PHYSICAL REVIEW VOLUME 124, NUMBER 4 NOVEMBER 15, 1961

Longitudinal Distribution of Čerenkov Light from Extensive Air Showers*

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(Received March 28, 1961; revised manuscript received August 15, 1961)

Measurements of the longitudinal distribution of the Čerenkov light associated with extensive cosmic-ray air showers of approximately 10^{15}-ev minimum energy are presented. These measurements are compared (1) with those of Bassi *et al.* resulting from their analysis of the electron component of extensive air showers and (2) with the distribution calculated by Monte Carlo techniques from Coulomb scattering of the shower electrons.

INTRODUCTION

THE production by extensive cosmic-ray air showers of easily detectable quantities of Čerenkov radiation in the night sky has been established by the work of Galbraith and Jelley[1–3] and others. This Čerenkov radiation is detected at the surface of the earth as a short duration light pulse accompanying the electronic component of an extensive air shower.

That the electronic component of an extensive air shower is primarily responsible for the Čerenkov light is seen by the following argument. At sea level the atmospheric refractive index sets the threshold energy for production of Čerenkov radiation by electrons at about 21 Mev and the shower electrons at this level have a mean energy on the order of 100 Mev. The increased energy thresholds for production of Čerenkov radiation by the heavier particles and their much lower abundances rule against these particles contributing appreciable light. For example, the μ-meson threshold energy is approximately 4.4 Bev. Therefore, since the Čerenkov radiation is produced in large measure by the electron component of the air shower, the characteristics reported here for the Čerenkov light are not expected to differ markedly from those determined for the shower electrons.

The primary purpose of this article is to report measurements of the longitudinal distribution of the Čerenkov light accompanying an extensive air shower. Bassi, Clark, and Rossi[4] have reported measurements of similar characteristics of the electron component of the showers. Their findings indicate that the electron component arrives at sea level in the form of a disk of mean thickness between one and two meters and with a lower limit of 1300 m to the radius of curvature of these disks. In the sense that the Čerenkov light is so directly connected with the shower electrons the measurements reported here are complementary to those of Bassi *et al.*, although as will be seen the present experiments permit a direct determination of (1) the photon density distribution through each shower disk and (2) a thickness spectrum of these light disks.

The measurements reported here were made between January 26, 1960 and April 4, 1960 at the Kitt Peak National Observatory in Arizona at 31°57′N, 111.6°W at an elevation of 2070 m.

In the following sections of this paper are discussed (1) the experimental apparatus used, (2) the treatment of the experimental data, (3) the Monte Carlo calculation of electron scattering, and (4) a calculation of the total energies of the showers recorded in this investigation.

EXPERIMENTAL APPARATUS

The longitudinal distribution of the photons in the Čerenkov radiation disk produced by an extensive cosmic-ray air shower was measured using a simple optical system in conjunction with a photomultiplier tube of low transit time spread and high current amplification, coupled directly to the deflection plates of a cathode-ray oscilloscope. The optical system consisted of a 16-in. diameter, 12-in. focal length spherical mirror. An RCA-7264, 14-stage, spherical photocathode, photomultiplier tube was positioned with the photocathode at the focal point of the mirror as indicated schematically in a block diagram of the apparatus in Fig. 1. The tube and mirror were surrounded by a light shield which together with the mirror system limited the angular acceptance of the detection device to approximately 0.03 steradian. Display of the pulses from the photomultiplier tube was made by direct connection via 197-ohm coaxial cable to the deflection plates of a Tektronix type 541 oscilloscope.

To insure that the longitudinal-distribution measurements of photon density would be made approximately normal to the leading edge of the Čerenkov light disk and to determine the approximate shower core location an array of four photomultiplier detection devices were placed about the RCA 7264 to measure the relative arrival times of the light disk. The detection devices in the roughly "square" array shown in Fig. 2 were similar

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* This research was supported in part by a grant from the National Science Foundation.

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[1] W. Galbraith and J. V. Jelley, J. Atmospheric and Terrest. Phys. **6**, 250 (1955).

[2] W. Galbraith, *Extensive Air Showers* (Academic Press, Inc., New York, 1958), Chap. 8.

[3] J. V. Jelley, *Čerenkov Radiation* (Pergamon Press, New York, 1958), Chap. 9.

[4] P. Bassi, G. Clark, and B. Rossi, Phys. Rev. **92**, 441 (1953).

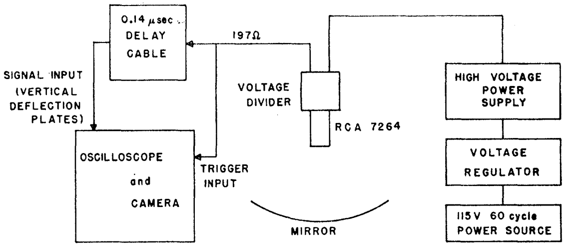


FIG. 1. Optical arrangements and block diagram of apparatus for measurement of longitudinal light distribution.

to that described above for the longitudinal measurement except that the rise-time requirements of this application allowed use of RCA-type 6810A photomultipliers. Signals from each of the four 6810A photomultipliers were individually directly coupled to the four pairs of deflection plates of two Tektronix type 551 dual-beam oscilloscopes. The horizontal deflection plates of the two cathode-ray tubes were connected in parallel to the horizontal amplifier of one of the oscilloscopes to provide synchronous horizontal sweeps for all four traces. An unblanking and sweep trigger signal for the oscilloscopes was obtained from cathode followers located in each of the four lines connecting the photomultiplier tubes to the deflection plates as indicated in Fig. 3.

All waveforms due to the passage of Čerenkov light disks were recorded photographically from the oscilloscope displays. Measurements of the relative delays of the four signals so obtained were used in conjunction with the site survey information of Fig. 2 to determine the light disk arrival direction.

A limited number of determinations of the radii of curvature of the leading edges of the light disks were made. These determinations were made by modifying the array of Fig. 2 so that detector 3 was located at the center point of the array. The four photomultiplier output signals from this roughly "triangular" array were also connected directly to the deflection plates of the two type 551 dual-beam oscilloscopes. Measurements of the relative delays of the four signals obtained from this modified array were used in conjunction with the site survey to make the radius determinations.

TREATMENT OF EXPERIMENTAL DATA

Figure 4(a) shows a typical set of four pulses produced by the arrival of a Čerenkov light disk at the four detectors of the array. The positions of these pulses along the 20 $m\mu$sec per major division sweep were measured to an accuracy of ±0.02 division using a Zeiss Opton microscope. The positions are a measure of the arrival times of the light at the detectors as modified by the differing photomultiplier transit times and signal cable transmission times in each of the four channels. Correction for these differing delay times was made by determination of the pulse positions for showers incident on the four detectors while all were located together at the center of the array.

As will be seen from the disk front radius data reported below and as is suggested by the similar Bassi *et al.* results on electron disk front radii, the arrival direction determinations may be made by approximating the light disk front by a plane surface over the area of the array. Using the corrected relative time delays for the "square" and "triangular" arrays and the appropriate survey information, the arrival directions were determined by a least-squares fit to a plane surface. These arrival direction determinations were used only to exclude from consideration those cosmic-ray showers detected which had produced light disk fronts with normals making an angle $\alpha>5$ degrees to the zenith. Less than 5% of the showers recorded were rejected on this basis indicating the efficiency with which the optical arrangements of the array select for vertical showers.

Using the corrected relative time delay data from 48 showers detected by the "triangular" array and the survey data the radii of curvature of these shower fronts were determined. These radii are uniquely determined from the corrected relative time delays of the four detectors under the approximation that $\cos\alpha=1$.

Figure 5 is a plot of the occurrence spectrum of the various Čerenkov light front radii for those showers possessing light disk front normals tilted less than 5 degrees with respect to the zenith. The plot is made as a function of $1/R$ so that all showers of very nearly infinite radius will appear together. In the limited sample of 48 showers recorded none with radii less than 1 km were observed while the majority have radii

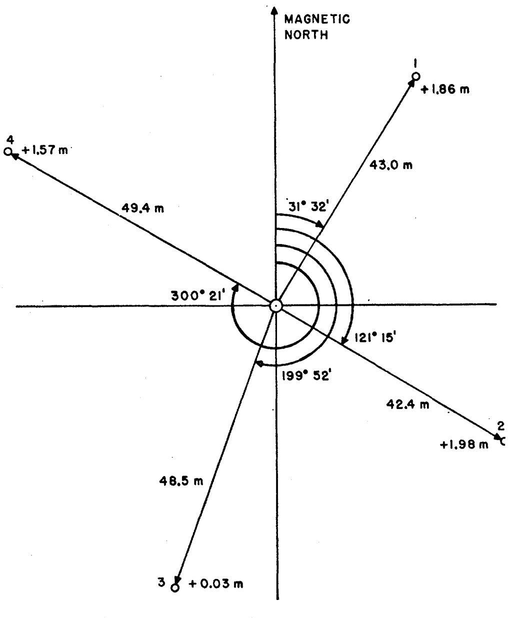


FIG. 2. Site survey of arrival direction determining photomultiplier array.

greater than 2 km. Thus the plane approximation of the light front is justified for the array size used.

Using the approximation that cos $\alpha=1$ but not the approximation of plane light front the timing data from the "square" array were used to determine the coordinates of the center of curvature and hence the approximate shower core location. The core locations of 84% of these showers fell within a circle of 5-m radius. Such a small range in core location was produced by requiring that all four pulse amplitudes from the array be of comparable size. An error propagation calculation was performed to estimate the accuracy of the core location determinations and the accuracy of these core locations was estimated to be ±5 m.

The photograph of a pulse from the RCA-7264 equipped detector due to the arrival of a Čerenkov radiation disk is shown in Fig. 4(b). A sweep speed of approximately 15 mμsec per major division was used. Such waveforms represent the longitudinal distribution of the Čerenkov photons in an extensive air shower modified by (1) the transit time spread of the photomultiplier tube, (2) the rise time of the oscilloscope tube, (3) the dispersion caused by the connecting signal cables, and (4) the nonlinearity of the oscilloscope sweep. Effects due to (1), (2), and (3) were determined by use of a millimicrosecond light pulser similar to that described by Kerns, Kirsten, and Cox.[5] Effects due to (4) were determined by use of a 50-Mc/sec sine wave generator for sweep calibration.

The pulse width at half maximum after correction for the four effects listed above was selected as a measure of the corresponding thickness of the Čerenkov light disk. Figure 6 is a plot of the occurrence spectrum of these pulse widths after the above corrections had been applied for disk fronts with normals within 5° of vertical. Pulse widths from 162 showers are shown in Fig. 6.

The occurrence spectrum indicates that the half intensity disk thicknesses are quite variable ranging from less than 0.3 m to 9 m. Not included in Fig. 6 are three showers of thicknesses between 11 m and 12 m. The most probable thickness is seen to be about 2 m and this thickness corresponds closely to that reported by Bassi *et al.* for the electronic component of showers. No correlation between pulse width and core distance was observed.

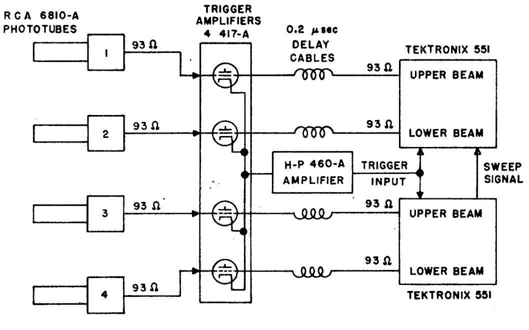
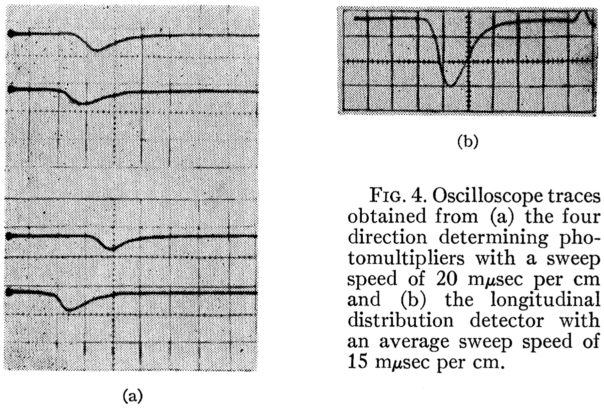


FIG. 3. Simplified circuit diagram of arrival direction determining apparatus.


(a)

(b)

FIG. 4. Oscilloscope traces obtained from (a) the four direction determining photomultipliers with a sweep speed of 20 mμsec per cm and (b) the longitudinal distribution detector with an average sweep speed of 15 mμsec per cm.

Most of the recorded Čerenkov light pulse shapes were similar to that shown in Fig. 4(b) indicating that under most circumstances the longitudinal light distributions and hence the electron distributions are similar. However, very occasionally a pulse shape substantially different from that shown was observed. The most common modification gave two peaks one of which may have been due to Čerenkov light production in the photomultiplier glass tube face by a shower electron. The few other differently shaped pulses have not as yet been subjected to careful study.

CALCULATION OF ELECTRON SCATTERING

To make an exact calculation of the effects of electron scattering upon the detected Čerenkov radiation it is necessary to know the relative light contributions from all altitudes. Results obtained elsewhere for the relative light intensities from different heights are in conflict. Cudakov and Nesterova[6] and Galbraith and Jelley[1] report appreciable contribution from great heights while White *et al.*[7] using detectors of wider acceptance angle report an upper limit of 20% contribution from heights above 800 m. Sufficiently detailed measurements of the relative contributions from various portions of the scattering path have not as yet been made.

In this paper the assumption is made that the light detected as described above is emitted by shower electrons at heights above the detector which are small compared with the total length over which Čerenkov emission takes place. Under this assumption it is meaningful to consider the total delays due to Coulomb scattering of the electrons as the cause of the observed disk thickness. A series of Monte Carlo calculations

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[5] Q. Kerns, F. Kersten, and G. Cox, Rev. Sci. Instr. **30**, 31 (1959).

[6] A. E. Cudakov and N. M. Nesterova, Suppl. Nuovo cimento **8**, 606 (1958).

[7] J. White, N. A. Porter, and C. D. Long, J. Atmospheric and Terrest. Phys. **20**, 40 (1961).

were performed in which electrons having the critical energy 84.2 Mev for air were incident upon various scattering thicknesses of atmosphere. The relative probabilities of various scattering angles were deduced from the Mott-Rutherford scattering cross sections, and the relative probabilities of various scattering lengths were deduced from the appropriate exponential scattering expression. The random selection of values from these two probability distributions was incorporated into the program of the Monte Carlo calculation which was performed on a Royal Precision LGP-30 computer.

Delay distributions of electrons which had undergone plural scattering were obtained by subtracting the vertical scattering distance from the sum of the electron path lengths. Calculations for several different atmospheric scattering thicknesses result in electron delay distributions which have the same asymmetrical appearance as the observed disk thickness distribution. Qualitative agreement is obtained with the atmospheric scattering thickness equal to the last 2.25 radiation lengths above the detectors and the normalized results of this calculation are shown as a set of points in Fig. 6.

Thus if a major part of the detected light is emitted by the shower electrons in the last scattering lengths the light pulse width spectrum can be accounted for by the electron scattering in the last 2.25 radiation lengths.

TOTAL SHOWER ENERGIES

The order of magnitude of the lower limit to the energy of showers detected with the present apparatus may be estimated from the rate of detection of light pulses and the detector geometry. The rate of detection of light pulses associated with showers arriving within the 0.030 steradian solid angle viewed by the apparatus and with pulse amplitudes greater than 2 v across the 200-ohm termination of the RCA-Type 7264 detector was 0.08 per min. Interpolating the results due to Galbraith and Jelley for the distribution of intensity of Čerenkov radiation to the 2070-m Kitt Peak elevation, the intensity is expected to be reasonably constant over a circle of 100-m radius. Thus the incident cosmic-ray flux is 1.4×10^{-10} cm^{-2} sec^{-1} sr^{-1}. This flux is expected for showers of energy $E\geq10^{15}$ ev.[8] Thus a pulse amplitude of 2 v in Fig. 4(b) is expected to be produced by a shower of roughly 10^{15} ev.

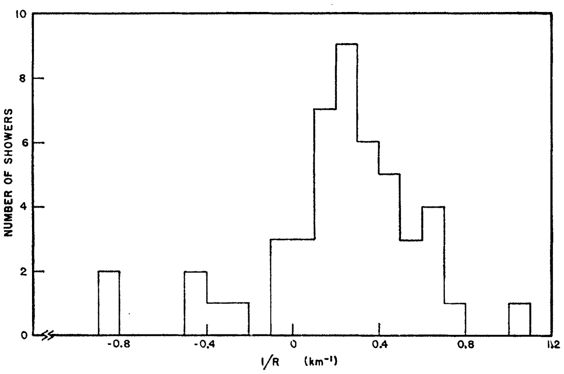

Fig. 5. Number of light fronts detected as a function of the reciprocal of the radius of curvature of the front.

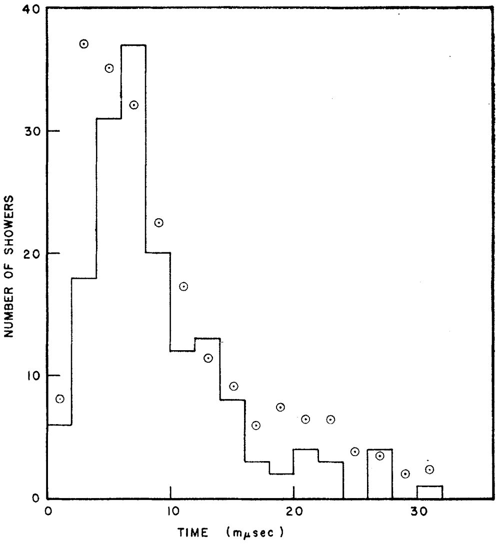

Fig. 6. Number of light fronts detected as a function of the thickness at half amplitude of the corrected voltage pulse. Circled points give normalized results of Monte Carlo calculation for electron scattering in the last 2.25 radiation lengths above detector.

ACKNOWLEDGMENTS

Due to the hospitality and kind assistance of Dr. A. B. Meinel and the staff of the Kitt Peak National Observatory the measurements at the mountain site could be carried out efficiently under pleasant circumstances. Dr. D. Schulte of the observatory staff performed many of the computer calculations of various shower parameters and his assistance is gratefully acknowledged. Many graduate and undergraduate students at Wesleyan University contributed to the work and it is a pleasure to thank them for their assistance. The contributions of N. H. Macoy were particularly valuable. W. Miglus performed many valuable tasks. The Monte Carlo calculation of the electron scattering was assisted substantially by William Jefferys.

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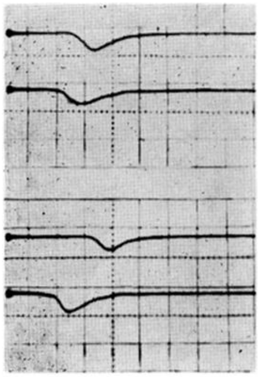
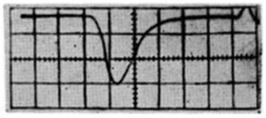
[8] G. Clark, J. Earl, W. Kraushaar, J. Linsley, B. Rossi, and F. Scherb, Nature **180**, 406 (1957).



(a)



(b)

FIG. 4. Oscilloscope traces obtained from (a) the four direction determining photomultipliers with a sweep speed of 20 mμsec per cm and (b) the longitudinal distribution detector with an average sweep speed of 15 mμsec per cm.