EAS Cerenkov Light Simulations Taking Geomagnetic Field Into Account

R.U. Beisembayev[1], V.I. Galkin[2], V.P. Pavlyuchenko[1] and Yu.N. Vavilov[1]
[1]*P.N.Lebedev Physical Institute, Moscow, 117924, Russia*
[2]*Nuclear Physics Institute of Moscow State University, Moscow, 119899, Russia*

Abstract

Monte-Carlo simulations of Cerenkov light emitted by proton initiated EAS of energy 10^{14}eV and 10^{15}eV were carried out stimulated by a series of observations made in Tien-Shan mountains. The observations showed an unexpected north-south asymmetry of the shower count rate (see Beisembayev et al., 1999) which couldn't be understood using simple estimates. A model of EAS Cerenkov light spatial-angular distribution was developed to make the estimates more realistic. Still the calculated asymmetry is far from the experimental one.

1 Introduction:

Cerenkov light observations were carried out at 3300m above sea level with a Cerenkov telescope incorporating a $1.9m^2$ parabolic mirror and FEU-63 photomultiplier. It has an aperture cone half angle of about 3.3^o. The telescope was alternately directed southward and northward at 30° with zenith for 10min. observation intervals. The reason for such aiming is that the telescope directed northward (we use magnetic poles as reference points rather than geographic ones) is expected to detect predominantly EAS with axes parallel to the local geomagnetic field which minimizes its effect on shower development. On the contrary, southward direction of the telescope gives an advantage to the showers coming at about 60° with the geomagnetic field. Mean south-to-north count rate ratio turned out to be about 2 (two!). Test runs with magnetically shielded PMT showed no difference which makes it
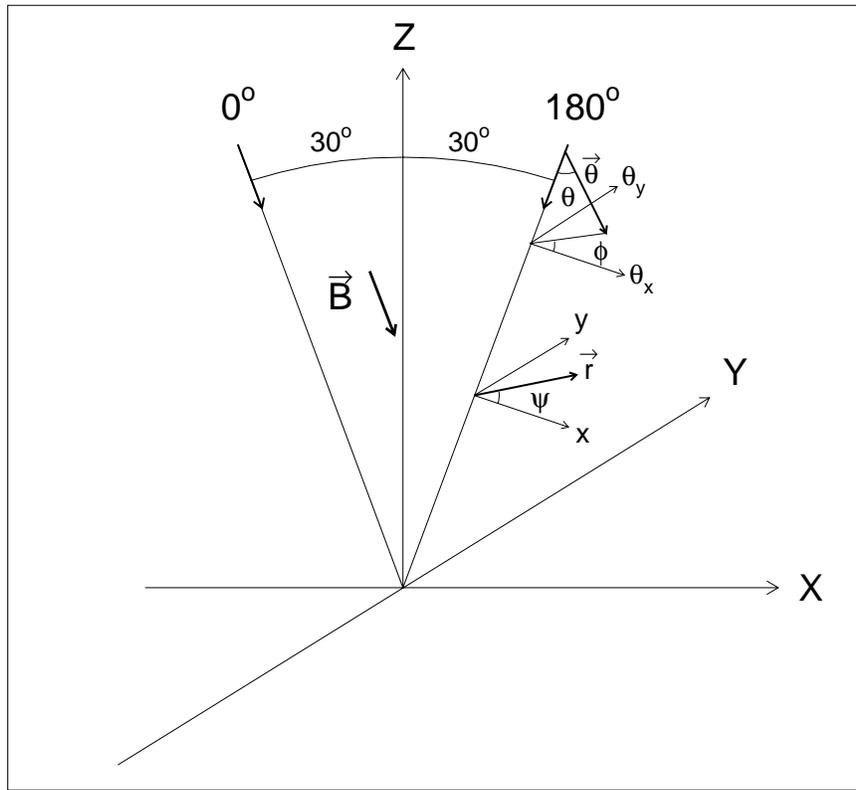

Figure 1: Coordinate system used, magnetic field vector, shower arrival directions, shower coordinates.

possible to rule out direct geomagnetic effect on the detector. Search for additional light sources yielded no result as well. It was decided to make Monte-Carlo simulations of EAS Cerenkov light for this particular telescope.

2   Simulations:

On one hand, direct Monte-Carlo takes a lot of time, on the other hand, the problem we try to solve requires mean Cerenkov light density to be calculated first of all. But still there is geomagnetic field to be taken into account. That is why we use CORSIKA 5.61 with QGSJET and light absorption added (40% per 1000 g/cm^2). Showers come from northward and southward directions (see Fig. 1) which are from now on denoted as "0°" and "180°", respectively, in accordance with CORSIKA conventions. Instead of a single detector we use an array of 81 detectors uniformly filling a circle of radius R with a center at the origin of coordinate frame where the axes of showers strike (see Fig. 2). Detector axes are parallel to shower axes. Narrow cone aperture of the real detector is changed to 60° half angle cone divided into 297 cells (12 divisions in polar ang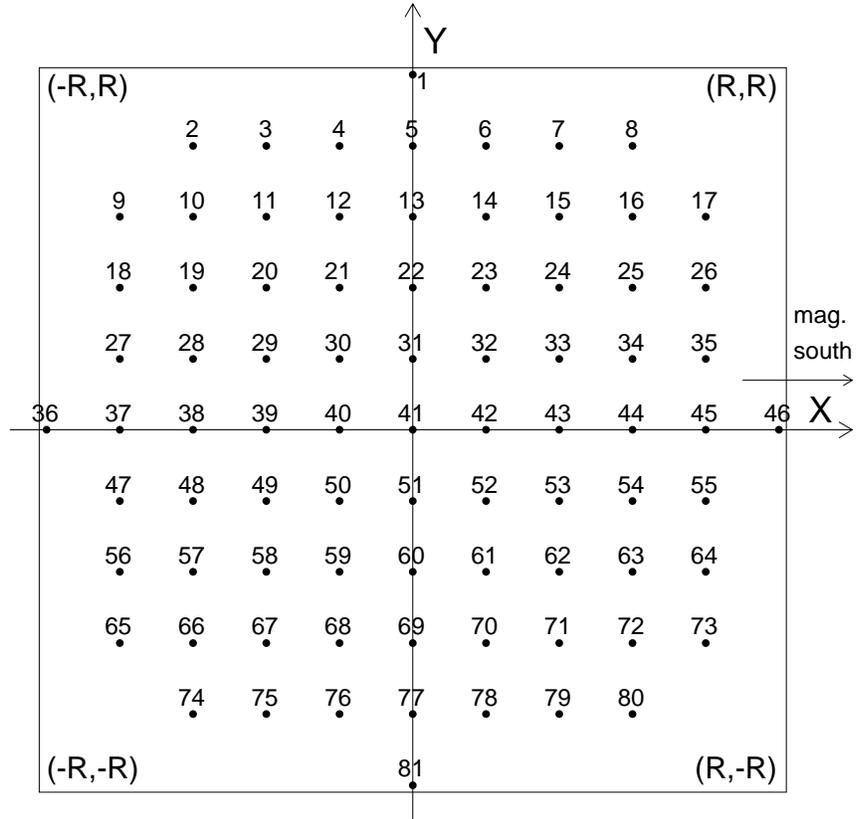le, 1 to 40 divisions in azimuthal angle) of body angle approximately equal to that of the real telescope. Detector area is remained unchanged. Cerenkov photons are distributed according to their arrival times between 28 6ns bins. Since the real telescope estimated threshold is about 100TeV we simulated 20 proton initiated 100TeV showers (R=0.3km) and 2 proton initiated 1PeV showers (R=0.5km) from each of two ("0°" and "180°") directions.

Figure 2: Detector array.

3   Cerenkov light spatial-angular distribution function:

One can analyze the simulated shower images in many ways. In particular, it forms a basis for construction of Cerenkov light spatial-angular distribution function (CLSADF) which is its joint distribution in lateral space and direction. We use the following approximation for mean CLSADF:

$$f(\theta, \phi, r, \psi; a, b, cx, cy, d) = d\, exp\left\{-\left[a\,\theta + \sqrt{(cx\, r\, cos\psi)^2 + (cy\, r\, sin\psi)^2}\right]\right\}$$
$$\times (0.8\,|\sin(0.5(\phi - \psi))| + 0.2)^{b\,(1 - exp(-3000\,\theta\, r))}; \tag{1}$$
$$\vec{r} = (r, \psi); \quad \vec{\theta} = (\theta, \phi)$$

Samples for different directions and primary energies are fitted separately which yields parameter values presented in Table 1.

Table 1 : CLSADF approximation (1) parameter values

E_0	100TeV		1PeV	
Detector direction	0°	180°	0°	180°
$a,\ sr^{-1}$	16.94	16.76	13.56	13.17
$b,\ km^{-1}sr^{-1}$	4.243	4.097	4.799	4.842
$cx,\ km^{-1}$	19.80	17.68	15.85	15.84
$cy,\ km^{-1}$	20.70	17.81	15.88	14.94
$d,\ photons$	94900.	63290.	788630.	699520.

One should bear in mind that approximations (1) with parameters from Table 1 may differ substantially from the true mean CLSADF of real showers not only due to inaccuracies of models involved (EGS4/GHEI-SHA/QGSJET/...) but also due to the chosen form of simulation data presentation which is a two-dimensional histogram in light arrival direction (with bins similar to the real telescope aperture) and a two-dimensional array of detectors in lateral space (each detector of area of the real telescope). One might call these approximations "CLSADF from the point of view of the real telescope".

4   South-to-North Count Rate Ratio Estimation:

After CLSADF approximations are calculated one can use them to estimate south-to-north shower count rate ratio. We do that in two steps:

1. calculate effective detection area for both directions and both primary energies;
2. calculate count rate for each of the cases by integrating cosmic ray flux over the detection area S and shower arrival direction cone Ω regarding telescope trigger condition and, finally, calculate count rate ratios.

4.1   Detection Area Calculation:
It is natural to expect that the largest detection area for a given primary energy appears for showers parallel to the telescope axis. Our CLSADF approximations are made exactly for that case.

To estimate an effective detection area one should apply telescope trigger condition to $f(0, 0, r, \psi)$. Minimum light yield that triggers the telescope is $Q_{thr} = 250 photons$ which gives detection areas presented in Table 2.

Table 2 : Detection areas S for proton showers, km^2

E_0	100TeV		1PeV	
Detector direction	0°	180°	0°	180°
	0.270	0.306	0.810	0.836

Of course, these should be regarded as the upper limits for detection areas but we mainly need them to set the lateral space integration limits while calculating the count rates.

4.2   Count rate calculation:
We don't need absolute count rates so we set all intensity coefficients to 1. We suppose shower arrival direction distribution to be isotropic and shower axes distribution over the observation level to be uniform. Under these assumptions count rate ξ for a given primary energy takes the form:

$$\xi = \int\limits_{S} \int\limits_{\Omega} z(\overrightarrow{r_0}, \overrightarrow{\theta_0}, Q_{thr}) d\overrightarrow{r_0}\, d\overrightarrow{\theta_0}$$

Here $\overrightarrow{\theta_0}$ is a shower arrival direction with respect to the telescope axis, $\overrightarrow{r_0}$ is a shower core location at the observation level with respect to the telescope location, $z(\overrightarrow{r_0}, \overrightarrow{\theta_0}, Q_{thr})$ is a function that represents the telescope trigger condition:

$$z(\vec{r_0}, \vec{\theta_0}, Q_{thr}) \quad = \quad \begin{cases} 1 \text{ if } g(\vec{r_0}, \vec{\theta_0}) \geq Q_{thr} \\ 0 \text{ otherwise} \end{cases}$$

Here $g(\vec{r_0}, \vec{\theta_0}) = \int \int F(\vec{r_0}, \vec{\theta_0}; \vec{r}, \vec{\theta}) d\vec{r} d\vec{\theta}$, $F(\vec{r_0}, \vec{\theta_0}, \vec{r}, \vec{\theta})$ is CLSADF for showers coming from $\vec{\theta_0}$ with core location at $\vec{r_0}$. As a matter of fact we don't know $F(\vec{r_0}, \vec{\theta_0}, \vec{r}, \vec{\theta})$ and thus cannot calculate $g(\vec{r_0}, \vec{\theta_0})$ but one can be sure that $g(\vec{r_0}, 0) = f(0, 0, r_0, \psi_0)$. One can learn two important things from the cascade theory: first, in homogenious medium without magnetic field one can swap the arguments of $F(\vec{r_0}, \vec{\theta_0}; \vec{r}, \vec{\theta})$ ($\vec{r_0}$ and $\vec{r}$, $\vec{\theta_0}$ and $\vec{\theta}$); second, F decreases rapidly with θ. The latter means that the most part of Cerenkov light is emitted approximately in the shower axis direction and the showers with large θ_0 have no chance to trigger the telescope. As long as one consider only arrival directions close to the telescope axis one can use approximation $f(\theta, \phi, r, \psi)$ instead of $g(\vec{r_0}, \vec{\theta_0})$ with (θ, ϕ) changed to $\vec{\theta_0}$ and (r, ψ) changed to $\vec{r_0}$.

Table 3 summarizes count rate calculations (errors show integration accuracy).

Table 3 : Count rates (arbitrary units) for two primary energies and two
detector directions and south-to-north count rate ratio

E_0	0° count rate	180° count rate	$180^o/0^o$ ratio
$100TeV$	0.00786 ± 0.00003	0.00777 ± 0.00003	0.989 ± 0.008
$1PeV$	0.0255 ± 0.0001	0.0268 ± 0.0001	1.051 ± 0.008

There is no definite effect for 100TeV showers which are about the telescope threshold but for 1PeV showers south-to-north count rate ratio is certainly greater that 1 but much less than observed 2. This estimate is based on only two pairs of 1PeV showers so further simulations are needed to get accurate count rate values.

Cerenkov light arival time distributions should also be used to understand the discrepancy between the experiment and calculations because telescope triggering system might be biased towards long light pulses which are characteristic of showers with large impact parameters which, in turn, lead to greater effect.

5 Conclusion:

Calculations show south-to-north count rate ratio of about 1 which contrasts with experimental value ~ 2. Further simulations should be done as well as further observations to clear up the situation.

References

Beisembayev, R.U., et al. 1999, Izvestiya RAN, ser.fiz. 63, 554