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A study on the lateral distribution of Cherenkov light in extensive air showers

Davoud Purmohammad · Safoora Tanbakooei
Physics group, Faculty of Science, Imam Khomeini International University, Qazvin, P.O.Box 34149 - 16818, Iran

Abstract. The dependence of the lateral distribution of Cherenkov light in simulated extensive air showers to the energy and the mass of the primary cosmic rays has been studied. It has been shown that a previous claim about mass independent proportionality of shower energy to the total Cherenkov photon number is not valid in energies below $E_{EAS} \sim 10^{14}$ eV. We have found that the core distance of the so called hump in the lateral distribution of Cherenkov light in gamma ray initiated showers is independent from shower energy. The hump disappears in showers with $E_{EAS} \gtrsim 10^{14}$ eV. Finally, a simple model for the lateral Cherenkov light lateral distribution has been proposed, which can be fitted to all types of cosmic ray showers. The fit parameters seem to be promising for primary cosmic ray mass discrimination.

Keywords: Cosmic Rays, Extensive Air Shower, Cherenkov Radiation

1 Introduction

When high energy cosmic rays and gamma rays enter the atmosphere, they interact with the nuclei of the molecules in the air. Hadronic interactions produce high energy mesons, which almost instantly decay into muons or photons. High energy secondary gamma rays produce e^-e^+ pairs. The products of the first interactions are still at high energy so that they can participate in next interactions. In this way, a huge number of interactions can occur in successive generation of secondary particles. The swarm of high energy secondaries originated from the same primary particle is called extensive air shower (EAS). An EAS traverses the whole atmosphere and covers an area of a few tens to a few thousands meters wide at the surface of the Earth. Electrons, photons, and muons are the main particles in an EAS, while hadrons such as nucleons and mesons have much lower abundances. The Hadronic population is usually concentrated in the shower core, which is the intersection of the shower front and the shower axis. The latter is almost the extension of the primary particle path. Observation of EASs relays on the detection of the shower particles by coincidence particle detectors, or detection of electromagnetic radiation from the particles. Secondary leptons can produce air fluorescent radiation as they excite nitrogen atoms in the air. They can also generate Cherenkov radiation when they move faster than the local speed of light in the medium. While the air fluorescent radiation is emitted isotropically, the Cherenkov radiation is directed in a narrow cone around the shower axis. The structure of an EAS is affected by its constituent random interactions, specially the first few ones [1]. As a result of these random events, the observable properties of EASs have considerable fluctuations. For this reason, most of our knowledge about EASs is based on Monte Carlo simulations. Several simulation codes have been emerged since the beginning of the EAS studies. A modern EAS simulation code takes care of almost all interactions and decay modes of particles. They can provide detailed information about secondary particles and radiations, including

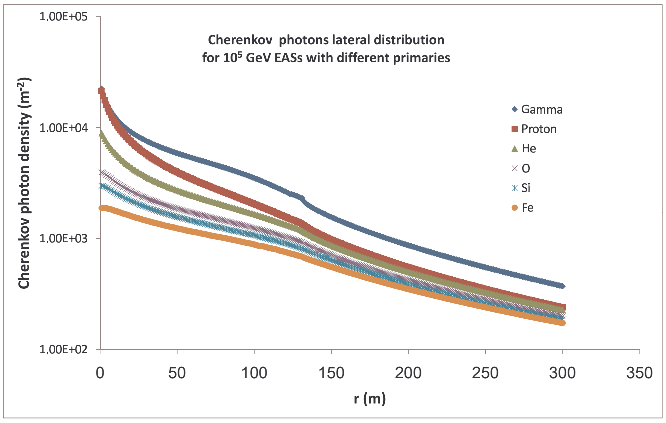

Figure 1: Lateral distribution of Cherenkov light for EASs with energy 10^{14}eV.

Cherenkov photons generated in a shower. In the present work, we have studied the lateral distribution of Cherenkov light in different EASs using CORSIKA simulation code [2]. A parameterization for the lateral distribution function (LDF) of Cherenkov light at ground level has been obtained. A discussion about possible use for the LDF in cosmic rays mass composition studies is also presented.

2 Simulations and results

We have used CORSIKA v.6.9 [2] for simulation of EASs. The user can direct the code to produce EASs from defined primary particles, and generate detailed information for secondary particles which reach the user-defined observation level. With Cherenkov option enabled, the code can produce and follow Cherenkov photons generated by charged particles. The number of photons and the arrival times of bunches of Cherenkov lights to the user-defined detectors are registered in the corresponding output file. In the present work, we have simulated EASs for 10^{12} to 10^{16} eV gamma rays, protons, and nuclei of He, O, Si, and Fe, with vertical incidence as primary cosmic rays using QGSJET [3] and GHEISHA [4] codes for the simulation of hadronic processes and EGS4 code [5] for the simulation of the electromagnetic component and Cherenkov radiation in the EASs. For each primary type-energy selection, 100 showers have been generated. In order to obtain maximum information, we defined the array of detectors so that they covered a whole 600m$\times$600m area around the shower core with 1m$\times$1m detectors. All Cherenkov photons of wavelength 300nm to 550 nm were taken into account. The loss of Cherenkov photons due to absorption in the atmosphere, and CORSIKA's default quantum efficiency for detector PMTs were taken into account by activating the corresponding options in the simulation code. The observation level was defined at 1200 m above sea level, the same elevation as Sharif University EAS array [6].

From Cherenkov outputs of simulations, the average densities of Cherenkov photons in

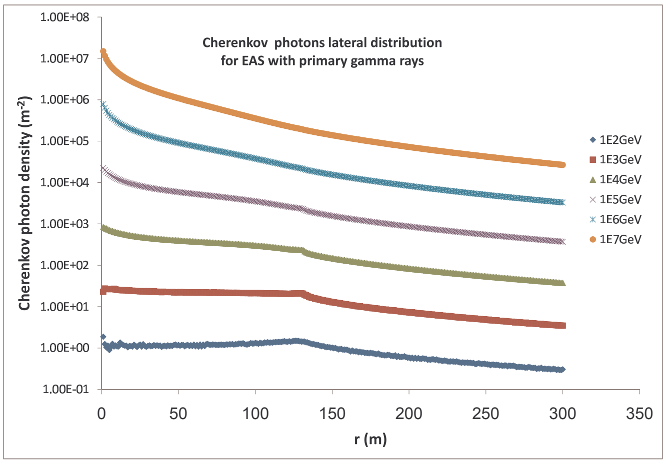

Figure 2: Lateral distribution of Cherenkov light for EASs initiated by gamma rays with different energies. Note that the place of the hump around 130 meters from the shower core is unchanged for different energies, though it almost disappears in high energy EASs.

rings of one meter width around the shower core were calculated for each shower. The densities were obtained for regions within 300 meters from the core of each shower. The average and standard deviation in densities among samples of 100 showers of the same type-energy were then calculated. To avoid making confusion in our dense data points, the standard deviations are not shown in the presented results, except in figure 5, where the sample standard deviations are plotted as error bars. As an example, the lateral distributions of Cherenkov photons for 10^{14} eV EASs are presented in figure 1. It is worth noting that the hump in the Cherenkov photon density for gamma ray initiated showers, at around 130 m from the shower core, previously reported by Rastegarzadeh & Najmi [7], as well as Arqueros et al. [8], and Portocarrero & Arqueros [9], is observable in our results. Figure 2 presents the Cherenkov light lateral distributions for gamma ray initiated showers with different energies. These results show that the place of the hump is independent from the energy of the EAS, and the hump disappears in high energy showers. The existence and position of the hump is widely discussed in references [8, 9]. A possible change in the distance of the hump from the shower core at different observation levels has been addressed in reference [10]. Figure 3 presents the lateral distributions for EASs generated by protons of different energies. Note that almost no hump is observable in Cherenkov light lateral distribution of the proton initiated showers. As one can deduce from presented results, the lateral distribution of Cherenkov light is apparently dependent on the energy as well as the mass of the primary cosmic ray which generates the EAS. It has been claimed that the total number of Cherenkov photons in an EAS is linearly proportional to the energy of the shower and is independent from the mass of the primary particle [11]. Although it seems to contradict our results in figure 1, we have calculated the total number of Cherenkov photons for all showers, and presented the results in figure 4. These results show that the mass independent proportionality of energy and total number of Cherenkov photons is acceptable for EAS energies above 10^{14}eV. If we can estimate the energy of an EAS from

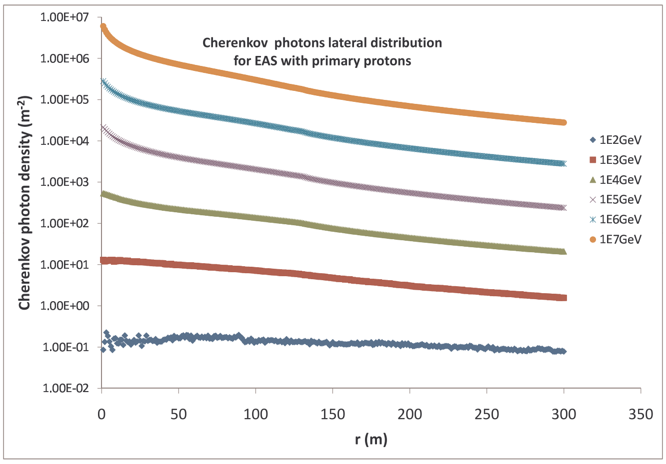

Figure 3: Lateral distribution of Cherenkov light for EASs initiated by protons of different energies.

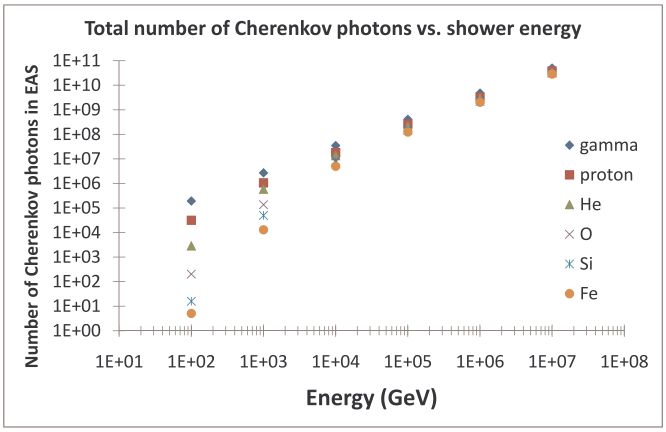

Figure 4: Total number of air Cherenkov photons vs. energy of EAS for different primary cosmic rays. Note that at high energies, the total number of photons is independent from the primary particle mass.

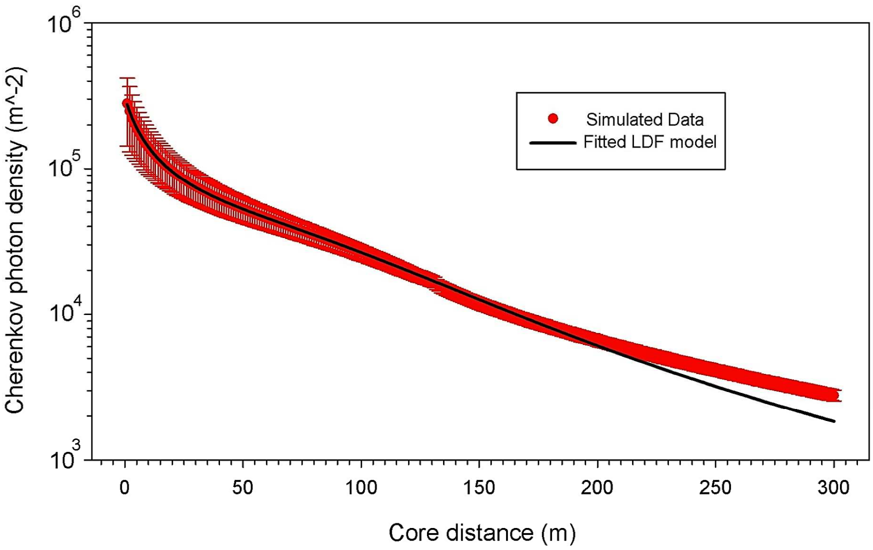

Figure 5: Lateral distribution of Cherenkov light for 10^{15}eV EASs initiated by protons (dots with error bars) is compared to the LDF model $\rho(r) = (a + br + cr^2 + dr^3)^{-1}$ (line). The data points are averages and the sample standard deviations are presented as error bars.

its total Cherenkov light, it would make the estimation of primary particle's mass much easier. For this reason, we have tried to find a simple model to fit the Cherenkov lateral distribution. The distributions can be fitted to a variety of models. We have chosen one of the simplest models with the least number of fit parameters that fits well to the data: $\rho(r) = (a + br + cr^2 + dr^3)^{-1}$. Here ρ is the Cherenkov photon density in cm^{-2}; r is the distance to the shower core in meter, and a, b, c, and d are the fit parameters. In figure 5, a comparison of a data set with the fitted LDF is presented.

The fit parameters are evidently dependent on the energy and the mass of the primary cosmic rays which generate the corresponding EASs. We have presented the fit parameters for 10^{14}eV, and 10^{13}eV showers of different primaries in tables 1 and 2 as examples. If one can estimate the energy of a shower independently, for example from the total number of Cherenkov photons, or by estimating electron size of the shower with the particle detector array of a hybrid experiment, he would use the Cherenkov LDF fit parameters to estimate the primary mass. In principle, the estimation of primary CR mass composition from secondary particles' information requires complicated and time consuming inverse problem solution. Even with a convenient parameterization, it will be hardly possible to reconstruct showers with large intrinsic fluctuations. The lateral distribution of Cherenkov light in EAS, which is sensitive to the shower maximum, will be affected by such fluctuations. Despite these complications, such methods have been developed in several works [12–15].

Table 1: Fit parameters of Cherenkov LDF, $\rho(r) = (a + br + cr^2 + dr^3)^{-1}$ for 10^{14}eV showers of different primary masses.

Primary particle	a	b	c	d
Gamma	0.4239	0.04173	-0.0004558	2.806e-006
P	0.4169	0.05202	-0.0003288	2.599e-006
He	1.061	0.06935	-0.0004926	3.069e-006
O	2.405	0.07416	-0.0004563	2.983e-006
Si	3.197	0.07552	-0.0003927	2.779e-006
Fe	5.101	0.06314	-0.0002147	2.311e-006

Table 2: The same as table 1 for 10^{13}eV showers.

Primary particle	a	b	c	d
Gamma	11.86	0.4641	-0.005353	2.925e-005
P	17.6	0.6909	-0.004191	2.854e-005
He	34.04	0.8187	-0.003555	2.567e-005
O	103	0.6201	0.0001008	1.707e-005
Si	141.5	0.2481	0.004907	4.261e-006
Fe	252.4	0.2629	0.00754	6.945e-008

3 Discussion

The development of techniques to discriminate ultra high energy cosmic rays from the properties of their EASs is an important job for high energy astrophysicists. Depending on the EAS observation technique, different methods have been developed to estimate the energy and the mass of the primary cosmic rays. As cosmic ray experiments are being developed among Iranian high energy astrophysicists [16–18], we found the wave front sampling Cherenkov techniques promising. As a first step, we tried to understand the available information from Cherenkov light of EASs. The wave front sampling experiments have to relay on the lateral distribution of Cherenkov light of EASs. Some of them had utilized charged particle detector arrays along with Cherenkov arrays in order to develop hybrid methods to improve the accuracy of EAS discrimination [19–21].

The measured lateral distribution of Cherenkov light is generally compared to the results obtained from Monte Carlo simulations. Other researchers have proposed different LDF for Cherenkov light in EASs [22–27]. With no simple function available to fit the Cherenkov light lateral distribution in the region within a few hundred meters from the shower core, reference [11] has introduced multifunction LDFs. Others proposed functions for limited distances, typically 20-150 meters from the shower core [22–25], have proposed a single complicated LDF to fit a set of simulated EASs in that region . Their model has 4 parameters which vary with energy and mass of the primary cosmic rays [27]. Our LDF seems to be simpler compared to previous works. The variation of the fit parameters of our model with the primary mass can be used for cosmic ray mass discrimination. We have started to study these mass dependent parameters in order to develop an event by event mass determination technique.

Gamma/hadron separation in ground based gamma astronomy is an important problem. The techniques based on air shower Cherenkov radiation have been developed and used by several groups [28–30]. The good news for the gamma ray astronomers is that the humps in lateral distribution of Cherenkov light of air showers are indicators of primary gamma rays, although the hump disappears in showers with $E > 10^{14}$eV. One should not expect to observe many gamma rays at these energies. These high energy gamma rays cannot travel more than a few ten parsec in the space due to e^-e^+ pair production in collision with cosmic background radiation [31]. In this way, air Cherenkov arrays can do gamma ray astronomy by filtering out hump-less showers.

Concerning the mass composition of primary cosmic rays, hybrid EAS experiments that use charged particle detector arrays along with air Cherenkov detector arrays seem to obtain more accurate results compared to mono-type arrays. After the installation and running of the array of 20 charged particle detectors by Cosmic Ray Laboratory in the Sharif University [32], we think that the addition of air Cherenkov detectors is worth being considered as a next step toward a full scale cosmic ray experiment. Such an experiment can be used to study cosmic ray energy spectrum around the "knee" as well as observing multi-TeV gamma ray sources like active galactic nuclei (AGN), pulsars, and supernova remnants [33, 34].

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