorescence detector (FD) and contributions of various processes to the total flux of light. We follow EAS evolution from the FD point of view and try to determine when the EAS light collected by the FD is dominated by fluorescence photons.

1 Introduction

Extensive air shower particles, while passing through the atmosphere, produce light that can be observed by a telescope on the ground. The yield of fluorescence photons is approximately constant per unit length of a charged particle track, so that the amount of fluorescence light emitted is directly proportional to the number of particles in the shower. However, the charged particles in a shower emit also Čerenkov photons. These photons are beamed predominantly in the forward direction, and in most cases contribute very little to the light received by the detector. However, the Čerenkov photons get scattered in the air, and some of these scattered photons arrive to the detector. In simulations one usually distinguishes four groups of photons of different origin which arrive to the detector: 1) fluorescence of the atmosphere; 2) direct Čerenkov radiation; 3) Rayleigh scattering of Čerenkov light and 4) Mie scattering of Čerenkov light. It's obvious that, for a given shower, the amount of photons of each kind depends on the direction of observation and the observed EAS development stage. We expect that the fluorescence flux can be sometimes overwhelmed by
the other components. It is of interest to find out when this is the case, and when the fluorescence component dominates in collected flux of light. The question is important since it is the number of fluorescence photons that lets us estimate the shower size and energy. The Čerenkov photons are the background which has to be subtracted from the signal, and the lower it is, the better the measurement.

Using the simulation code Hybrid_fadc released in 1997 by Bruce Dawson, we analyse the amount of EAS light received by a detector and contributions of various processes to the total light flux. Following the shower evolution from the FD point of view we try to answer the following question: when is the EAS light collected by the FD dominated by fluorescence photons?

This work is an extension of that presented in paper [1], in which we analyzed the influence of EAS lateral spread on FD triggering.

2 Geometry and Dominance of Fluorescence

The contributions of various light components change with a shower development stage as well as with the shower geometry. To settle the attention we restrict our considerations to shower-detector plane (SDP) perpendicular to the ground. We also fix the azimuth of SDP $\phi = 0^\circ$. The shower geometry and main parameters are shown in Figure 1. $\psi$ is what we call the shower inclination angle, $\chi$ is the angle of observation (viewing angle), and $x$ is the distance from the eye of fluorescence detector to the shower core landing point, or shortly the core distance. Listed below are the technical parameters used by Hybrid_fadc that are meaningful and useful for our purposes.

- PMT (pixel) effective diameter: 1.5°
- PMT elevation range: $(4^\circ, 30^\circ)$ (in our SDP it is equivalent to the observation range)
- investigated range of $\psi$: $(30^\circ, 150^\circ)$
- FD atmospheric depth: $860 g/cm^2$
- minimum track length for trigger: 5°
- shower size is calculated using Gaisser-Hillas shower development function [2]
- all the fluctuations are switched off (variations in signal, depth of first interaction, sky noise)
Since the simulation code provides the photoelectron signals from all the components, it is easy to follow their changes due to changing direction of observation and tell when the fluorescence component dominates. If we do so for different shower parameters such as $x$, $\psi$, $E$ (initial energy) and $\tau_0$ (slant depth of first interaction), we should be able to determine the ranges of the parameters for which the fluorescence dominates.

Let’s start with three typical, highly energetic showers. Their evolutions are shown in Figure 2(a)-(c). The plots differ only by the shower inclination angle $\psi$. As was said, we follow the changes of the four components of photomultiplier signal (in photoelectrons) for different directions of observation angle $\chi$. The sum of all the components is shown by the solid line and an arbitrarily selected light threshold: 50% of the total signal (dashed line). All the signal values are shown on the right-hand Y scale while the left-hand Y scale shows the number of shower particles. The number of shower particles is represented by crosses. For the three showers the fluorescence component is much larger than direct and scattered Čerenkov components within all the range of observation. We note that the viewing angle for maximum shower size (i.e. maximum number of particles in the shower) and viewing angle for maximum fluorescence photon flux do not necessarily coincide. This is because the fluorescence photon flux depends not only on the number of shower particles at given
Figure 2: Three examples of shower evolution as recorded by the detector, as a function of the viewing angle $\chi$. We compare the number of particles in the shower (left Y axis) with the total FD photoelectron signal and with signal components of different origins (fluorescence, direct or scattered Čerenkov). All the signal values are shown on the right Y axes. Also shown is a curve of 50% of the total sum of light coming from a given direction.
viewing angle, but also on the atmospheric attenuation, distance from the shower to the detector or the length of the shower track from which the signal is collected.

Now let's turn to more complicated examples in Figure 3(a)-(c). All symbols and axes are the same as in Fig. 2 but now we study the most inclined ($\psi \geq 130^\circ$) and nearby ($x = 5km$) showers. One can easily observe that the fluorescence component can be of comparable importance to what we call the background (the sum of other components). In Fig. 3, the slight change of $\psi$ (plots a, b, c) causes a dramatic change in direct Čerenkov component. Plot 3(a) (the less inclined shower) is the only one where Čerenkov photons don’t influence the total light curve much. The larger the inclination, the greater the importance of the Čerenkov component. This means that for these showers the direct Čerenkov "beam" is visible at the detector eye position. We define an arbitrary light threshold which would help us to determine if the fluorescence is dominating. Namely, if the fluorescence component is more than 50% of the total signal, we regard it as dominating. Then, for a given shower we can find the angular interval within which the fluorescence is dominating, which will be called the fluorescence interval. Now, looking at Figure 3(a)-(c) we can get this interval for 3 showers. For $\psi = 130^\circ$ it is greater than 20° (for angle $\chi$ between 8° and 30°) while for $\psi = 135^\circ$ it is a bit less than 15° (between $\chi = 13^\circ$ and $\chi = 26^\circ$) and for $\psi = 140^\circ$ the fluorescence component never reaches the 50% threshold. For comparison, in showers shown in Figure 2(a)-(c) the fluorescence interval is equal to the whole observational range, which is quite a comfortable situation.

Scattered or direct Čerenkov light can cause that the light curve maximum doesn't coincide with fluorescence curve maximum. In some cases the direction of maximum light can lay outside quite a large fluorescence interval. This effect is especially apparent in Figure 3(a) ($\psi = 130^\circ$). Although for this shower we have relatively large fluorescence interval, the maximum light comes to the FD from the direction away from the the maximum fluorescence direction by about 10°. Moreover, the maximum light direction is not well defined for that shower, and the problem becomes even worse if we consider the FD triggering capabilities.

The following circumstances make the procedure of reconstructing the shower maximum relatively effective:

- The light collected by PMTs is dominated by fluorescence photons for wide range of the observational directions (large fluorescence interval). The importance of the correction due to
Figure 3: Evolution of inclined (large $\psi$) and nearby ($x = 5\,\text{km}$) showers. Compare to Fig. 2
the background is relatively small in this case.

- The direction which the maximum COLLECTED signal comes from lays within the fluorescence interval. 'Collected' means that we talk about a direction laying within the FD observation range. As we shall see later, the maximum collected light flux can be dominated by background photons (direct or scattered Čerenkov).

Since the number of fluorescence photons emitted from a given direction is known to be proportional to the number of shower particles found in this direction, the latter condition allows for finding the shower maximum.

The question is: when do the above circumstances take place? Figures 2 and 3 give the answer for some showers only. In the next section we present much more extensive studies using the terms introduced above.

3 Results

An extensive set of showers was studied. For each shower a range of viewing angles $\chi$ was determined corresponding to the fluorescence interval (i.e. the angular range in which fluorescence photons dominate in the received signal). Found are also the viewing angles corresponding to the shower maximum and to the direction from which maximum total signal arrives. These viewing angles were studied as functions of following shower parameters: initial energy $E$, slant depth of first interaction $\tau_0$ and geometric parameters $\phi$ and $x$. The results are shown in Figures 4, 5, 6 and 7 respectively. The markers used are the same for all the plots:

- crosses: the lower and upper limits of the fluorescence interval (only one cross at $\chi = 0$ means that the fluorescence component never reaches the 50% threshold for this shower);

- black triangles: the direction for the shower maximum;

- open triangles: the direction for maximal signal reaching the FD;

- continuous lines: the begin and end of the range of pixels which get triggered by the shower (these must be between 4° and 30°).
Figure 4 shows a dependence of the above mentioned $\chi$ angles on shower energy and shower inclination angles $\psi$, with fixed core distance $x = 5 km$ and depth $\tau_0 = 70 g/cm^2$. Each plot in this Figure shows the energy dependence for different $\psi$, ranging from 30° in plot (a) to 150° in plot (e). We see that only for the most inclined showers ($\psi = 30^\circ$ or $\psi = 150^\circ$) the fluorescence interval doesn’t overlap the triggering interval. This means that none of the triggered pixels was triggered by the light dominated by fluorescence photons from these showers. The pixel triggering intervals for showers at the other inclinations $\psi$ are all covered by the fluorescence interval (all pixels triggered by light dominated by fluorescence photons). In these cases almost all directions of both shower maximum and maximum light received are inside the triggering range. We also note that the shower maximum depth decreases with increasing energy and that the directions of shower maximum and maximum light can differ from each other even by several degrees (see plot $\psi = 120^\circ$).

Fixed in Figure 5 are: core distance $x = 5 km$ and energy $E = 10^{20} eV$. Showers in each plot have a fixed inclination $\psi$ while depth of first interaction $\tau_0$ varies from 0 to 350 $g/cm^2$. Again, in the most inclined showers the fluorescence interval and triggered pixel path do not overlap, which means that less than 50% of the light received by the triggered pixels are fluorescence photons. In addition, showers starting deeper in the atmosphere can reach the ground level before reaching their maximum development (see plots $\psi = 60^\circ, 90^\circ$ and 120° at $\tau_0 > 200 g/cm^2$).

The next Figure 6 shows the dependences on inclination angle $\psi$. Here, $\tau_0 = 70 g/cm^2$ and $E = 10^{20} eV$ are fixed and each plot in Fig. 6 presents showers with the same $x$ (5, 10, 15 and 20 km). We see that the most favorable core distance is $x = 20 km$ (plot 6d) – for all the inclinations almost all the pixels are triggered mostly by fluorescence photons and all the maxima lay within (or very near) the triggering pixel path. Looking at closer showers (plots 6a, 6b, 6c) one can see that some inclination angles become less reliable for the purpose of the precise shower reconstruction.

For a given $x$ one can ask about the range of $\psi$, where the fluorescence interval covers large enough part of the triggering path and where viewing directions of maximum lay within this common part.

From Fig. 6 one can learn that such a range of satisfactory inclinations becomes narrower with decreasing $x$ and for $x = 5 km$ it is only between $60^\circ$ and $130^\circ$. One can see significant discrepancies between direction of shower maximum and that of maximum light around $\psi = 130^\circ$ in $x = 5 km$ plot. These have been already discussed with the help of Fig. 3.
The next Figure 7, similarly to the previous one, deals with geometry only. Now we fix $\tau_0 = 70g/cm^2$ and $E = 10^{20}eV$ and vary $x$, for different inclinations $\psi$ shown in each plot. Here one can see more precisely how the core landing distance $x$ can influence the domination of fluorescence.

On every plot of Fig. 7 the borders of the fluorescence interval are not smooth at certain point. Now let us explain this feature. It can be easily understood by analyzing Figure 8. Shown in plot 8a is the shower evolution for $\tau_0 = 70g/cm^2$, $E = 10^{20}eV$, $\psi = 90^\circ$ and $x = 2km$. The shower begins observed at the direction $\chi$ of over $80^\circ$ and the fluorescence for this direction is less than 50% of the total signal. The evolution of a twice more distant ($x = 4km$) shower is shown in Fig. 8b. Now the initial direction $\chi$ is less than $80^\circ$ and the fluorescence dominates from the very beginning.

Now we can look once more at Fig. 7. The discussed unsmoothness is due to the fact that for some distant showers the fluorescence photons are dominating just from the first (the largest) observation angle $\chi$. The smaller core landing distance $x$, the smaller the angle between the shower direction and the first direction of observation. Starting from certain value of this angle, direct Čerenkov photons start to dominate, and the beginning of the interval of dominating fluorescence is no longer equivalent to the shower initial observation angle, but start to follow its own function, producing the sharp peak we discuss.

Figure 9 summarizes the above studies by answering two questions for different showers:

1. Does the light COLLECTED (from the direction of maximum light flux) by the FD consist mainly of fluorescence photons? "Mainly" means the level of 50% in Fig. 9a, 80% in Fig. 9b and 90% in Fig. 9c.

2. Is the overlap of the fluorescence interval and the triggering pixel range at least $5^\circ$ long (compare Figures 4, 5, 6 and 7)?

The filled circles in Figure 9 mean the negative answer for question 1, i.e. in such a case the fluorescence photons constitute the collected maximum flux of light in less than a chosen threshold. This threshold is 50% in Fig. 9a (upper row), 80% in Fig. 9b (center row) and 90% in Fig. 9c (lower row). The open circles mean the positive answer for question 1, i.e. the maximum collected flux of light is dominated by fluorescence photons (they constitute at least 50% (Fig. 9a), 80% (Fig. 9b) or 90% (Fig. 9c), of the total signal). The squares mean the negative answer for question 2, i.e. the overlap of the fluorescence interval and the triggering pixel range is shorter than $5^\circ$. No symbol is
Figure 4: Fluorescence interval, triggering interval, viewing angle of shower maximum and viewing angle of maximum light, as functions of energy, for different inclinations $\psi$. The core distance is fixed at $x = 5km$ and depth of first interaction is set to $\tau_0 = 70g/cm^2$. Viewing angles $\chi$ are shown for shower maximum (black triangles) and for maximum light received (open triangles). The crosses mark the angular interval, where the ratio of fluorescence photons to the total number of observed photons exceeds 0.5, and the continuous lines are for begin and end of the triggering pixels range. See text for further explanation.
Figure 5: Viewing angles as functions of depth of first interaction $\tau_0$, for different inclinations $\psi$, with fixed core distance and energy. For more details see the text and caption to Figure 4.
$\tau_0=70 \text{ g/cm}^2$, $E=10^{20}$ eV

Figure 6: Viewing angles as functions of inclinations $\psi$, for different core distances $x$, with fixed depth of first interaction $\tau_0$ and energy $E$. See text and caption to Figure 4 for more details.
Figure 7: Viewing angles as functions of core distance $x$, for different inclinations $\psi$, with fixed depth of first interaction $\tau_0$ and energy $E$. See text and caption to Figure 4 for more details.
Figure 8: Percentages of Čerenkov and fluorescence components (left Y axes) for two showers differing only in core landing distance $x$ (compare Figure 7). For further comments see the text.

drawn if a given shower does not trigger the detector. The slant depth of first interaction is fixed at $\tau_0 = 70\,\text{g/cm}^2$. An example: for a shower in Fig. 9a, with $\psi = 30^\circ$, $x = 5\,\text{km}$ and $E = 10^{21}\,\text{eV}$, the maximum signal reaching PMT array is not dominated by fluorescence photons – they constitute less than 50% of the total signal. For this shower the part of the pixel track triggered mostly by fluorescence photons is shorter than $5^\circ$.

4 Summary

The light arriving to the Fluorescence Detector from an air shower always contains an admixture of Čerenkov photons. For precise determination of shower energy, it is important to know what fraction of the total signal received is due to fluorescence photons. The purpose of this paper was to find out when fluorescence photons constitute a required percentage of the signal received by the detector.

For a rather mild requirement of at least 50% of the signal contributed by fluorescence, this condition is not met only in very inclined, nearby showers. With a requirement of higher dominance
Figure 9: Summary of conditions for dominance of fluorescence in light received from a shower. The dominance threshold is set to (a) 50% in top row, (b) 80% in center row and (c) 90% in bottom row. Open circles mark dominance of fluorescence in the received signal (at the specified threshold), black dots mark the opposite. Squares indicate when the overlap of fluorescence dominance interval with triggered pixels path is shorter than 5°. Lack of any symbol means that the shower doesn’t trigger the detector.
of fluorescence in the received signal, like 80% or 90%, much fewer showers meet this requirement.

The results are compiled in Figure 9.

The studies presented in this paper were based on the Hybrid_fadc simulation software, which uses the old reference design of the detector. In the real detector, the triggering conditions may differ somewhat from what was assumed in the simulations. Thus the results presented should be treated as guidelines only, but nevertheless they will be very useful in data analysis.

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References
