Reconstruction of the cascade curve for development of extensive air showers from the Ĉerenkov pulse shape at an energy $E_0 > 10^{17}$ eV

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We show a possibility of reconstructing the cascade curve for development of individual extensive air showers (EAS) from the shape of the Cerenkov radiation pulses at energies $E_0 > 10^{17}$ eV. The cascade curves obtained in this manner are in agreement with the accepted models for the development of EAS.

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In recent years, we have systematically investigated the shape of the Cerenkov EAS pulse produced by primary cosmic particles with energies 10^{15}–10^{18} eV, by using a method initially proposed in 1971 in Ref. 1. The results of these investigations are presented in Refs. 2–4. The basic result that follows from these studies is the dependence of the height of the shower maximum on its intensity $t_m(N_e)$.[3,4]

In view of this, we believe the foregoing method[1] is not limited to only determining the position of the EAS maximum height, but can also be used to study the longitudinal EAS development in a broad range of atmospheric depths. A similar attempt to study the shape of the EAS cascade was made by Orford and Turber.[5] However, the latter failed to determine the number of shower particles at different depths; instead, they determined the values proportional to the number of Cerenkov photons emitted at different angles at different depths.

Our method consists of reproducing the shape of the cascade curve from the shape of an experimental pulse of Cerenkov radiation from the EAS by using the following space-time function:[1]

$$\tau = (\bar{n}(H)/c)\sqrt{H^2 + R_\perp^2} - (H/c) \qquad (1)$$

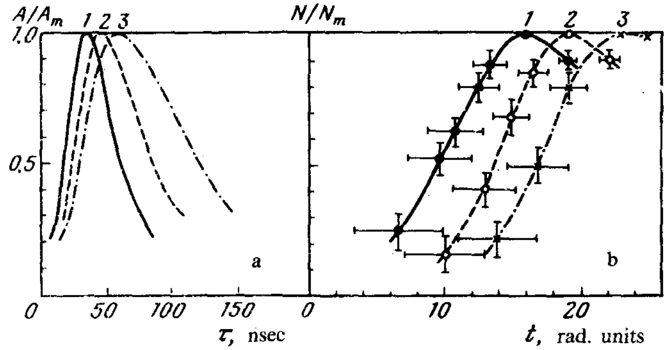

FIG. 1. Cerenkov EAS pulses (a) and corresponding EAS cascade curves (b) in relative units. 1, 2, 3-the number of pulses and of the corresponding cascades.

and the angular distribution of the EAS electrons that emit the Cerenkov light.[6] In the above equation H is the geometrical distance along the shower axis from the sea level to any point along the axis in the atmosphere (at any zenith angle θ), τ is the time of arrival of the light from the height H, $R_\perp$ is the distance from the shower axis to the detector projected on a plane perpendicular to the shower axis, $\bar{n}(H)$ is the effective refractive index of light in the air, which depends on the height H and is obtained with allowance for a barometric formula,[1)] and c is the speed of light.

The data base for constructing the cascade curves were the experimental events with the EAS Cerenkov light pulses that were recorded on film and selected in such a way as make the signal-to-noise ratio of the night sky not less than 15. As was pointed out,[2,3] the device for recording the shape of the Cerenkov pulse in Yakutsk allowed us to determine the following shower parameters for each experimental event: $R_\perp$, θ, t_m, and N_e, where t_m is the location of the shower maximum in the atmosphere and N_e is the number of EAS particles at sea level. Knowing the orientation of the shower axis ($R_\perp$, θ), we can go over from the time coordinates τ to the space coordinates H (km) by using relation (1) and, then to the t coordinates (g/cm^2) by using the barometric formula. It should be pointed out that the pulses were recorded in relative time units during the experiment. However, knowing the location of the maximum t_m, we can determine the original pulse distribution with respect to time.

Figure 1 shows examples of three (out of six analyzed) experimental pulses (a) and the corresponding EAS cascades (b), which were obtained by using the above method and which pertain to the range $N_e = 3.5\times 10^7$–3.5×10^8. The error bars in Fig. 1, which are characteristic of the method used, are due to errors in the measurement of the time pulse parameters ($\Delta\tau = \pm 5$ nsec), of the pulse amplitude ($\Delta A = 7\%$), $\Delta\theta = \pm 5°$, $\Delta R_\perp \approx \pm 10$ m, and $\Delta t \approx \pm 10$ g/cm^2.

Figures 1 and 2 show pulses and cascades in relative units of A/A_m and N/N_m, where A_m and N_m are the maximum pulses and cascades, respectively. However, the absolute measurements of pulses and the related cascades at different heights in the atmosphere t and different values of N_e are also possible. We shall address this problem in the future. We should also note that the events that analyzed by us pertain to a range of distances from the axis $R = 300$–450 m.[2)] If we would proceed with the recording of events with large $R_\perp$, a more detailed investigation of the initial part of the cascade would be possible, including the location of the first interaction point.

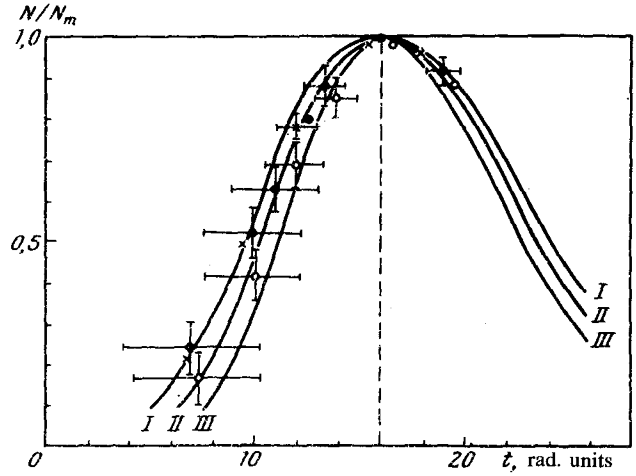

FIG. 2. EAS cascade curves normalized at the point $t_m = 16$ rad. units. Curves—EAS cascades for the scaling models: (I), SKR (II), and MVM (III).

However, such an approach has definite technical difficulties and the use of large-aperature detectors. On the other hand, a more detailed study of the part of the cascade beyond its maximum requires investigation at small $R_\perp < 100$ m, which has technical difficulties of recording small time intervals τ.

Finally, we note that in one of the six events under consideration we examined pulses at two different distances $R_\perp$ for the signal-to-noise ratio $\geqslant 15$. The cascades constructed from these independent experimental data coincide within the accuracy of $\Delta t \approx 0.6$ t units, which is a good verification of accuracy of the method used by us to reproduce the cascades.

As seen in from Fig. 2, in which the cascades shown in Fig. 1b are normalized at the point $t = 16$ rad. units, the total error in determining the shape of the cascade is sufficiently high to establish a difference between the existing models of EAS development (MVM, SKR, scaling, see, for example, Ref. 7). However, we believe that the development of a cascade at $E_0 > 10^{17}$ eV occurs within the framework of the generally accepted models.

[1]Since the observations were made in the vicinity of Yakutsk during the winter, the barometric formula made allowances for the average temperature during the measurements (−30 °C): $t = 1020/\cos\theta\, e^{(-H\cos\theta/6.85)}$ g/cm^2, where H is in km.

[2]The width for different values of A/A_m and the time distribution of the pulses in Fig. 1a are reduced to a time scale that corresponds to $R_\perp = 400$ m (see, for example, Ref. 2).

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