Greisen: The angles of scattering of the electrons that emit Cerenkov radiation are 10°, on the average. How is it that you expect the Cerenkov detectors to have an angular resolution as small as 1°?

Zatsepin: If we use the detection with a given threshold, the contributions of different distances will be presented by the function:

$$\rho^{\chi}(r)\cdot r\cdot dr$$

were $\rho(r)$—lateral distribution of light, χ—the exponent of the spectrum of total light emission ($\chi\simeq1.7$). Because of this average distance from the core for detected showers should be much less than for average distance of light spread. This will lead to selection of photons emitted on small angles.

JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN Vol. 17, SUPPLEMENT A-III, 1962
INTERNATIONAL CONFERENCE ON COSMIC RAYS AND THE EARTH STORM Part III

III-2-10. Cerenkov Radiation Associated with Extensive Air Showers*

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The Cerenkov light flashes accompanying the passage of EAS through the atmosphere were studied at 200 m above sea level by means of telescopes with 4.9° half-opening angle, used in conjunction with an eight-tray hodoscope. Preliminary results show that the spectrum of events accompanied by a light signal is flatter than that of all showers in the range of $\sim10^5-5\times10^6$ particles. The light intensity per shower electron is found to decrease with increasing shower size, while the fluctuations in this quantity increase with the size. The lateral light distribution between 5–80 m, rather flat ($\sim r^{-0.7}$) for showers of $<2\times10^5$ particles, increases steeply with increasing shower size. It was possible to obtain information on the angular distribution of the Cerenkov light in EAS with respect to the shower axis as viewed from a given distance from the center of the shower. It was found that the light intensity falls off by half at 10°.

First results are presented of the Technion EAS experiment being carried out in Haifa at 200 m altitude to study the Cerenkov radiation emitted in the passage of charged EAS particles through the atmosphere.

Experimental method

An eight-tray hodoscope serves as the basic shower-detection system. Each tray contains sixteen Geiger counters of 207 cm² area each. The tray positions are shown in Fig. 1: the

* Supported in part by the Air Force Cambridge Research Center, Office of Aerospace Research, U. S. A. F., through its European Office.

** Part of the research for the degree of Doctor of Science.

array has an efficiency approaching unity for showers with $\sim 10^5$-2×10^6 particles at the observation level over an area of $\sim 2800\,\mathrm{m}^2$, with pockets sensitive to smaller and larger showers. A tray signal is received by the coincidence circuit whenever at least two counters have been discharged in it. (This condition reduces the rate of chance coincidences.) The results reported were obtained using as the array trigger the coincidence of signals from at least three trays simultaneously with a signal from a Cerenkov light detector, corresponding to ≥ 100 photons.

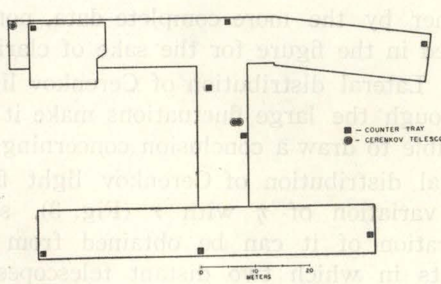

Fig. 1. Diagram of the EAS array.

Each shower was reconstructed from the hodoscope data by maximizing the function $P(k_i;\, N, x, y)$ giving the probability that a shower with a size between N and $N+dN$ particles, whose axis fell at a point with co-ordinates between x and $x+dx$, y and $y+dy$, produced the observed numbers k_i of counter discharges in each of the eight trays ($0\leq k \leq 16$, $i=1, 2, \cdots, 8$). The lateral distribution function used is the "exponential function" of the M.I.T. group[1]. The computations were carried out on the Wegematic 1000 digital computer, at the Weizmann Institute of Science, Rehovoth.

The Cerenkov light detectors used consist basically of a 61 cm parabolic mirror pointing at the zenith with a Dumont 6292 photomultiplier (40 mm photocathode diameter) at the focus. The telescope have a 4.9° half-opening angle. A 1:1000 dynamic range is provided for the photomultiplier pulses. A zener-diode logarithmic pulse amplifier[2] is used to compress this range for a 32-channel pulse-height analysis. Each photomultiplier was calibrated by measuring the average pulse height corresponding to the release of one photoelectron from the photocathode. Manufacturers' data were then used to convert the number to photoelectrons into the number of photons with wavelength corresponding to the peak of the spectral response curve (4400 Å).

The pulse-heights are indicated on "dekatron" counting tubes, whose properties have been used for the pulse-height analysis itself[3]. The hodoscope readings are also converted to pulse heights by adding signals from the counters discharged in each tray, and are analyzed and displayed uniformly with the photomultiplier pulses for photographic recording.

Results

The apparatus was in partial operation during Spring 1961. Full-time operation began in July. Utilizing all nights when the moon was not too close to zenith, it was possible to operate the telescopes for 17 nights during that month, averaging eight hours per night. This probably constitutes the maximum utilizable time per lunar month, attainable when the sky is clear of more than passing clouds. The rate of events was ~ 10 per night.

The following results were obtained:

a) Fluctuations in the light flux. The Čerenkov light-flux fluctuations were measured by closely placed telescopes. The distribution of the differences in the pulse heights recorded by the detectors in individual events was analyzed by the χ^2-test

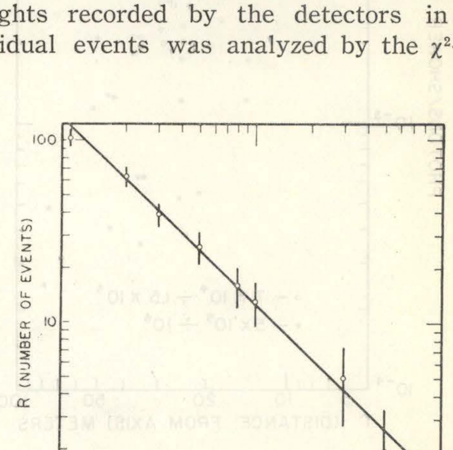

Fig. 2. Integral size spectrum of EAS coincident with a light signal. The straight line has slope close to -1.0.

and found to be consistent with a Poissonian density distribution in the light flux with superimposed fluctuations in photomultiplier response and errors due to finite channel width.

b) Size spectrum of showers accompanied by a light signal greater than the threshold. The spectrum of events satisfying the above-mentioned trigger requirements, based on a sample of 102 showers, is shown in Fig. 2. The showers were selected so as to lie in the size range for which the array is fully efficient, and within a relatively narrow distance from a telescope (25–40 m). This was done to avoid bias due to the fact that the detection efficiency of the telescopes presumably depends on the distance from the shower axis. It can be seen from Fig. 2 that the spectrum fits well a power law with a relatively small exponent ($\sim$1.0). This form of the spectrum is probably only a

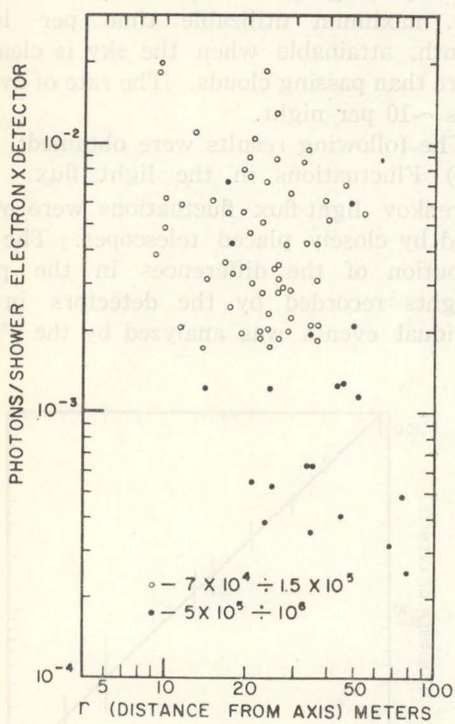

Fig. 3. Number of Cerenkov photons per shower electron detected, in individual events, by 4.9° telescopes at different distances from the shower axis.

○—EAS in the size range of 7×10^4—1.5×10^5 particles;

●—in the range of 5×10^5—10^6 particles.

convenient approximation in the range studied; the significant fact is that it is markedly flatter than that of all showers.

c) Čerenkov efficiency of showers. The number of Čerenkov photons per shower electron, detected by a telescope ("Čerenkov efficiency") is shown as a function of the distance from the shower axis in Fig. 3 for two shower size groups: 7×10^4-1.5×10^5 and 5×10^5-10^6. The fluctuations observed are larger than at mountain altitudes[4]. It can be seen that the fluctuations increase with the shower size, while the average efficiency decreases with it. These results are verified further by the more complete data, not included in the figure for the sake of clarity.

d) Lateral distribution of Čerenkov light. Although the large fluctuations make it impossible to draw a conclusion concerning the lateral distribution of Čerenkov light from the variation of η with r (Fig. 3), some indication of it can be obtained from the events in which two distant telescopes recorded a light signal. It was found that, in these cases, the ratio of the pulse heights recorded by detectors at two different distances from the shower axis is such that, when plotted to a log-log scale, the straight lines joining the points have a similar slope, equal to -0.71 ± 0.12 throughout distances from 5 to 70 m, for showers of 5×10^4-2×10^5 particles. Thus, the lateral distribution (based on 25 events) is rather flat, $\varphi(r)\sim r^{-0.7}$. Less data is available on larger showers: statistics based on 12 events in the range 2×10^5–10^6 (having a greater spread of slopes than the smaller showers) gives an exponent of -2.0 ± 0.4. Thus, we can only say that a change in the lateral light distribution occurs; its exact nature must be revealed by continued investigation.

Conclusions

From the rates of the coincidences between the Čerenkov detectors and the counter arrangement, information can be obtained on the angular distribution of the Čerenkov light. Since, at least to a good approximation, the total Čerenkov light intensity collected at any point is proportional to the number N of shower particles, we can, because of the smallness of the aperture, define a maximum zenith angle $\theta_m(r)$ by

$$h_r(\theta_m)=i_0/N \quad (1)$$

where $h_r(\theta)$ stands for the angular distribution of Čerenkov light with respect to the shower axis at a distance r from the center of the shower, and i_0 is the threshold intensity. The shape of the integral spectrum of the coincidences can then be written as

$$\Sigma(>N)=\int_N^\infty\int_0^{\theta_m} s(N)(m+1)\cos^m\theta \sin\theta d\theta dN \quad (2)$$

where $s(N)=AN^{-\gamma}$ is the differential spectrum of the showers recorded by the counter arrangement alone, and the $\cos^m\theta$-law is used for the zenith angle distribution of the showers. If we assume a $\cos^n\theta$-law for the distribution of the Čerenkov light, we derive from Eqs. (1) and (2)

$$\Sigma(>N_{\min})=S(>N_{\min})\left[1-\frac{n(\gamma-1)}{m+1+n(\gamma-1)}\right] \quad (3)$$

where $\Sigma(>N_{\min})$ and $S(>N_{\min})$ are the rates of the coincidences and of the counter arrangement alone, of events greater than the minimum size $N_{\min}$ which can produce light intensity greater than i_0. The preliminary analysis of the data already processed gives $n\simeq 44$. While the assumbe form of the angular distribution may de not very esthetic, the significant result is that Čerenkov radiation changes little for $\sim 2°$ from the shower axis, falls to 50% at 10°, and to $\sim 0.6\%$ at 20°.

The difference in the spectra of the coincidences and of all showers is readily understood as a consequence of the varying efficiency with which showers of different size are collected. The threshold intensity i_0 required by the Čerenkov detector will be attained by a larger shower even at an oblique angle of incidence, while events below a certain minimum size will not be accepted even when travelling vertically.

The same considerations explain qualitatively the observed increased fluctuations of the Čerenkov efficiency with the shower size: the zenith-angle interval of showers accepted is larger, and the limiting sizes of light flashes correspondingly differ more. Since the light intensity decreases rapidly with the angle, the average over such a wider interval decrease. However, there may be additional factors involved. The grouping of the points in Fig. 3 does not indicate clearly that a maximum efficiency η_0 independent of shower size exists as expected. This fact, together with the remarkable steepening of the lateral distribution of the light, indicates an apparent contradiction to the known fact that neither the lateral nor the angular spread of the electron component varies conspicuously within the size interval studied. However, it would be premature to draw final conclusions from the present preliminary results; the point must be considered in the analysis of the completed data.

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