Separation of Gamma and Proton Showers ($1 - 10^4$ TeV) using the Lateral Distribution of Čerenkov Light at several Observatory Depths

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Abstract

A simulation of the development of γ and hadron showers in the energy range $1 - 10^4$ TeV has been carried out. Radial distributions of the Čerenkov light detected at observatory depths ranging from 500 to 1000 g/cm^2 have been studied. Capabilities of the angle integrating Čerenkov technique for separation of γ and proton initiated showers as a function of the observation altitude are discussed.

1 Introduction

Angle Integrating Čerenkov (AIC) detection is a promising new approach to ground based γ-ray astronomy due to its high precision in the determination of the direction and energy E_0 of primary cosmic rays together with a high capability for hadron rejection [1]. A γ/hadron separation method (LES method) for AIC arrays in the energy range 20 - 500 TeV has been recently proposed [2] and used by the HEGRA collaboration [3]. The present work aims at exploring the capabilities of this separation technique in a wider primary energy interval (1 TeV - 10 PeV) at several observatory depths X_{obs}.

A Monte Carlo simulation of vertical showers initiated by γ-rays and protons has been carried out by means of the CORSIKA code [4]. For the electromagnetic component of the shower the well-known EGS4 code has been used (cutoff energy 5 MeV). In order to reduce the computing time, the thin sampling technique [5] has been applied to all electromagnetic particles with energy lower than $10^{-5} \cdot E_0$. Also, for the generation of Čerenkov radiation, photons were gathered in bunches (see ref [6]) of 500 Čerenkov photons. Both procedures (usage of thinning and high bunch size) have allowed us the simulation of very high energy showers with a modest computing power. For each shower, the Čerenkov light (atmospheric absorption taken into account) in rings centered on the shower core and the shower size N_e at several observatory depths have been recorded. Also, the depth of the maximum development has been noted. In this work we will present some results at sea level and $500 g/cm^2$. In order to check our approach, we have also carried out calculations at $793 g/cm^2$, for which a more accurate MC simulation already exists [2][6].

2 γ/hadron separation

The so-called LES method [2] is based on the fact that proton showers are 'longer' than γ-showers and therefore, for a fixed X_{max}, the ratio N_e/N_e^{max} is higher for hadrons as compared with γ-showers. All these parameters can be determined by means of an AIC array measuring the lateral distribution of the Čerenkov light in conjunction with a scintillator array (which measures N_e). As is well known, the Čerenkov light density ρ is well described by an exponential function of the distance r to the core position for $r \leq 100m$

$$\rho = a \cdot exp(-br) \tag{1}$$

The slope of the lateral distribution function (b) provides an experimental determination of X_{max} [5]. Finally, the Čerenkov light density near the hump position is a good estimator of N_e^{max}. An alternative parameter (and even better for separation purposes) is the integrated light ($r < 90m$) L_{int} [2]). In ref. [2] it is shown that at the observation level of the HEGRA experiment ($X_{obs} = 793g/cm^2$) hadron and γ-showers can be efficiently separated in a plot of N_e/L_{int} vs b (see fig. 1b).

For high altitude observatories X_{max} is very close to the observation level (or else the maximun has not been reached yet). Therefore, the power of a separation method based on the measure of N_e/L_{int} at a fixed X_{max} decreases for lower X_{obs} values. In fig. 1a we show the mean value of N_e/L_{int} versus X_{max} in the energy range 0.1 - 10 PeV for three observatory depths. It can be seen that the power of the method

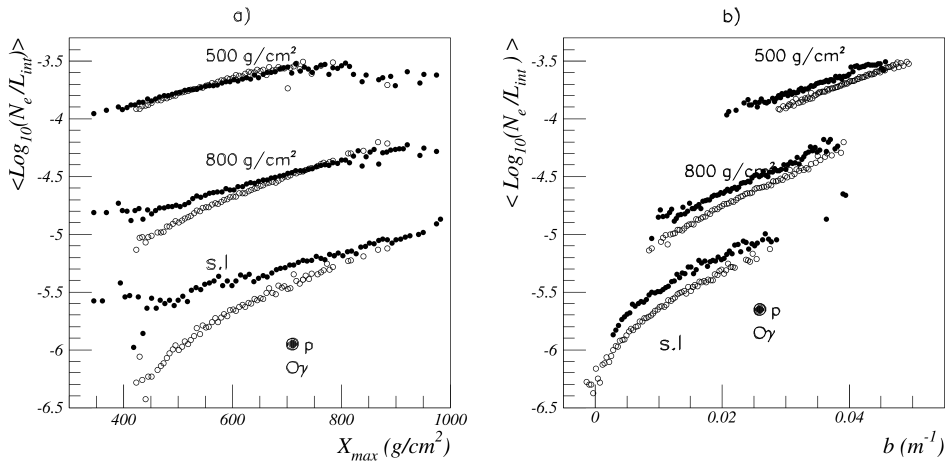

Figure 1: N_e/L_{int} *against a)* X_{max}*, and b) parameter* b *for showers in the range 0.1-10 PeV at three observation depths. Plots at 500* g/cm^2 *and s.l. have been vertically shifted to avoid congestion by 0.5 and* -0.5 *units respectively.*

increases with X_{obs}.

As mentioned above, in a real experiment the value of b (slope of the lateral distribution of Č-light) is used as an estimator of X_{max}. In fig. 2 we show the relationship between b and X_{max} for γ and proton showers in the energy range of this work ($1 - 10^4 TeV$). It can be seen that the dependence between these magnitudes (sligthly) varies with the primary type and therefore, separation of proton and γ-showers achieved in a diagram N_e/L_{int} versus b is different from that observed in a diagram N_e/L_{int} versus X_{max}. In fig. 1b it can be seen that this fact favours γ/proton separation for lower values of X_{obs} while it makes it worse at sea level.

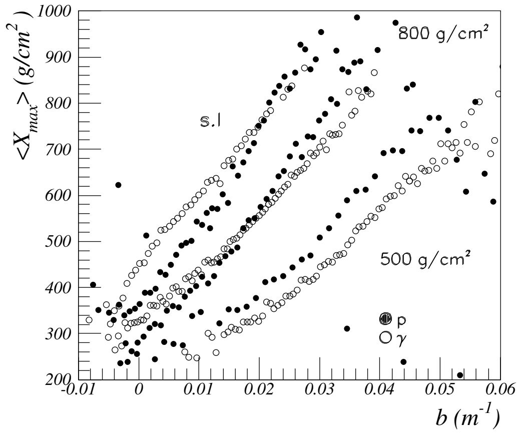

Figure 2: *Relationship between depth of shower maximum and the steepness of the Č-light lateral distribution.*

A simple estimate shows that the difference between fig. 1a and 1b is due to the abovementioned dependence between X_{max} and b on the primary particle (proton or γ).

3 Results

A quantitative study of this γ/h separation method in several energy ranges and observatory depths is being carried out. As an example we show in fig. 3 the result for showers in the energy range 5 - $100 TeV$ as observed at $500 g/cm^2$ depth. The lower limit (5 TeV) is close to the threshold energy which is currently being achieved by scintillator arrays at very high altitude observatories [7]. As can be seen in this figure a significant separation can be achieved. Applying the appropriate cut we have found an increase in the significance of a γ-signal with respect to the hadronic background (only protons have been considered) of $Q = 6$ where the quality factor Q is defined as $S_\gamma / \sqrt{S_p}$ and S_γ and S_p are the fractions of γ and proton showers respectively, remaining after the cut.

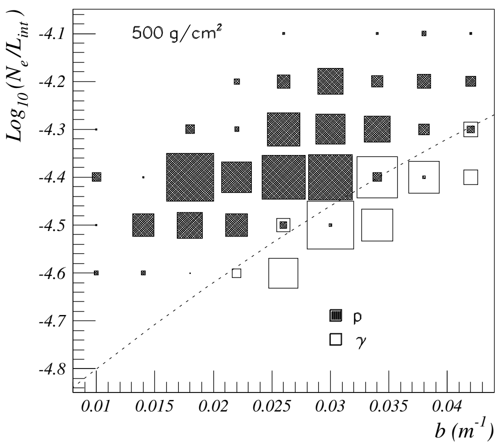

Figure 3: N_e/L_{int} *against parameter* b *for* γ*'s and protons in 5-100 TeV. The size of the symbol in one bin is proportional to the logarithm of the number of events. The dashed line shows a possible cut.*

According to our calculations the method seems to be very efficient for γ/p separation at sea level in the energy range 0.5 - 10 PeV. A value of $Q = 20$ (preliminary) has been found. This energy interval is typical for many scintillator arrays at sea level.

4 Conclusions

In principle, according to the physical foundations of the LES method for γ/h separation (considered in [2]), this method should cease to work at very high observatory altitudes. However, the relationship between X_{max} and its experimental estimator b is primary dependent. This fact favours γ/p separation at higher altitudes while it makes it worse at lower levels. A plot of N_e/L_{int} versus b allows separation between γ and proton initiated showers in a wide energy range ($0.1 - 10 PeV$ at s.l.) and at high altitude observatories ($5 - 100 TeV$ at $X_{obs} = 500 g/cm^2$).

The simulations shown in this work do not include the signal smearing of a realistic detector which is particularly large for N_e near threshold energy. However, a comparison of the results of this work with those of ref [2] shows that our simulation procedure (see section 1) has introduced non-negligible artificial statistical fluctuations and therefore our separation results (Q) have to be considered as a lower limit for an ideal detector. Calculations in several energy intervals taking into account the effect of realistic detectors are in progress. In this work only protons have been considered. Although the hadronic background contains a non-negligible amount of heavier nuclei, the LES method is more efficient for rejection of heavier hadrons and therefore the Q factor increases when taking into account a realistic chemical composition.

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