Contribution of Multiple Scattering of Cherenkov Photons to Shower Optical Image

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Abstract

Charged particles in an extensive air shower generate a large number of Cherenkov photons. Depending on geometry of the shower, a fraction of these photons is emitted directly towards the detector or gets to it after being scattered in the atmosphere. Thus the Cherenkov photons constitute a background for fluorescence signal from the shower. So far, only direct and singly-scattered Cherenkov photons have been taken into account in analyses of the shower optical image. In this paper, a Monte Carlo method of evaluating the contribution of multiply-scattered Cherenkov light to the optical image of the shower is presented. Preliminary results of these simulations are shown.

1. Introduction

Charged particles of an extensive air shower produce a large number of Cherenkov photons on their way through the atmosphere. Most of these photons are emitted at small angles to the parent particle's direction, and so they fly together with the shower. As the shower develops, they accumulate into a beam of light. This light must be regarded as a background for fluorescence signal from the shower, because the number of photons in this beam relates to history of shower development, not to current number of particles in the shower.

Optical image of the shower consists mainly of fluorescence and singly-scattered Cherenkov photons [2]. Direct Cherenkov light makes a significant contribution to the signal in the fluorescence detector only when the shower lands close to the detector site (small impact parameter). Scattered light may be relatively strong in all geometrical configurations, especially in the late stages of shower development. The Cherenkov photons in the shower may scatter at different angles. A small part of them flies directly to the detector and, with attenuation proper to their path, is measured together with the fluorescence light. Other scattered photons, traveling in the atmosphere, after some time may scatter again, possibly in the direction towards the detector. Thus the Cherenkov photons may reach the detector after a longer series of scatterings. This light is expected to be distributed over an area of the sky larger than the image of the shower alone,

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and to be also delayed with respect to photons arriving without scattering.

Until now multiple scattering of Cherenkov light has not been routinely taken into account in shower analyses. The objective of our simulations is to find out how much light can reach the detector due to this effect.

2. Method of simulation

In this analysis, multiple scattering of Cherenkov photons was simulated using the "Hybrid_fadc" program [1]. In the program, calculations are done in steps corresponding to a change of 0.04° in shower position on the sky, as seen from the detector. In each step the program calculates the shower size (Gaisser-Hillas parameterization) and the number of emitted Cherenkov photons. Based on these, fluorescence and Cherenkov light (both direct and singly-scattered) are calculated. The shower is assumed to have no lateral distribution. Calculations are done in 16 wavelength bins covering the range from 276 to 420 nm.

In calculations concerning multiple scattering of Cherenkov photons produced in a given step, it is of course impossible to trace all photons separately, so that some simplifications are inevitable. The total number of photons is divided into smaller "packets" (typically 10 thousand packets in each step). All following calculations are done for each packet separately. A packet starts from the shower axis at the point corresponding to a current shower development step, at an angle drawn from a simple exponential angular distribution. Assuming that all photons in a packet scatter at one point, the point of first scattering is randomly chosen. This is done using scattering probabilities formulas taken from "Hybrid_fadc". From the two calculated points, for Rayleigh and Mie scattering respectively, the closer one is chosen as the place where the scattering takes place. Based on the angular distribution of scattering (Rayleigh or Mie respectively), a portion of the packet scattered directly towards the detector is determined. Knowing the geometry of the event and including attenuation factor for the path toward the eye, the signal at the detector due to this portion of the packet is calculated. With the information about the whole path in the atmosphere, the time of arrival is found. In order to trace the rest of the photons in a packet, it is assumed that they continue their flight together. For this smaller packet, a direction is randomly chosen and all calculations, just as for the first scattering, can be repeated several times. These calculations give as output information about each packet: size of the signal, arrival direction on the sky and time of arrival to the detector.

3. Preliminary results

As an example, we present some of the results that can be obtained from one program run. The simulation was done for a vertical shower of energy 10^{20} eV, landing 8 km from eye. To obtain the shower image, we use the program

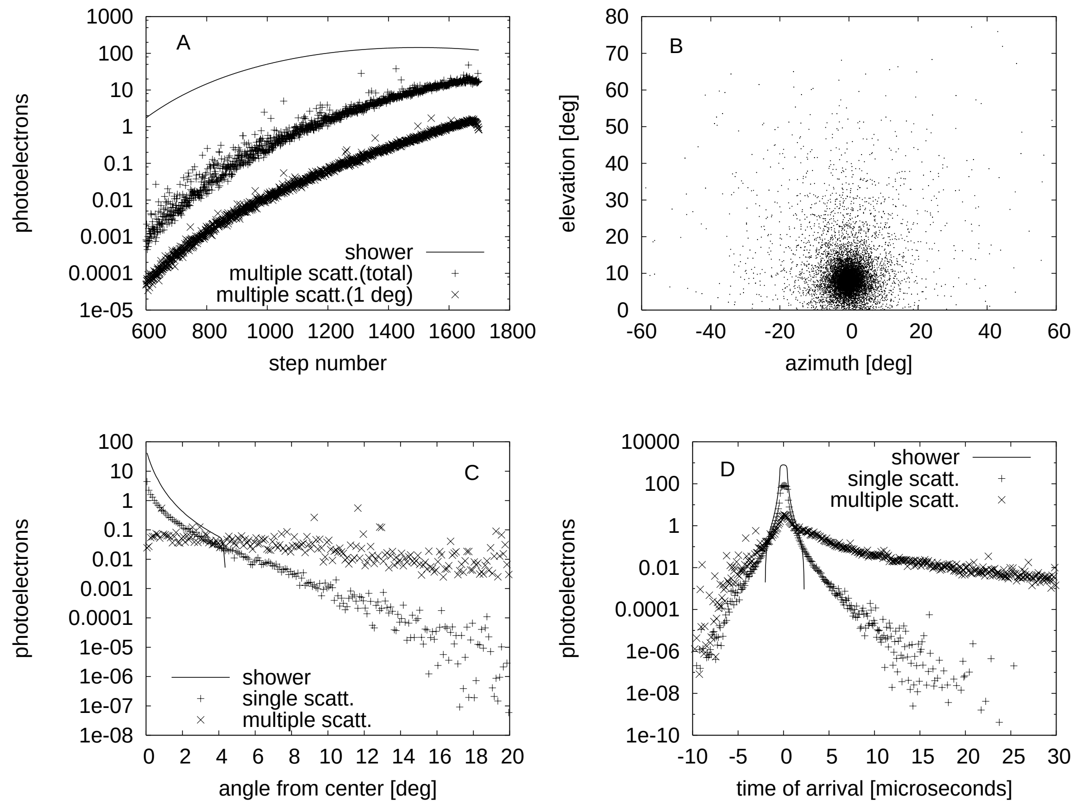

Fig. 1. A (top-left): signal due to direct photons from the shower and from multiple scattering (from whole sky and 1°-radius circle separately); B (top-right): angular distribution of light arriving at the detector in shower maximum program step; C (bottom-left): radial distribution of light in the same step; D (bottom-right): arrival time of signal from shower and scattered Cherenkov light (single and multiple); see text for details.

described in Ref. [2].

Our objective is to determine how big is the additional contribution to the measured signal due to multiply-scattered Cherenkov light. In Fig. 1A marked are values calculated for each program step: total shower signal, including direct and singly-scattered Cherenkov (original "Hybrid_fadc" values) and multiply-scattered Cherenkov light - separately integrated over the whole sky and in a circle of 1° radius centered on the shower position at each step. The total signal from multiple scattering contributes to the shower signal even ten or more percent, but when we look only at the 1° circle (an area comparable to shower image and detector pixel size), the contribution is about 1%.

The angular distribution of light from multiple scattering arriving simultaneously with the direct light from the shower at its maximum is shown in Fig. 1B. This light comes from a very large area of the sky, compared to the shower image size (1°-radius circle contains about 90% of the signal). Fig. 1C shows the radial distribution of light on the sky arriving during a single step (maximum of the shower). The light from the shower (original "Hybrid_fadc" program values) and scattered Cherenkov (our new calculations, single and multiple scattering separately) has been integrated in rings 0.1° wide. Multiply-scattered photons have a very broad distribution: the shown range of angles (up to 20° from the center of the image) contains only about 2/3 of this light. Also singly-scattered photons can be seen further from the shower image, but most of them are contained within the shower image. We note that the total signal from singly-scattered Cherenkov light calculated with our new procedure is in a very good agreement with corresponding results from the original "Hybrid_fadc" program. As both results are evaluated by means of two much differing methods, it means that single scattering is well understood.

The broad angular distribution means also that a fixed pixel will record the light even before and after the passage of the shower through the field of view of that pixel. Figure 1D shows the time distribution of the signal integrated over a 1°-radius circle around the position of shower maximum on the sky, in 100 ns bins. The light from multiple scattering is spread over time period much longer than the main shower signal or Cherenkov light from single scattering.

4. Conclusion

Multiple scattering of Cherenkov photons makes a sizeable contribution to a signal received by the detector. As our calculations show on the presented example, it contributes quite large amount of light which is distributed over a wide area of the sky. Thus, the contribution to intensity of the shower image will be rather small ($\sim$ 1%). Multiply-scattered photons arrive over a much longer time than the direct photons.

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1. B. Dawson, private communication
2. D. Gora, et al., Astropart. Phys. 16 (2001) 129-136