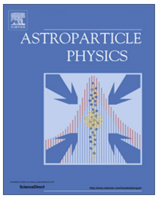
Astroparticle Physics 60 (2015) 47–53

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart



Asymmetry of the angular distribution of Cherenkov photons of extensive air showers induced by the geomagnetic field

P. Homola [a,b,c,*], R. Engel [d], H. Wilczyński [a]

[a] H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Poland
[b] University of Siegen, Germany
[c] University of Wuppertal, Germany
[d] Institut für Kernphysik, Karlsruhe Institute of Technology (KIT), Germany

ARTICLE INFO

Article history:
Received 8 April 2013
Received in revised form 15 May 2014
Accepted 18 May 2014
Available online 2 June 2014

Keywords:
Extensive air showers
Cherenkov light
Geomagnetic field

ABSTRACT

The angular distribution of Cherenkov light in an air shower is closely linked to that of the shower electrons and positrons. As charged particles in extensive air showers are deflected by the magnetic field of the Earth, a deformation of the angular distribution of the Cherenkov light, that would be approximately symmetric about the shower axis if no magnetic field were present, is expected. In this work we study the variation of the Cherenkov light distribution as a function of the azimuth angle in the plane perpendicular to shower axis. It is found that the asymmetry induced by the geomagnetic field is most significant for early stages of shower evolution and for showers arriving almost perpendicular to the vector of the local geomagnetic field. Furthermore, it is shown that ignoring the azimuthal asymmetry of Cherenkov light might lead to a significant under- or overestimation of the Cherenkov light signal especially at sites where the local geomagnetic field is strong. Based on CORSIKA simulations, the azimuthal distribution of Cherenkov light is parametrized in dependence on the magnetic field component perpendicular to the shower axis and the local air density. This parametrization provides an efficient approximation for estimating the asymmetry of the Cherenkov light distribution for shower simulation and reconstruction in cosmic ray and gamma-ray experiments in which the Cherenkov signal of showers with energies above 10^{14} eV is observed.

1. Introduction

Many imaging and non-imaging techniques of observing air showers are based on the detection of the abundant number of photons produced as Cherenkov radiation of the secondary electrons and positrons in these showers (see, for example, [1–5]). Cherenkov light also constitutes an important contribution [6] to the optical signal recorded by fluorescence telescopes built for the observation of air showers above 10^{17} eV [7–10].

With a typical Cherenkov angle of the order of 1° in air, the angular distribution of Cherenkov light around the shower axis reflects the angular distribution of the charged particles, mainly electrons and positrons. A proper estimation of the angular distribution of the Cherenkov light produced at various stages of the shower evolution is important for the reconstruction of the shower observables and, hence, the parameters of the primary particle.

Already Hillas noticed in his pioneering work on Cherenkov light production in electromagnetic showers that the energy and angular distributions of electrons exhibit universality features [11,12]. He derived compact analytic approximations based on the simulation of showers initiated by photons of 100 GeV. Hadronic showers are subject to much larger fluctuations, limiting the applicability of universality-based approximations to much higher shower energies. Only at energies above $\sim 10^{17}$ eV, the energy, angular, and lateral distributions of electromagnetic particles in hadronic showers can be efficiently described by universal functions of shower age and lateral distance in Molière units, e.g. [13–18].

Based on such approximations several parametrizations of the angular distribution of Cherenkov light have been derived, see [11,7,15,19]. In these studies, the angular distribution of Cherenkov photons is considered as approximately symmetric about the shower axis and the influence of the local magnetic field has been

---

* Corresponding author at: H. Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, Poland. Tel.: +48 12 662 8348; fax: +48 12 662 8012.

E-mail address: Piotr.Homola@ifj.edu.pl (P. Homola).

http://dx.doi.org/10.1016/j.astropartphys.2014.05.008
0927-6505/

neglected. The effects of the geomagnetic field have been studied so far only for primary photons with energies not larger than 100 GeV [20–22] and a compact parametrization was derived in Ref. [20].

The purpose of this work is the quantification of the expected asymmetry of the Cherenkov light distribution of air showers for a wide range of primary energies, extending up to the highest cosmic ray energies. Using CORSIKA [23] simulations a parametrization of the angular asymmetry induced by the geomagnetic field is derived for air showers from TeV energies up to the highest energies. Considering different local magnetic field strengths and shower geometries it is discussed under what conditions this asymmetry needs to be taken into account.

Furthermore we show how the asymmetry of the azimuthal distribution of Cherenkov photons varies for different shower parameters and geomagnetic conditions. We replace the commonly used angular distribution of Cherenkov photons, assumed to depend only on the viewing angle to the shower axis, $F(\theta)$, with a more accurate function $F(\theta, \phi)$ that also depends on the azimuth angle in the plane perpendicular to the shower axis. The definition of the angles is shown in Figs. 1 and 2.

Throughout this paper we will use the term *viewing angle* for the angle θ between the trajectory of a Cherenkov photon and the shower axis (see Fig. 1). The azimuth angle ϕ used in this study is the angle between the projection of a Cherenkov photon trajectory onto the plane perpendicular to the shower axis, see Fig. 2, and the projection of the geomagnetic field vector onto this plane, which will be referred to as $B_\perp$.

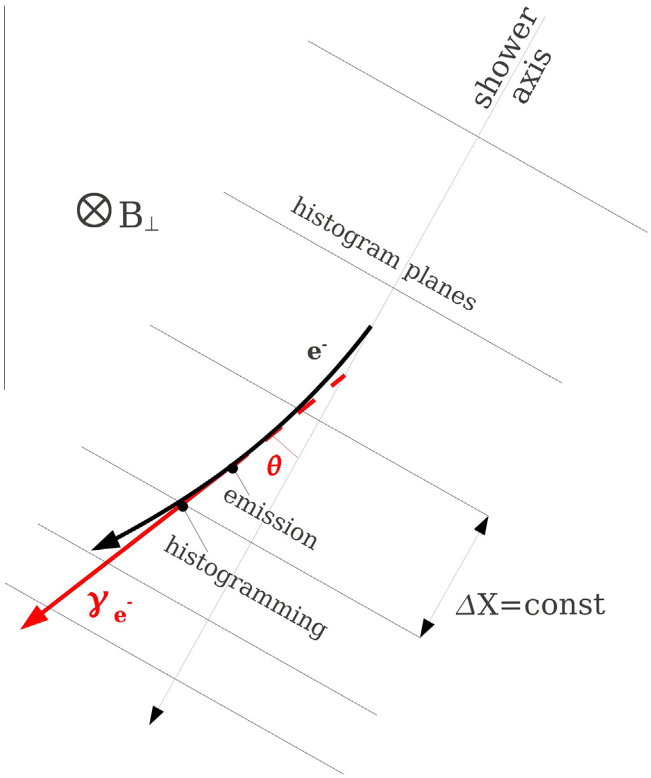


Fig. 1. Definition of geometric quantities of relevance to this study. An observer viewing the shower under the angle θ with respect to the shower axis will see the Cherenkov photons as drawn. The viewing angle θ is the angle between the trajectory of a Cherenkov photon and the shower axis, and $B_\perp$ denotes the component of the geomagnetic field vector perpendicular to the shower axis. To derive a parametrization the angle of the Cherenkov photons emitted by shower electrons is histogrammed at planes perpendicular to the shower axis. Since we are only interested in the angular distribution of the Cherenkov photons, the lateral distance of the place of their production relative to the shower axis is not considered.

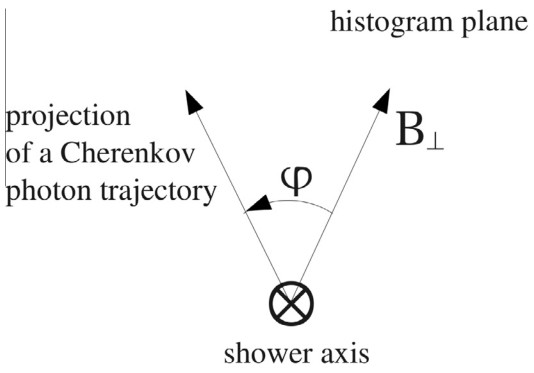


Fig. 2. The view of the plane in which the Cherenkov photons are histogrammed. The azimuth angle ϕ used within this document is the angle between $B_\perp$ and the projection of a Cherenkov photon trajectory onto the plane perpendicular to the shower axis. The angle ϕ is measured counter-clockwise starting from $B_\perp$.

The Monte Carlo simulations presented throughout this paper were carried out with CORSIKA 6.970 [23]. The high energy interactions were processed with the QGSJET 01 model [24] and particles in low energy ($E < 80$ GeV) were treated with GHEISHA [25]. All the simulations were performed using the US Standard Atmosphere density profile [26]. To optimize the computing time we used the thinning algorithm [27] available in CORSIKA. This algorithm keeps only a fraction of the secondary particles in a shower below an adjustable threshold energy, the so-called thinning level. Only one of the particles of each interaction below this energy threshold is followed and an appropriate weight is given to it, while the other particles are dropped. Although the thinning algorithm introduces additional, artificial fluctuations, it is necessary to apply it to keep the computing times manageable. For the purpose of this study we used the thinning level of 10^{-6}.

The Monte Carlo results produced with CORSIKA were processed with COAST 3.01 with the *rootrack* option [28]. COAST (COrsika dAta accesS Tools) is a library of C++ routines providing simple and standardized access to CORSIKA data. The option *rootrack* enables histogramming shower particles within user-defined planes perpendicular to the shower axis. For the purpose of this study a few dedicated modifications were introduced into both the CORSIKA and COAST codes to enable histogramming of Cherenkov photons. All the shower simulations used for deriving the parametrization were made with 40 observational levels (planes perpendicular to the shower axis) spaced by a constant atmospheric depth interval $\Delta X = 25$ g/cm^2 (see Fig. 1). The width of the binning in θ is 2°, while the bin width of the azimuth ϕ is 10°.

With use of the above tools we have developed an efficient parametrization that can be used at an arbitrarily selected experimental site if the local geomagnetic field vector is known. As an example, the location of the Tunka experiment [3] (51° 48′N, 103° 04′E) is considered in the following. In this experiment a surface array of non-imaging photon detectors is used to record the Cherenkov light emitted by extensive air showers of energies between 10^{14} eV and 10^{18} eV. With the geomagnetic field being exceptionally strong at the Tunka site ($B = 0.6$ G), it is well-suited to verify the results of this study experimentally. Even though the angular distribution of the photons cannot be measured directly with the Tunka detectors, it can be derived straightforwardly from the measured lateral distribution of the Cherenkov light at ground.

2. Cherenkov radiation in extensive air showers

Cherenkov radiation in air showers is emitted by charged secondaries traveling with velocity larger than the speed of light