Cerenkov radiation of cosmic ray extensive air showers. Part 1. Lateral distribution in the energy region of $10^{15} \div 10^{17}$ eV

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Abstract. The EAS Cherenkov radiation in the showers with energies $10^{15} \div 10^{17}$ eV has been measured. The maximum depth of the EAS development has been estimated by a form of the lateral distribution function. It is shown that in the framework of the QGSJET model the mass composition of primary particles becomes heavier in the energy region of $3 \cdot 10^{15} \div 3 \cdot 10^{16}$ eV.

1 Introduction

After the discovery of the Vavilov-Cherenkov radiation in 1934 (Cherenkov P.A., 1934) and its further study in the Earth's atmosphere, the Cherenkov radiation became the important instrument in the complex study of the extensive air shower (EAS) phenomenon.

The first study of the Cherenkov radiation of the showers was carried out by Jelley (Jelley , 1951), Nesterova (Nesterova and Chudakov, 1955) and Krieger (Krieger and Bradt, 1969). Those experiments showed the perspective use of the Vavilov-Cherenkov effect for the EAS identification and also for obtain of information about the energy of the primary particles, the processes of the energy dissipation by EAS particles in the Earth's atmosphere (Nikolsky, 1962; Chudakov et al., 1960), of the transparency of the atmosphere low layers (Dyakonov et al., 1991). The further observation method development of the Cherenkov radiation from the EAS, especially for showers of super high energies is connected with the Yakutsk complex EAS array (Artamonov et al., 1994). Here, since 1970 the Cherenkov EAS radiation are continuously carried out. At present, the Cherenkov radiation in showers with $E_0 > 10^{19}$ eV has been registered.

2 Array. Methods. Analysis

After modernization in 1993, the Yakutsk complex EAS array presents the branching local network operating in the real-time regime (Afanasiev et al., 1996). The network includes the main array of 12 km^2 control area, the small Cherenkov array of $3 \cdot 10^5$ m^2 control area and the large muon detector with the threshold energy 0,5 GeV and the area of 190 m^2. Thus, the array complex controls the energy region of $10^{15} - 10^{20}$ eV. The small Cherenkov array supplemented by new observation stations (see Fig.1) is located in the center of main array and consists of 50 informational channels (Cherenkov, scintillation, temporal).

Fig.1. The small Cherenkov array

The observation stations are symmetrically located relative to the center of the main array and form the net of equilateral triangles with sides of 50,100,250 and 500 m. At the array a few types of Cherenkov detectors with the receiving areas of 176 cm^2 and 530 cm^2 are used. The EAS events are selected by a coincidence of responses from three Cherenkov detectors located in the tops of equilateral triangles during the time of 2,5 ms. For showers with $E_0 > 10^{17}$ eV the small array operates synchronously with the large array, that gives a possibility to control in addition the operation of all measuring channels of the small array and effectively register showers up to energy $5 \cdot 10^{17}$ eV. Since the operation of the small Cherenkov array (February 1995) we carried out ~ 2716 hours of EAS Cherenkov radiation observations and registered ~$2,5 \cdot 10^5$ EAS events with energy $> 10^{15}$ eV. The total registration time by years are presented of Table 1. We took the periods of observations when the transparency of the atmosphere was estimated like the normal, high and very high. Also in Table 1 the mean integral atmosphere transparency is given (Dyakonov et al., 1999) for every period.

To estimate the shower parameters more correctly we have created the programs of the primary and secondary treatment of data. Those programs allowed consistently to take into account the readings of the separate detector groups with various amplitudes when we determined the

angles θ and φ using the maximum likelihood method. In order to find a shower core, the readings of the Cherenkov and scintillation detectors are used. The determination of the shower core doesn't depend on detector location geometry and *a priori* accepted charged particles LDF or the EAS Cherenkov light.

In formation of the data bank of the small array, the atmosphere condition is taken into account. The atmosphere transparency is determined by the repetition frequency of low energy showers relative to the night when the Rayleigh light scattering is only observed (Dyakonov et al.,1991). The shower selection is carried out by the Q(100) parameter (the density of the Cherenkov light flux at a distance of 100 m of the shower core). This parameter depends little on a zenith angle (Belayev et al., 1980) and is measured in every shower. The transition to the primary shower energy is made according to the formula:

$$E_0 = (5,2\pm1,1)\cdot(Q(100)/10^7)^{0,96 \pm 0,\ 02} \qquad (1)$$

which is obtained by the calorimetric method (Afanasiev et al.,1993).

We have used the calculations of the nuclear and electromagnetic cascades by the QGSJET model (Knurenko et al.,1999). Calculating the EAS Cherenkov light the spectral characteristic, the threshold of the light receiver and the Cherenkov detector aperture are taken into account. All calculations are carried out for Yakutsk winter conditions.

3   Results and Discussion

It is known that the Cherenkov light LDF is sensitive to the maximum depth X_{max} of the EAS development (Belayev et al., 1980; Lagutin et al., 1989). By this reason, the most physicists use the Cherenkov radiation for the reconstruction of the longitudinal EAS development. Fig.2 and 3 show the experimental Cherenkov light LDF for two intervals of $10^{15} \div 10^{16}$ eV and $10^{16} \div 10^{17}$ eV.
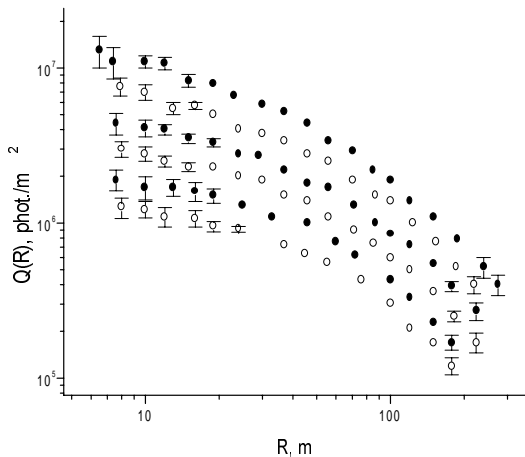
Fig. 2. The Cherenkov light LDF for energies: $1,8\cdot10^{15}$; $2,7\cdot10^{15}$;

$3,5\cdot10^{15}$; $4,5\cdot10^{15}$; $7,2\cdot10^{15}$; $1,1\cdot10^{16}$ eV.

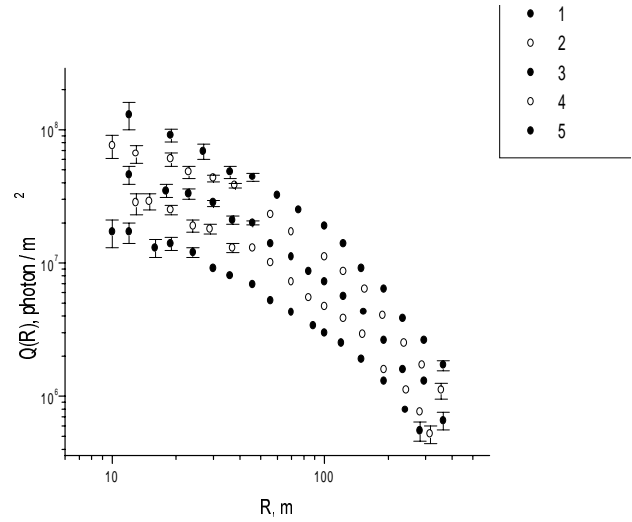**Fig.3.** The Cherenkov light LDF for energies: 1. - $1,6\cdot10^{16}$;

2. - $2,6\cdot10^{16}$; 3. - $4,0\cdot10^{16}$; 4. - $6,6\cdot10^{16}$; 5. - $1,0\cdot10^{17}$eV.

The Cherenkov light LDF's are constructed by the large number of showers (~ $5\cdot10^4$ EAS events). The form of the Cherenkov light LDF is analyzed by the parameters
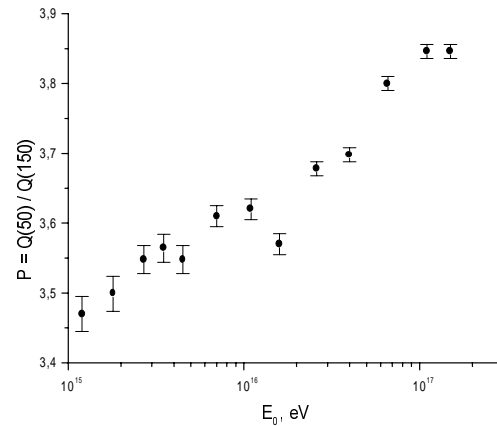
Fig. 4. The form lateral distribution of Cherenkov light versus

the primary energy.

P=lg(Q(50)/Q(150)), r.m.s. (a root-mean-square radius of the Cherenkov light LDF) and the ratio F/N (F is a total flux of the Cherenkov light and N is the total number of charged particles).
As it is seen from Fig.4, the form of the Cherenkov light LDF changes in the range of ~$3\cdot10^{15} \div 3\cdot10^{16}$ eV.
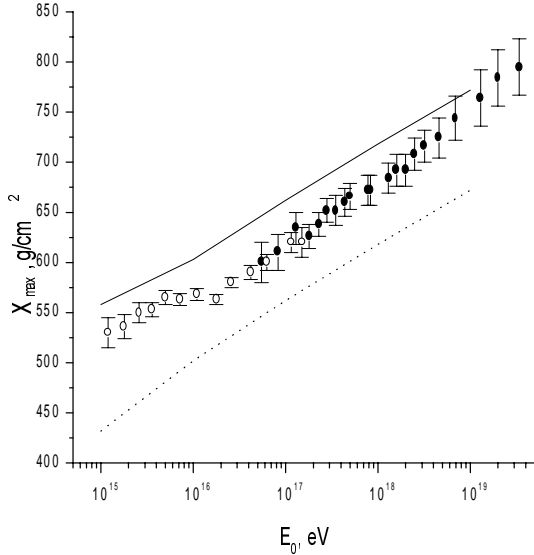
The comparison of the experimental data with the calculations by the QGSJET model for the primary nuclei CNO, Fe and protons show that in the framework of this model the mass composition of primary particles is lighter at $E_0 = 10^{15} \div 3 \cdot 10^{15}$ eV, and then becomes heavier in the energy region of $3 \cdot 10^{15} \div 3 \cdot 10^{16}$ eV.

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Knurenko S.P., Sleptsova V.R., Kalmykov N.N. et al. // Proc. 26th ICRC, v. 1 (1999), p. 372.

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Fig. 5. The shower maximum depth versus the primary energy.

(o) - new data; (•) - Yakutsk array data (Dyakonov et al., 1993).

QGSJET predictions: (--) - pure proton; (…) - pure iron nuclei

(Knurenko et al., 1999).

Fig. 5 shows the dependence of X_{max} on the primary energy. It is seen that in the region of energy $3 \cdot 10^{15} \div 3 \cdot 10^{16}$ eV the advancement of X_{max} deep into the atmosphere becomes slower. For example, the shift of X_{max} with the increase of energy is 63 ± 6 g/cm^2 in the energy region of $\sim 10^{15} \div 4 \cdot 10^{15}$ eV at $E_0 = \sim 4 \cdot 10^{15} \div 3 \cdot 10^{16}$ eV it is 45 ± 8 g/cm^2, and at $E_0 > 3 \cdot 10^{16}$ eV it is 65 ± 5 g/cm^2.

Table 1. Characteristics of various observation periods.

Years	95	95 - 96	96 - 97	97 - 98	98 – 99	99 – 00	00 - 01
T, min	9960	19164	22563	26586	28457	29683	27233
P, arb. un.	0,61	0,59	0,62	0,58	0,64	0,60	0,62