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Air Cherenkov light measurement and EAS development at energies around 10^{16} eV

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Detectable characteristics of Cherenkov radiation emitted by extensive air showers (EAS) of cosmic rays in atmosphere used to be connected with longitudinal development parameters of the electron cascade. In this paper we present the results of the Yakutsk array data analysis concerning air Cherenkov light measurements with autonomous sub-array. Light intensity at 100 m from the shower axis is used as a measure of the primary energy. A connection is discussed between the shower attenuation and measured characteristics.

1. Introduction

Investigation of EAS in the energy range $10^{15}\div10^{17}$ eV is very interesting due to the knee in the energy spectrum and to testing the applicability of the diffusive model of cosmic ray propagation in Galaxy. On the other hand, there are a number of papers [1-4] where the attempts have been made to explain the knee in the spectrum by the change of interaction parameters in nuclear cascade and the manifestation of 'new' particles or high energy muons [2], the generation of long flying component in EAS [3]. The last one should be revealed effectively in inclined showers, i.e. after the cascade passage through $1500\div2500$ g/cm^2 in atmosphere. In this connection, the study of longitudinal EAS development far beyond the shower maximum can give the answer to these questions.

2. The Yakutsk Complex EAS array

At present, the charged particles density, the density of muons with $E \geq 1$ GeV and air Cherenkov radiation of EAS are measured at the Yakutsk array [5]. The atmospheric monitoring is carried out. The structural scheme of the array local network is shown in Figure 1. The network includes a large array (LA), a mini Cherenkov array (S Cher.A), a large muon detector (LMD), a Cherenkov differential detector (ChDD) on the basis of OBSCURE chamber, a lidar for the measurement of atmospheric transparency, aerosol extinction and a mini-meteorological station for the measurement of the atmospheric pressure, temperature and so on. The distributed system of collection, accumulation and treatment of the array data is created on the basis of Ethernet LAN by which all the experimental subsystems are connected.

As it is seen from Figure 1, a mini-Cherenkov array for the measurement of showers in the energy range $10^{15}\div10^{17}$ eV is a part of the Yakutsk array. The mini-array operates 10 years already. The Table 1 presents the following characteristics of observation periods: the total annual observation time, the average temperature, the pressure and the atmospheric transparency. The data have been averaged over the Cherenkov array operation periods.

3.Results

3.1.The lateral distribution function of EAS Cherenkov light

The lateral distribution functions (LDF) of Cherenkov light in Figure 2 are given exactly in the form as authors of the Yakutsk [6], Tyan-Shan [7], Dugway [8], Samarkand [9] and Chalaltaya [10] arrays presented them. The data have been obtained at different levels in atmosphere. It is seen from Figure 2 that steepness of LDF changes depending on the observation level. The similar change follows from model calculations in QGSJET, too. The calculations have been carried out at the depth 630 g/cm2 and 1030 g/cm2 for the vertical shower initiated by the primary proton [11]. The calculations and experimental data are in good agreement at the core distance 100 m. The discrepancy takes place at large distances for the Yakutsk LDF and at distances less than 100 m for Tyan-Shan LDF. The agreement of the Yakutsk data with calculations becomes noticeably better for θ ~ 17°. Under similar conditions of the shower selection, LDF of the Tyan-Shan array nevertheless appears to be steeper than LDF obtained at the Chakaltaya depth (530 g/cm^2) in contradiction with calculations by the QGS model for the primary proton. The experimental data of other arrays do not contradict the simulation results.

Table 1. Characteristics of various observation period

Years	95	95 - 96	96 - 97	97 - 98	98 – 99	99 – 00	00 - 01	01 - 02	02 - 03	03- 04	04- 05
T., min	9960	19164	22563	26586	28457	29683	26530	26525	26342	32180	29240
n., eas	9362	17823	23465	24130	30876	29089	25734	25729	25156	33628	27778
< T>, C	-27,9	-27,8	-29,4	-26,9	-26,8	-23,4	-27,2	-24,3	-25,2	-28,4	-29,4
<P>, μб	1003	1005	1004	1003	1003	1002	1003	1001	1002	1005	1006
P_λ,ob un	0,64	0,62	0,61	0,60	0,59	0,61	0,59	0,58	0,61	0,63	0,62

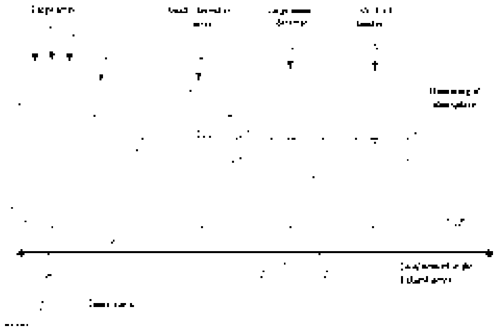

Figure 1. A flow chart of the data processing in the Yakutsk array LAN.

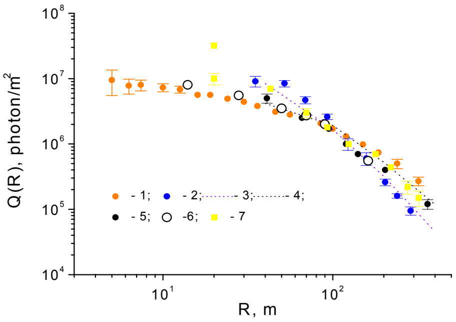

Figure 2. The lateral distribution of EAS Cherenkov light at the sea level and the mountain altitude. Symbols: 1-The Yakutsk array, θ = 17°; 2-The Tyan-Shan array, θ = (0÷30)°; 3-Calculations by the QGS model [11], X = 690 g/cm^2, $E_0 = 1\times10^{16}$ eV, θ = 0°; 4-The same for X = 1030 g/cm^2, $E_0 = 1\times10^{16}$ eV, θ = 0°; 5-The Dugway array θ = 14°; 6-The Samarkand array, θ = 18°; 7-The Chakaltaya array, θ = (0 ÷30)°.

3.2. The estimation of energy

It is seen from Figure 2 that experimental data coincide at R = 100 m from the shower core. In the same point the simulation curves cross the data as well. As it follows from [12,13], the fluctuation of Q(R) at this core distance is nearly minimal. Thus, the intensity of Cherenkov light flux at a distance of 100 m from the shower core, Q(R=100), can be used as the energy estimator. The primary EAS energy at the Yakutsk array is evaluated using energy balance method [14] and is independent of the cascade model. One can use this for the inter-calibration of energy estimation methods of the arrays where EAS Cherenkov light is not measured. The relation of E_0 to Q(R=100) was derived using the Yakutsk array data

$$E_0 = (5.75 \pm 1.21)\times 10^{16}\times(Q(R=100)/10^7)^{0.96 \pm 0.03}. \qquad (1)$$

For the arrays where the charged particles only are measured, the relation of E_0 to the total number of charged particles can be found via the correlation of N_s and Q(R=100):

$$\lg N_s(0°) = (5.74 \pm 1.08) + (1.10 \pm 0.04)\times\lg(Q(r=100)/10^6). \qquad (2)$$

Using the formula (1) and (2) we obtain the relation of E_0 to N_s for the vertical showers:

$$\lg E_0 = (10.79 \pm 1.75) + (0.87 \pm 0.03)\times\lg N_s(0°). \qquad (3)$$

Thus, we suggest the cross calibration of energy estimation methods of all compact arrays using the relation (3). The values of E_0 obtained by formulae (1) and (3) are given in Table 2. It follows from Table 2 that in [8] the primary energy is overestimated by a factor of two.

Table 2. Characteristics of EAS evaluated at the arrays

n/n	Array	X, g/cm^2	Q(r=100), $phot./m^2$	$N_s(\theta)$, particles	$N_s(\theta=0°)$, particles	E_0, eV	E_0', eV	E_0'', eV
1	Yakutsk	1020	$1{,}95\cdot10^6$	$1{,}26\cdot10^6$	$1{,}31\cdot10^6$	$1{,}21\cdot10^{16}$	$1{,}21\cdot10^{16}$	$1{,}35\cdot10^{16}$
2	Tyan-Shan	690	$1{,}86\cdot10^6$	$7{,}51\cdot10^6$	$1{,}58\cdot10^6$	-	$1{,}05\cdot10^{16}$	$1{,}63\cdot10^{16}$
3	Samarkand	940	$1{,}70\cdot10^6$	$1{,}69\cdot10^6$	$1{,}13\cdot10^6$	$1{,}20\cdot10^{16}$	$9{,}57\cdot10^{15}$	$1{,}22\cdot10^{16}$
4	Dagway(USA)	862	$1{,}66\cdot10^6$	-	-	$2{,}30\cdot10^{16}$	$9{,}36\cdot10^{15}$	
5	Chacaltaya (Boliviya)	530	$1{,}25\cdot10^6$	$10{,}0\cdot10^6$	$1{,}03\cdot10^6$	-	$7{,}13\cdot10^{15}$	$1{,}11\cdot10^{16}$

Here E_0 is the estimation obtained by authors; E_0' is from the expression (1) and E_0'' is according to the expression (3).

3.3.The reconstruction method of cascade curve

Using the method [15] we have reconstructed the cascade curve in the depths from ~X_{max} to the sea level. At the lowest depth the cascade curve has been reconstructed from the correlation of N_s and Q(R) parameters measured at different zenith angles and fixed energy. Points in Figure 3a show the results of reconstruction. Other signs indicate the direct measurement results of total number of charged particles at arrays located at different levels in atmosphere. As it is seen from Figure 3a, N_s measurements coincide within experimental errors with the reconstructed cascade curve. One can conclude that the method [15] suggested by the Yakutsk group reproduces well the longitudinal development of showers and can be useful in the longitudinal development study of showers.

In Figure 3a the simulation result with QGSJET model is presented. It seems that experimental cascade curve is significantly flatter than calculated one for the primary proton. The calculated curve for the iron nucleus will be still flatter than for the primary proton. Thus, the experiment gives a flatter cascade curve. This disagreement can be explained by two reasons. The first is caused by the error in zenith angle measurement. The second one may be due to higher threshold of muons in the used model.

Unfortunately, there are no calculations of the influence of long-flying component on the tail of cascade curve. Perhaps at the lowest depths the excessive flatness of experimental curve is connected with this component.

3.4. The charged particle absorption length

One can measure the absorption length of particles using data obtained with arrays located at different levels in atmosphere. For these purpose we used the value N_s measured at the sea level (Yakutsk) and the mountain altitude (Tyan-Shan). The resultant λ is shown in Figure 3b as a square. It follows from Figure that at $E_0 \sim 10^{16}$ eV λ well coincides with the estimation given in [16] (points). Therefore, N_s measured at different EAS arrays do not have systematic errors connected with measurement methods and the shower treatment. The particle absorption lengths in atmosphere well coincide with value $\lambda = (212 \pm 8)\ g/cm^2$.

4.Conclusion

As the result, one can reconstruct the cascade curve of the shower in the ultra-high energy region using either mathematical methods or experimental data of the arrays located at different altitudes. The data analysis has shown that the tail of cascade curve is flatter than follows from QGSJET model calculations for the case of primary proton. The obtained cascade curve contradicts the cascade from heavy primaries as well. Such a cascade curve is possible in the case of long-flying component or so. One can verify this hypothesis using the study of the very inclined showers and corresponding simulations.

Acknowledgements

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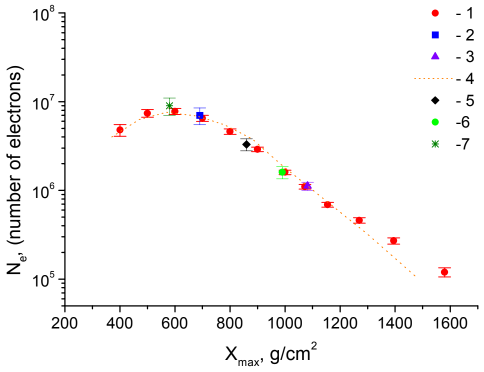

Figure 3a. The cascade curve reconstructed by measurements obtained at the of EAS Cherenkov light at the Yakutsk array. Symbols: 1 – using the method [15]; 2,3,5,6,7 – are direct measurements; 4- calculations by QGSJET model.

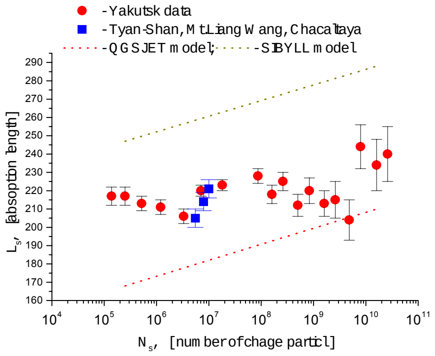

Figure 3b. The charged particle absorption length obtained at the Yakutsk array. Curves are calculations with QGSJET model and SIBYLL for the primary proton. Symbols: circles are the data from [16]; squares are results obtained from observational data at different depths in atmosphere.

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