CHERENKOV RADIATION OF EXTENSIVE AIR SHOWERS*

Совместно с Н. М. Нестеровой

Short light flashes superimposed on the background of the night-sky glow, correlated with the passage of cosmic rays in the atmosphere, were first detected in 1952 [1, 2]. It was soon established that at least some of these flashes are caused by Cherenkov radiation of extensive air showers [3-5].

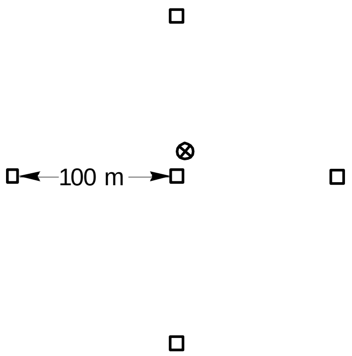

Fig. 1. - The arrangement of the hodoscope units. □ , hodoscope units, ⊗ , light receiver.

Further experiments in this direction were conducted by the authors in the autumn of 1955 in the Pamir Mountains (altitude 3860 *m*). The purpose of this work was to study the lateral distribution of the light flux relative to the core of the showers and also to investigate the relation between the intensity of the light flash and the size of the shower.

The arrangement included an optical receiver that registered the light flashes, and a Geiger counter hodoscope. The latter consisted of 5 units, each containing 96 counters (each counter of area 330 cm^2). The position of the units is shown in Fig. 1. The hodoscope was triggered at the instant of registration of the light flash. The hodoscope registers were photographed on film at all five units.

The point of incidence of the core and the total number of particles in the shower N were found for each shower of sufficient size, using the readings of all hodoscope units. This operation was carried out using the lateral distribution function of particle flux, which function was obtained in [6] and it was used only in those cases when not less than three counters in each unit were triggered in the central and at least in two periphery units. Given such a criterion that ensured sufficiently determined condition for the analysis of the hodoscope data, it was found possible to analyse showers with 10^5 or more particles, when the distance from the centre of the system to the shower axis did not exceed 150 *m* (for $N < 10^6$) and 250 *m* (for $N > 10^6$).

The optical arrangement consisted of eight light receivers. Each reciever consisted of a parabolic mirror at the focus of which the cathode of a photomultiplier tube (type FEU-19, diameter of photocathode 3.5 *cm*) was placed. The mirror of diameter 45 *cm* and focal length 19 *cm* had a front surface coated with an Al reflecting layer. The coincident pulses from two receivers, whose axes were oriented parallel to each other, were used to present a master pulse.

This made it possible to increase the stability of the system, especially in the case of a relatively low triggering threshold.

The master pulse which ensured the passage of pulses through all eight channels for subsequent recording was produced at the output of the coincidence circuit. This

---

* *Nuovo Cimento, vol.* ***8***, *Ser. X, Suppl., no. 2, p. 606 (1958).*

same signal operated the hodoscope. The resolving time of the electronic apparatus for measuring pulse amplitudes from the photomultiplier tubes, was $2 \cdot 10^{-8}$ *s*, and for the hodoscope of the Geiger counters it was $5 \cdot 10^{-6}$ *s*.

Thus, the intensity of the light flash in all eight receivers and the flux density of particles at five hodoscope units, were simultaneously registered.

Two series of measurements were made with this apparatus. In both cases, the two master receivers were placed in the centre of the hodoscope system and oriented vertically, which determined the vertical direction of the showers registered (in a solid angle of 1/40 *sr*).

The sensitivity of the light receivers was adjusted so that about 100 pulses per hour were registered. It turned out that, on an average, each flash was accompanied by triggering of twenty hodoscope counters, while the number of cases when no counter was triggered, was 4%.

Thus, it was established that practically all light flashes of a given intensity were produced by extensive air showers.

The number of events, when it was possible to determine the point of passage of the shower core, amounted to 10 per hour.

In all these cases, a determination was made of the distance from the shower axis to the light receivers, and then the magnitude of the pulses from the photomultiplier tubes was correlated with the distance from the shower axis, and with the total number of particles in the shower.

In the first series of measurements, six receivers were situated in different places at a distance of about 40 *m* from the centre, and were oriented vertically (just as for the master receivers). This made it possible in principle to determine for each shower the light intensity at various distances from the core. However, in this experimental arrangement errors of light intensity measurements proved so great that the results could not be used. These errors were principally due to a dependence of sensitivity of the light receivers on the angle of incidence of the shower. Since the cathodes of the photolmultiplier tubes were not uniform, the angular characteristics of the telescopes (the dependence of sensitivity on the angle of incidence of the light) were likewise not identical, especially in the region of angles close to the limit of the field of view of the receiver.

To reduce errors due to registration of inclined showers, in the second series of measurements the receivers were disposed as follows. Two master receivers remained as before, in the centre of the hodoscope system, and were oriented vertically. The remaining six were placed around the circumference at a distance of 2 *m* from the master receivers and were inclined at an angle of 5° to the vertical towards the center of the circle.

Thus, all receivers registered the intensity of the light flash practically at the same place, namely in the centre of the system, but on the other hand it was possible to estimate the angle of inclination of the registered shower from the ratio of the pulse amplitudes from different receivers.

In order to avoid errors due to inclined showers, we selected only those cases for which the angle of inclination was sufficiently small (not more than ($3 \div 4°$). The criterion for this was the requirement that the pulse amplitude in the vertical receivers should be at least not less than in any one of the inclined receivers.

To determine the intensity of the light flash use could be made both of the readings of the master and the inclined receivers. It was found that the most precise measure of the intensity of a flash is that corresponding to the sum of the pulse amplitudes in the six inclined receivers, which is apparently explained by a certain averaging of non-uniformities of the cathodes in this method of analysis.

During 80 hours of running, 230 showers were registered which satisfied the criterion of “verticality” and at the same time permitted hodoscope analysis. For each one of these, we know the total number of particles *N* and the intensity of the light flux φ at a certain distance *R* from the axis, which distance varies at random from shower to shower.

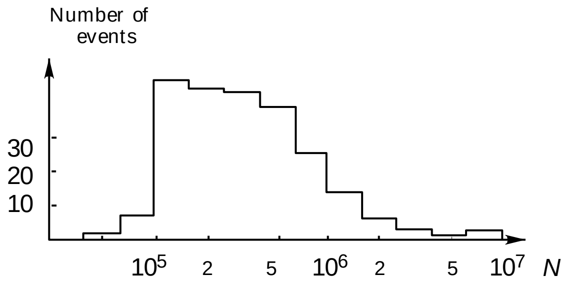

Fig. 2. - The shower size distribution of the events. N, the total number of particles in the

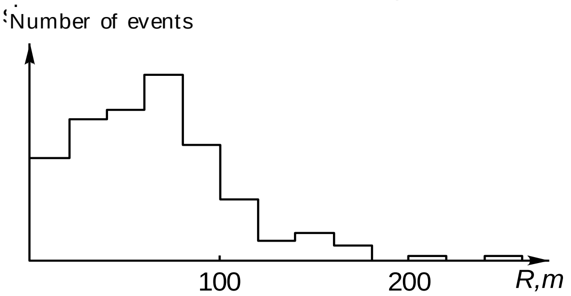

Fig. 3. - The distribution of the events with respect to *R*. *R*, the distance between the shower core and the light receiver.

Fig. 2 and 3 show the distribution of these showers according to *N* and to *R*. Because of the existence of hodoscope and optical “threshold”, large distances (R > 100 *m*) are represented principally by greater size ($N > 3 \cdot 10^5$), and small distances (R < 30 *m*) are naturally represented principally by showers of size $N < 3 \cdot 10^5$.

Correspondingly, data concerning the intensity of the light flux at small distances from the axis were obtained for showers with $N < 3 \cdot 10^5$, and at great distances only for showers with $N > 3 \cdot 10^5$ in the interval 30 *m* < R < 100 *m*. Showers from $N \approx 10^5$ to $N \approx 3\ 10^6$ are represented.

If we assume that the form of the lateral distribution of the light does not depend on the shower size, and the light intensity is simply proportional to the number of particles in the shower, namely

$$\Phi(R,N) = N \cdot \varphi(R,N) \qquad (1)$$

we may obtain the function $\varphi(R) = \Phi/N$ in the range of distances from 10 to 250 *m*, using for this purpose all registered cases, Fig. 4.

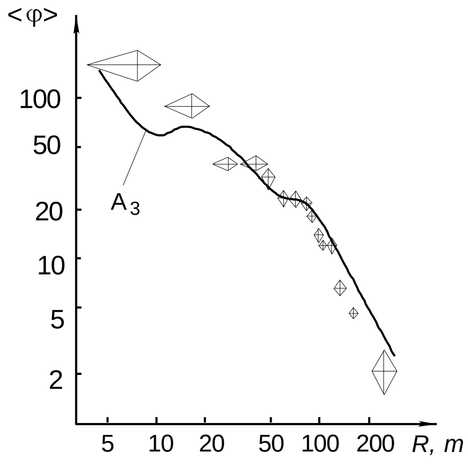

Fig. 4. - The lateral distribution of light intensity with respect to the shower core position. *R*, the distance from the core, <φ>, the average light intensity in arbitrary units. The solid line is one of the theoretical curves (suitably normalized).

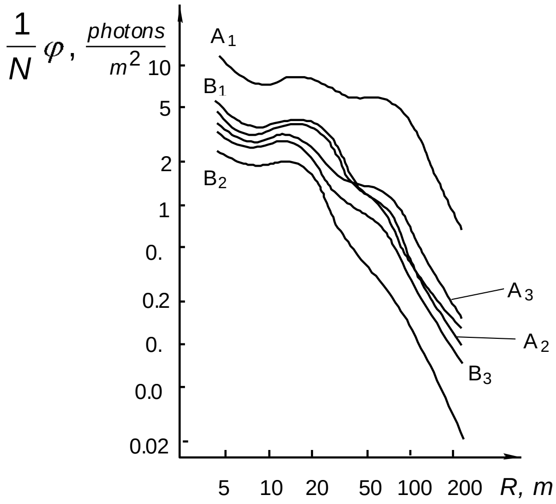

Fig. 5. - The theoretical lateral distributions of light for different models of shower development. Curves A_1 and A_2 correspond to the purely electromagnetic cascade with initial energy of electrons 10^{11} and 10^{13} eV. A_3 corresponds to a cascade curve of the type: $N(p) \sim p\ exp[1-p/p_0]$, $p_0 = 150\ g/cm^2$. Curves B_1, B_2, B_3 correspond to the same models of development of showers, but with the point of origin on the depth 200 g/cm^2 in the atmosphere.

In this same figure, the solid line denotes one of the theoretical curves shown in Fig. 5 appropriately normalized, normalization is necessary due to the fact that in these experiments only relative measurements of the light intensity were conducted. By suitable normalization it is also possible to reconcile approximately the experimental results with curves A_2, B_1, B_2, and B_3.

The errors of the experimental points in Fig. 4 are presented on the basis of the observed spread of $\varphi(R)$ for each interval *R*, taking into account the number of cases averaged. For all intervals of distances, the average deviation of the φ from the mean value at $R = const$ is of the order of a factor 1.5 ÷ 2 times.

These deviations (especially in the case of small *R*) may be explained to a certain extent by errors in the apparatus, but it is possible that they were mostly due to fluctuations in the development of the showers.

A trivial source of such fluctuations is a spread in altitude in the atmosphere, of the point of origin of the showers, which fact depends greatly on the cross-section of the interaction of the primary particle with the atomic nuclei of the air. It is possible that the subsequent development of the shower can also have fluctuations.

To get an idea of how variations in the form of the cascade curve, which describes the number of particles as a function of depth in the atmosphere, influence the intensity and lateral distribution of Cherenkov radiation, we calculated the function $\varphi(R)$ using several types of cascade curves. During the calculations it was found that the lateral distribution of light is to a large extent determined by the angular and lateral distributions of the electrons, and that, consequently, scattering cannot be neglected.

The effect of scattering is determined by the form of the energy spectrum of the electrons. To simplify calculations the spectrum was taken as constant (namely, equilibrium) throughout the depth of the atmosphere. This approximation corresponds to that made in paper [3]. Fig. 5 gives the results of calculations that refer to the level of observation at an altitude of 3850 *m*.

Curves A_1, A_2, and A_3 correspond to the origin of the shower at the top of the atmosphere, while B_1, B_2, and B_3 correspond to a depth of 200 g/cm^2.

The following cascade curves were taken.

1) The cascade curve for a purely electromagnetic development of a shower with initial energy of the electrons $E_0 = 10^{11}$ eV.

2) The same, but with $E_0 = 10^{13}$ eV.

3) $N \sim exp[-P/P_0]$, where P is pressure, P_0 =150 g/cm^2.

As is seen from Fig. 5, the displacement of the point of origin of the shower by 200 g/cm^2 leads (in the distance range 50 to 200 m) to a change of φ of several times, and for curves A_1 - B_1 even of 10 times.

Thus, the observed fluctuations of φ (by 1.5 to 2 times) can be explained if fluctuations of the depth of origin are less than 200 g/cm^2 .

It may be expected that it will be possible later to obtain in this manner valuable estimates for the cross-section of interaction of primary particles producing extensive air showers.

Another possible development of such experiments consists in the verification of the assumption (1), which is naturally valid only if the form of the cascade curve does not depend on the initial energy. Such a verification requires an extremely large quantity of statistical material, since in this case it is necessary to average over the relatively narrow intervals N and R.

The results obtained up to the present time are insufficient for such an analysis.

References

1. W. Galbraith and J. V. Jelley, Nature, **171**, 349 (1953).
2. J. V. Jelley and W. Galbraith, Phil. Mag., **44**, 619 (1953).
3. V. I. Gol’danskij and G. B. Zhdanov, JETP, **26**, 405 (1954).
4. N. M. Nesterova and A. E. Chudakov, JETP., **28**, 384 (1955).
5. J. V. Jelley and W. Galbraith: Journ. of Atmos. and Terr. Phys., **6**, 304, 250 (1955).
6. S. I. Nikol’skij and V. M. Selesnev, JETP, **32**, 1250 (1957).