Proceedings of ICRC 2001: 310 © Copernicus Gesellschaft 2001

ICRC 2001

EAS depth of maximum estimation by Cherenkov light lateral distribution and pulse shape

V. I. Galkin

Faculty of Physics, Moscow State University, Moscow 119899 Russia

Abstract. A sample of 1PeV, 2PeV and 5PeV EAS was simulated using CORSIKA 5.61/QGSJET with CERENKOV option on for Tunka array conditions. The Cherenkov light data are analyzed from the point of view of shower parameter determination, primarily X_{max} and E_0. Some general conclusions are drawn on the informativity of the light lateral distribution and pulse shape characteristics.

1 Introduction

It is well-know that Cherenkov light coming from EAS contains versatile information on air cascade. Namely, the total amount of Cherenkov photons emitted can serve as a primary energy estimate, light lateral distribution shape is a measure of shower maximum depth, Cherenkov light pulses near the shower core and far enough from it ($R \geq 200m$) are closely related with the shower transition curve. Still these general statements need some concrete realization as far as certain physical problem and detector array are concerned. The present paper deals with Cherenkov light measurement abilities for a special case of Tunka array studying the 'knee' region of the primary cosmic ray spectrum. Still I hope some conclusions drawn are of general value.

2 Simulations

CORSIKA 5.61/QGSJET/QGSSIG/CERENKOV was used to simulate 1, 2 and 5 PeV vertical (0^o) and inclined (30^o) air showers originated by protons and iron nuclei. Each combination of the primary parameters (primary energy, zenith angle and primary type) defines a separate sample. Number of events in samples are shown in Table 1. Model of the atmosphere chosen was AT115 (European winter). Observation level was set to 530 m which is 990.1 g/cm^2 according to AT115. Detector array was defined as a rectangular 400m-long strip along CORSIKA Y axis. Strip width was 5 m for 1 and 2 PeV showers and 1 m for 5 PeV showers. The strip was divided into 80 5m-bins which might be called elementary detectors. Every photon that hit the strip was called 'detected'. The data presented in the paper are for 400-600 nm wavelengthband, 100% transparent atmosphere and detectors without any angular cut. Inclined showers are tilted towards Y axis. All lateral dependences are expressed in $R_\perp$ which is the core distance in a plane normal to the shower axis.

3 Results and conclusions

The basic goal of each EAS detector array is to estimate primary particle parameters: energy, type and direction. Let us assume that the shower direction determination is carried out successfully using the fast timing technique. Let us concentrate on energy and type determination possibilities. The primary type is often thought of as a certain dependence of depth of shower maximum on primary energy. Let us see how primary and secondary characteristics of a shower are connected to one another. Secondary characteristics of the simulated showers could be divided into integral (like depth of shower maximum), more differential (Cherenkov light lateral distribution) and the most differential (light pulse shape i.e. distribution in space and time).

3.1 Primary and integral secondary characteristics

Table 1 shows mean values and relative fluctuations (for each sample separately) of four quantities: h_{int} — height of the first nuclear interaction, X_{max} — depth of shower cascade maximum, Q_{tot} — total number of Cherenkov photons emitted, Q_{det} — total number of Cherenkov photons detected by the sensitive strip.

One can see from the table that the behaviour of the means is not always regular. For instance, mean X_{max} for given primary type should increase steadily with primary energy. This is not so for protons which is definitely because statistics

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Correspondence to: V.I.Galkin (glk@dec1.npi.msu.su)

is rather poor and typical error of mean X_{max} for protons is about 15-20 g/cm^2.

Table 1

Quantity	h_{int}, km	X_{max}, g/cm^2	Q_{tot}, photon	Q_{det}, photon
1 PeV vertical protons, 12 showers				
mean	23.8	536.7	2.02+10	1.39+8
rel.fluct.	0.351	0.122	0.049	0.199
1 PeV inclined protons, 12 showers				
mean	25.1	457.8	2.05+10	8.59+7
rel.fluct.	0.317	0.105	0.045	0.236
1 PeV vertical iron nuclei, 12 showers				
mean	33.4	445.7	1.64+10	8.07+7
rel.fluct.	0.265	0.045	0.031	0.095
1 PeV inclined iron nuclei, 12 showers				
mean	32.2	384.4	1.61+10	5.19+7
rel.fluct.	0.218	0.042	0.025	0.065
2 PeV vertical protons, 12 showers				
mean	25.7	519.3	4.06+10	2.66+8
rel.fluct.	0.312	0.089	0.049	0.166
2 PeV inclined protons, 16 showers				
mean	24.8	458.2	4.08+10	1.72+8
rel.fluct.	0.247	0.077	0.048	0.175
2 PeV vertical iron nuclei, 16 showers				
mean	31.4	450.2	3.40+10	1.76+8
rel.fluct.	0.135	0.063	0.017	0.110
5 PeV vertical protons, 14 showers				
mean	23.3	570.4	1.05+11	1.65+8
rel.fluct.	0.351	0.096	0.034	0.170
2 PeV vertical iron nuclei, 8 showers				
mean	35.3	474.2	9.22+10	1.05+8
rel.fluct.	0.129	0.034	0.048	0.052

Q_{tot} shows substantial fluctuations for a fixed primary energy as cascades develop higher or lower in the atmosphere and height-dependent Cherenkov radiation threshold rules the total amount of light. Q_{det} fluctuations could be rather high for protons (about 20% for total detector area as large as 400 to 2000 m^2) which compromises it as a measure of the primary energy.

Table 2 presents correlation coefficients of the four quantities for 1PeV vertical proton and iron nuclei. Here one can see that h_{int} and X_{max} are not strongly related for protons and fully independent for iron nuclei. Q_{det} can hardly be a measure of h_{int} or Q_{tot} but correlates well with X_{max} as if a shower is a lamp hung up at X_{max}.

3.2 Primary characteristics and Cherenkov light lateral distribution

Table 3 shows Cherenkov light lateral distribution (CLDF) $Q(R)$ correlations with Q_{tot} and its slope characteristic $Q(R)/Q(150m)$ correlations with X_{max} as a function of R for 1 PeV vertical proton and iron nucleus samples. $Q(R)/Q(150m)$ appears due to the fact that at $R \sim 150m$ $Q(R)$ displays a minimum of relative fluctuation (at least for protons) and different individual CLDFs intersect here.

Table 2

Quantity	h_{int}	X_{max}	Q_{tot}	Q_{det}
1 PeV vertical protons				
h_{int}	1.000	-7.67-1	-2.46-1	-6.80-1
X_{max}	-7.67-1	1.000	3.77-2	9.53-1
Q_{tot}	-2.46-1	3.77-2	1.000	-6.60-2
Q_{det}	-6.80-1	9.53-1	-6.60-2	1.000
1 PeV vertical iron nuclei				
h_{int}	1.000	2.86-2	3.60-1	-4.19-2
X_{max}	2.86-2	1.000	7.57-1	7.87-1
Q_{tot}	3.60-1	7.57-1	1.000	5.08-1
Q_{det}	-4.19-2	7.87-1	5.08-1	1.000

Table 3

R, m	50	100	200	300
1 PeV vertical protons				
$Q(R)$-Q_{tot}	0.04	0.57	0.99	0.88
$Q(R)/Q(150)$-X_{max}	0.95	0.98	-0.49	-0.95
1 PeV vertical iron nuclei				
$Q(R)$-Q_{tot}	0.53	0.87	0.98	0.94
$Q(R)/Q(150)$-X_{max}	0.61	0.91	-0.30	-0.78

According to Table 3, $Q(R)$ at about R=200 m is a measure of Q_{tot} and hence of the primary energy. On can also deduce that $Q(100)/Q(150)$ correlates strongly with X_{max}. Unfortunately, this quantity is not easy to measure in a real experiment with detector grid spacing of a few ten meters because one needs an CLDF model for each particular shower. Fig. 1 demonstrates CLDFs and transition curves of two 1 PeV showers with similar X_{max}. It is clear (plot A) that CLDF shapes differ substantially at $R < 150m$ and are the same at $R > 150m$. Plot B shows the same CLDFs but normalized by the total amount of light emitted (Q_{tot}) and confirms this statement. Plot C shows the reason for CLDFs' discrepancies at $R < 150m$: in this core distance range the major part of Cherenkov light comes from the atmospheric layers which are close to the observation level and the charged particle transition curves of the showers differ markedly at $t > 800g/cm^2$. To conclude, CLDF slope at $R < 150m$ is not a reliable measure of X_{max} of an individual shower.

3.3 X_{max} and Cherenkov pulse FWHM

Light pulse full width at half maximum τ shows impressive correlation coefficients with X_{max}: -0.7 to -0.9 at $R < 50m$ and above 0.8 at $150m < R < 350m$. Fig. 2 presents τ-X_{max} correlation plots of all available 1 PeV showers for core distances 150,200,250,300m.

One can deduce from the figure that τ-X_{max} correlation is not so strong at $R = 150m$ and even at $R = 200m$ but is definitely very strong at $R > 200m$. τ at $R > 200m$ is much better index of X_{max} (or, more precisely, of $\Delta X = (X_0 - X_{max})/cos\theta$, here θ is the shower zenith angle, X_0 is the observation depth) than CLDF slope parameter $Q(100)/Q(150)$ or the like.

Acknowledgements. Author would like to thank the National Organizing Committee of the Conference for financial support.

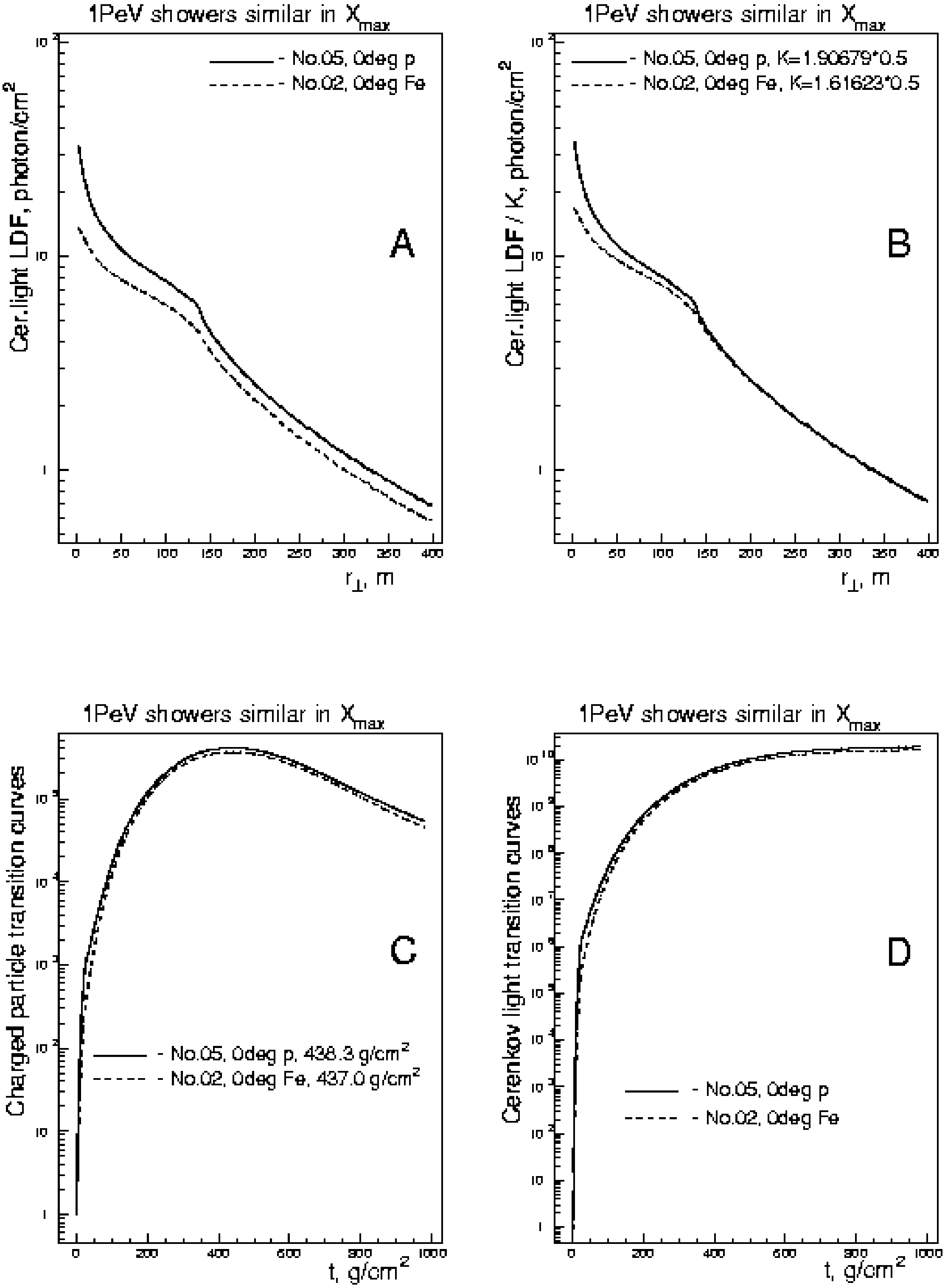

Fig. 1. CLDFs, charged particle and Cherenkov light transition curves for 1 PeV showers with nearly the same X_{max}

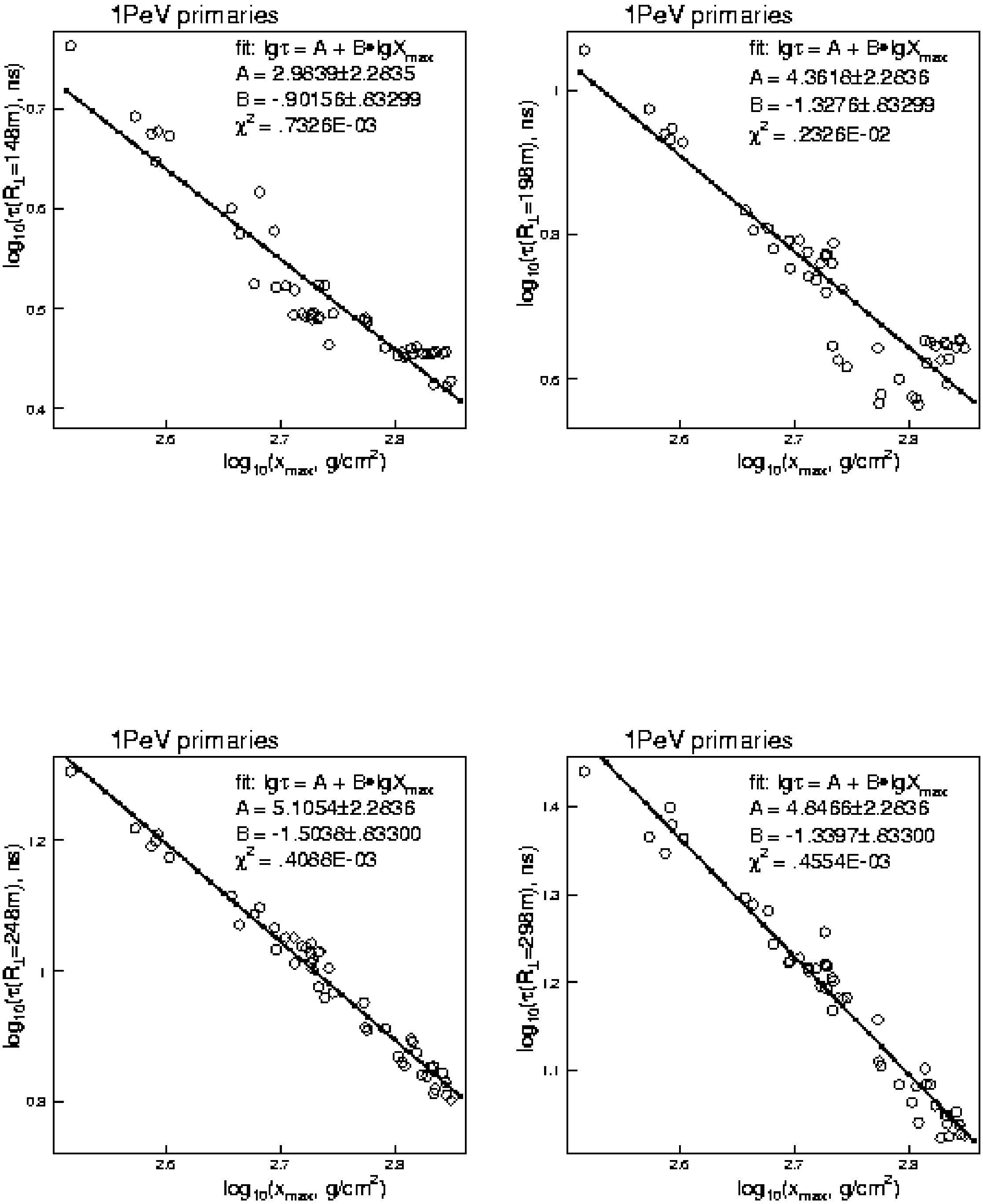

Fig. 2. 1 PeV shower τ-X_{max} correlation plots for core distances 150,200,250,300m