tory for Nuclear Science at M.I.T., and was supported in part by A.E.C. Contract A.T. (30-1)-2098, by funds provided by the U.S. Atomic Energy Commission, the Office of Naval Research, and the Air Force Office of Scientific Research.

References

1) W. Galbraith: *Extensive air showers*, Butterworth, London, (1958) 181-191.
2) J. V. Jelley: *Cerenkov Radiation*, Pergamon, London, (1958) 212-235.
3) M. H. Brennan, J. Malos, D. D. Millar, and C. S. Wallace: Nature, **182** (1958) 973.
4) J. White, N. A. Porter, and C. D. Long: J. Atmos. Terr. Phys. **20** (1961) 40.
5) A. E. Chudakov, N. M. Nesterova, V. I. Zatsepin, and E. I. Tukish: Proc. Moscow Cosmic ray Conf. **2** (1960) 50.
6) Caldwell: Proc. Belgrade Conf. on Nuclear Instrumentation. May 1961.
7) F. Barclay, and J. V. Jelley: Proc. Oxford Conf. on Extensive air showers, A. E. R. E. Harwell, (1956) 74.
8) L. Kh. Eidus, M. I. Adamovich, I. A. Ivanovskaya, V. S. Nikolaev, and M. S. Tulyankina: Zh. Eksper, Theor. Phys. **22** (1952) 440,
9) T. E. Cranshaw, J. F. De Beer, W. Galbraith, A. M. Hillas, S. Norris, and N. A. Porter: Phil. Mag. **3** (1958) 811.

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-2-12. Cerenkov Radiation from E.A.S.

J. MALOS, C. D. MILLAR
and O. S. WALLACE

School of Physics, University of Sydney*
Sydney, Australia

Exploratory experiments have been made using narrow angle detectors of the atmospheric Cerenkov light emitted by E.A.S. whose size, core location and direction of incidence were determined with a scintillator array. The results are consistent with a proposed interpretation which leads to the conclusions (i) that the angular distribution of the light is broad and is determined by the Coulomb scattering of the emitting electrons, (ii) that the Cerenkov light pulse received is to a first approximation proportional to the mean particle density integrated along the axis of the detector and (iii) that for such a detector close to the shower axis the maximum contribution to the detected light pulse from most of the detected showers is generated below an altitude of one kilometre.

Introduction

As has been pointed out by Chudakov[1] the Čerenkov radiation emitted by an air shower in its traversal of the atmosphere, together with its size on reaching ground-level, may be expected to provide information about the development of the shower through the atmosphere.

With this same purpose in mind experiments were commenced in Sydney in 1957. A directional Čerenkov detector was used consisting of one or more photomultipliers at the focus of a parabolic mirror staring into the night sky as part of the Sydney scintillator array. From this array were obtained the shower size, core location and direction of each shower recorded (Brennan *et al*[2]). With this apparatus light pulses were ob-

* Also supported by the Nuclear Research Foundation within the University of Sydney.

served at angles up to 30° to the shower axis indicating the importance of the Coulomb scattering of the emitting particles in determining the angular distribution of the light from a shower, as compared with the Čerenkov angle of emission of 1.3° at sea level.

To investigate further the angular distribution of the emitted light later experiments were made, also with directional detectors. These were consistent with the previous experiments and confirmed the wide angular distribution of the emitted light. Quantitative results, however, were of limited significance because of poor seeing conditions at the observing site and because of apparatus limitations.

Apparatus

Observations were made with the following two detectors:

i) A cluster of seven photomultipliers (E.M.I. 6260) at the focus of a parabolic mirror of diameter 110 cm, one central photomultiplier looking vertically, the other six with axes of their acceptance cones (each of half-angle 3°) at 7° to the vertical and at intervals of 60° in azimuth. Pulse heights were digitised and recorded on paper tape along with other data from the scintillator array, whose response to the incident air showers triggered the recording apparatus.

ii) A single photomultiplier (Dumont 6364, with photocathode stopped down to 3 cm diameter) at the focus of a 60 cm diameter mirror. The acceptance cone was again of half-angle 3° and the optic axis vertical. Pulses were recorded on a fast oscilloscope along with a timing reference pulse provided by one of the four scintillators used to obtain shower directions by the M.I.T. method.

Observations

It may be readily shown[2c] that for a directional detector with vertical axis and of half-angle ε, and with a mirror of area a, the expected contribution to the Čerenkov light pulse from a height h, dh above the detector is proportional to $f(\theta)a\varepsilon^2\overline{x(h)}dh$ where $f(\theta)d\omega$ is the angular distribution relative to the shower axis of the emitted light—for the particular case of a vertical-looking detector θ is also the zenith angle of the shower (fig. 1)—and $\overline{x(h)}$ is the mean density of emitting particles over the cross-section of the acceptance cone of the detector at height h. Provided $f(\theta)$ does not vary over the shower front—and since the threshold energy for Čerenkov emission by an electron at sea level is only 21 Mev, this is not unreasonable—the total light pulse received will be proportional to $f(\theta)a\varepsilon^2\int_0^\infty \overline{x(h)}dh$. Using the shower structure function $x(r)=(N/2\pi r_0)\exp(-r/r_0)/(r+1)$ m^{-2} this integral was computed on SILLIAC for each of the 7 detecting channels and for each shower whose core location, size and direction were known. The averaging of the density was performed by dividing each of the seven acceptance cones into seven smaller cones of equal solid angle. The total integral

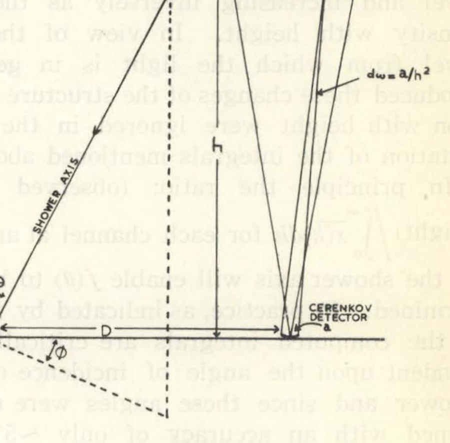

Fig. 1.

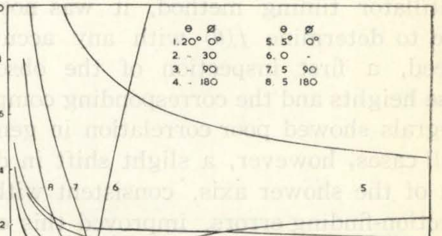

Fig. 2.

for each channel was computed, the height of the maximum contribution to that integral and the angle between the optic axis and the shower axis.

Illustrative of the results of such a computation is figure 2 which shows $x(h)$ as a function of h along the axis of a vertical detector for showers all of one size with core falling 30 m away from the detector and for different angles of incidence. It will be noted that the maximum contribution to the pulse height in general comes from heights below 1 Km since, from considerations of solid angle, few near-vertical showers are ever detected. This conclusion has also been reached by White *et al*[3] from their experimental observations.

The computations leading to figure 2 were carried out on the assumption that the shower size N occurring in the above structure function increases with height with an attenuation length of 190 gm cm^{-2} and the increase in the spread of the shower with height is accounted for by taking $r_0=75$ m at ground level and increasing inversely as the air density with height. In view of the low level from which the light is in general produced these changes of the structure function with height were ignored in the computation of the integrals mentioned above.

In principle the ratio: (observed pulse height) $\big/ \int_0^\infty \overline{x(h)}dh$ for each channel at angle θ to the shower axis will enable $f(\theta)$ to be determined. In practice, as indicated by figure 2, the computed integrals are critically dependent upon the angle of incidence of the shower and since these angles were determined with an accuracy of only $\sim 5°$, the errors produced largely by transit-time fluctuations in the photomultipliers used in the scintillator timing method, it was not possible to determine $f(\theta)$ with any accuracy. Indeed, a first inspection of the observed pulse heights and the corresponding computed integrals showed poor correlation in general; in all cases, however, a slight shift in direction of the shower axis, consistent with the direction-finding errors, improved this correlation considerably.

With the second detector, pulse shapes and delays relative to the arrival of the shower front at the light detector were investigated. Light entering a vertical-looking detector which has been produced at a height h above the detector will be delayed by a time $h(1-\cos\theta)/c$ after the arrival of the shower front at the detector. The light pulses however were all observed to have rise-times ~ 20 nanoseconds and widths ~ 50 nanosec. These observations were found to be entirely consistent with the measured transit-time fluctuations in the photomultiplier. Delays between arrival of the light and of the shower front at the detector were looked for: 43 showers for which $90° < \phi < 270°$ (figure 1) and 24 showers with $|\phi| < 90°$, $\theta > 5°$ and pulse height less than about 1000 photons had these delays measured. The respective mean delays were -1.0 ± 1.8 nanosec and $+3.8 \pm 2.3$ nanosec, consistent with the expected effect but scarcely of significance except as indicating the degree of simultaneity of arrival of shower front and light at the detector and therefore indicating also the validity of the method of measuring shower directions by the timing method applied to atmospheric Čerenkov detectors as used by White *et al*[3].

The zenith angle distribution of showers with a detected Čerenkov pulse larger than about 300 photons was found to be narrower (median angle 12°) than that of all showers (median angle 21°), confirming earlier results. This result is qualitatively to be expected, even assuming isotropic distribution of the emitted light, from the analysis already given: small showers incident in the near-vertical direction may give as large a pulse as do larger showers traversing the optic axis at large angle. The *effective* acceptance angle of the detector on the other hand is considerably greater than the opening angle of the acceptance cone: as in earlier experiments light pulses were received from showers of quite large zenith angle—up to 40°.

The above observations were made on showers of size in the range 10^5 to 10^6 particles. The Čerenkov light pulses were estimated to be in the range of 300 to several thousand photons. Absolute magnitudes are however of doubtful significance since it was observed that the varying opacity of the city smog at the observing site in Sydney affected considerably the frequency from one night to another with which Čerenkov pulses were detected.

Conclusion

The experiments reported here were all carried out with directional detectors and were regarded as exploratory only. It appears that further experimental observations could be better carried out with the technique described by Porter and Hill[4], and indeed one may regard the multi-element device described in this paper as a crude approximation to the instrument described by these authors, an instrument which has a wider angle field of view and finer angular resolution within that field of view than had the instrument used by ourselves. If further development of the elegant technique of these authors permits measurement of the variation of the light intensity over the field of view of the instrument it may be possible to examine the angular distribution of the emitted light, $f(\theta)$, to distinguish between the light generated at low and at high altitudes, and to gain information about shower development, less ambiguously than is possible with photomultiplier detectors such as we have used.

Acknowledgements

It is a pleasure to acknowledge the support of Professor Messel and of the Nuclear Research Foundation which made this work possible, also the assistance provided by Dr. M. H. Brennan and other members of the air shower group and by members of the Basser Computing Laboratory.

References

1) A. E. Chudakov, N. M. Nesterova, V. I. Zatsepin, and E. I., Tukish: Proceedings of the Moscow Cosmic Ray Conference, I. U. P. A. P. Moscow **2** (1960) 50.
2) a) M. H. Brennan, J. Malos, D. D. Millar, and C. S. Wallace: Nuovo Cimento Supplement No. 2, **8** Ser. X, (1958) 662.
b) M. H. Brennan, D. D. Millar, and C. S. Wallace: Nature **182** (1958) 905.
c) M. H. Brennan, J. Malos, D. D. Millar, and C. S. Wallace: Nature **182** (1958) 973.
3) J. White, N. A. Porter, and C. D. Long: Journ. Atmos. and Terr. Physics, **20** (1961) 40.
4) D. A. Hill, and N. A. Porter: Nature **191** (1961) 690. N. A. Porter, and D. A. Hill, III-2-11 of the present Proceedings.

Discussion

Wolfendale, A. W.: I should like to ask Millar a question. Is not $f(\theta)$ a function of height in the atmosphere, because of the variation in electron energy (and scattering) and consequent change in angular distribution?

Millar, D. D.: Since for the majority of showers we detected, the Čerenkov light was produced from altitudes less than 1 km, the variation of $f(\theta)$ was not considered.

Wolfendale: Is the reduction in Čerenkov efficiency for Kasha's showers of high N due to the increase in mean energy of the electrons and the reduction in angular spread of the Čerenkov radiation, arising from the reduction in scattering?

Kasha, H.: The decrease in the Čerenkov efficiency with increasing shower size can, at least in part, be attributed to the fact that larger showers are accepted over a greater zenith angle interval. Inclined showers, however, produce small light intensities, which lower the average. The reason Wolfendale mentions may constitute a contributory cause.