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# OBSERVATIONS OF EXTENSIVE AIR SHOWERS BY AIR FLUORESCENCE
# RESULTS OF THE MEASUREMENTS

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The production of scintillation light in air by air showers has been observed using a prototype of the Utah "Fly's Eye" at Volcano Ranch. Shower size measurements from simultaneous observations made with the optical system and the EAS array are presented. As expected, light production was found to peak at small emission angles (<30° relative to the shower axis ) due to Cherenkov light. At larger angles (>45°) light production is only weakly dependent on the emission angle. The amplitude of the light production agrees roughly with expectations based on the sizes measured by the Volcano Ranch Array.

## 1. Introduction

This paper presents results of the comparison of light production by EAS to measured shower sizes. The optical apparatus was designed to detect light produced by air fluorescence, thus enabling the apparatus to detect showers at large distances and at large light emission angles (measured between the direction of the shower's motion and the direction of the observed light rays). This work was done in November 1976 at Volcano Ranch Array with an optical system consisting of 3 of the 67 mirror units being produced for the Utah Fly's Eye EAS detection system. In other papers in these proceedings, details of the experiment are presented by Mason et al. (1977) and the sensitivity of the system is analyzed by Cassiday et al. (1977). This paper concentrates on the analysis of the sizes of the observed showers and on the properties of a sample of 20 showers which were detected by the Volcano Ranch EAS Array, but which were not detected by the optical system.

Before discussing the treatment of the data, a description of the sources of the observed light is useful. A major source of light is air scintillation or fluorescence produced by the charged particles passing through the air.

This light is emitted isotropically and the production is only weakly dependent on altitude when expressed in terms of photons per meter per particle. This weak dependence results from competition between increased ionization per meter and increased losses of energy by means other than fluorescence at higher air densities. A second major source of light is the Cherenkov process. A particle travelling at more than the local (altitude-dependent) speed of light emits photons almost in the direction of the particle's motion. The angular distribution of electrons with more than the threshold energy is sharply peaked about the direction of the shower. This light can be received directly by the optical system or it can be received after a scattering of the light by air molecules (Rayleigh scattering) or aerosols (Mie scattering). The beam of Cherenkov light increases as the shower passes through the atmosphere, so that, neglecting losses from scattering, the scattered Cherenkov light depends on a certain integral over the earlier development of the shower. The above processes are expected to be significant sources of produced light from EAS, although aerosol-scattered Cherenkov light may be minimal under favorable atmospheric conditions.

## 2. Determination of Shower Sizes

The Volcano Ranch Array (VRA) measured shower sizes, shower direction zenith and azimuthal angles, and core locations for large EAS falling within the array area. The optical shower detector (OSD) was located 1530 ± 30 m from the center of the VRA and measurement results were printed for events which triggered both the VRA and the OSD. There were 44 such events. Of these, 16 were judged to be "reconstructable" using the OSD data. The selection of these events was partly subjective but, roughly, events were selected in which at least three photomultiplier tubes could be classified as "active" and "interior" as defined below. Active tubes are defined as tubes in which an above threshold signal was detected in a given event. Interior tubes are those which are not on the upper or side edges of the OSD aperture. In addition, photomultiplier tubes in which the signals were less than 1.5 times the threshold signal were not included in the shower size determination because the response of the electronics was irregular very near the threshold. After this cut was applied to the data, 15 events remained for the size analysis.

The next step in the analysis was the conversion, for each tube in each event, of the integrated charge collected at each tube's anode to a quantity of photons incident upon the mirror. The factors entering this conversion are analyzed by Cassiday et al. (1977). Then the trajectory of the shower was used to convert this signal into an apparent number of electrons, $N_i$, which would produce the observed amount of light <u>if only scintillation light is present</u>. The quantity $N_i$ is observed within the aperture of the i'th tube along the shower trajectory.

The maximum angular aperture of each tube is 0.10 radians and the distances from the shower are often as short as 1 Km so the width of the light-producing region often exceeds the aperture of a single tube. The shower images are frequently 1, 2, or even 3 tube apertures wide. The procedure of adding together the contributions of the various tubes starts by defining a large number (100) of evenly spaced points spanning the OSD aperture along the shower's fitted trajectory. At each such point, a cross section of the track is taken and the $N_i$ values for all active tubes within this cross section are added, forming a rather irregular histogram of the measured shower sizes. The resulting distribution is shown for Event 14 by the small points in Fig. 1. (Some of the points are covered by the bars described below.)

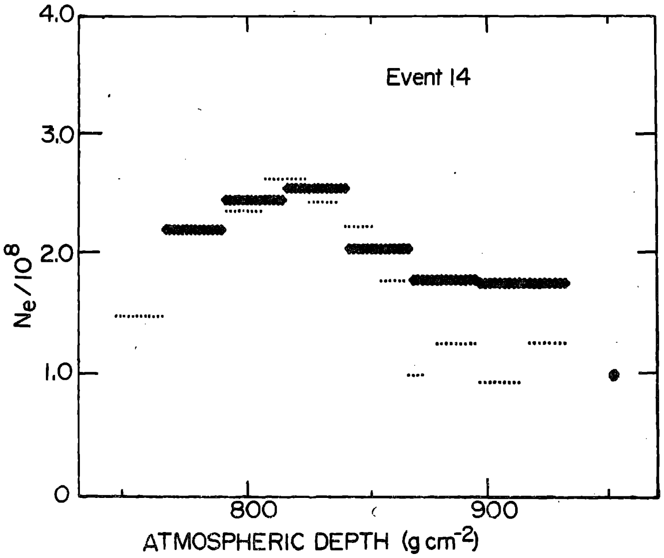

Fig. 1. Measurements of the shower size versus atmospheric depth for a shower observed with both the optical shower detector (small dots and bars) and the Volcano Ranch Array (heavy point at right). The optical measurements are calculated using fluorescent light only. (See text for details.)

Often a track from a shower that is near the detector is only one tube wide although light is received from a wider angular region. This occurs when adjacent tubes receive light but are below threshold. A procedure has been found which adjusts the measurements to compensate for this "lost" light. The amount of lost light can be estimated by considering the cases in which a track shifts from a width of 2 or 3 tubes perpendicular to the shower to a width of one tube. A correction should adjust the size of the shower in the region where the track is one tube wide to be about the same as the size of the adjacent part of the shower in which the track is 2 or more tubes wide. For regions of the track which are one tube wide, the correction procedure is to multiply the size measurements by D/250 meters, where D is the width of the part of the shower within the tube's aperture. The correction factor is not allowed to be greater than 1.6 or less than 1.0. The parameters of this adjustment (250 m and 1.6) were obtained by a fit to the measurements.

In order to obtain a shower curve which is relatively unaffected by such irrelevant accidents as tube aperture boundaries, the following procedure is used to condense the data into a whole number of effective measurements. The total angular extent of the usable data from each shower in the OSD is divided into the nearest whole number of tube apertures. Then the average size is obtained in each such interval by averaging the data (as adjusted above) occurring in the interval. The 6 resulting effective measurements for Event 14 are shown by the solid bars in Fig. 1. Let us call these measurements the "apparent optical sizes." Note that points on the right side of the figure have been corrected upwards by the shower width correction discussed above. The solid heavy point at the far right in the figure shows the size measured of the VRA for this shower.

## 3. Results of the Size Measurements

As an indication of the relative contributions to the optical signal from scintillation and Cherenkov light it is useful to plot the ratio of the apparent optical sizes to the VRA size for each event as a function of the light emission angle, θ, between the shower's direction and the direction the light travelled to reach the OSD. Fig. 2a shows this distribution. The first thing to note is that a curve is defined reasonably well by the set of measurements.

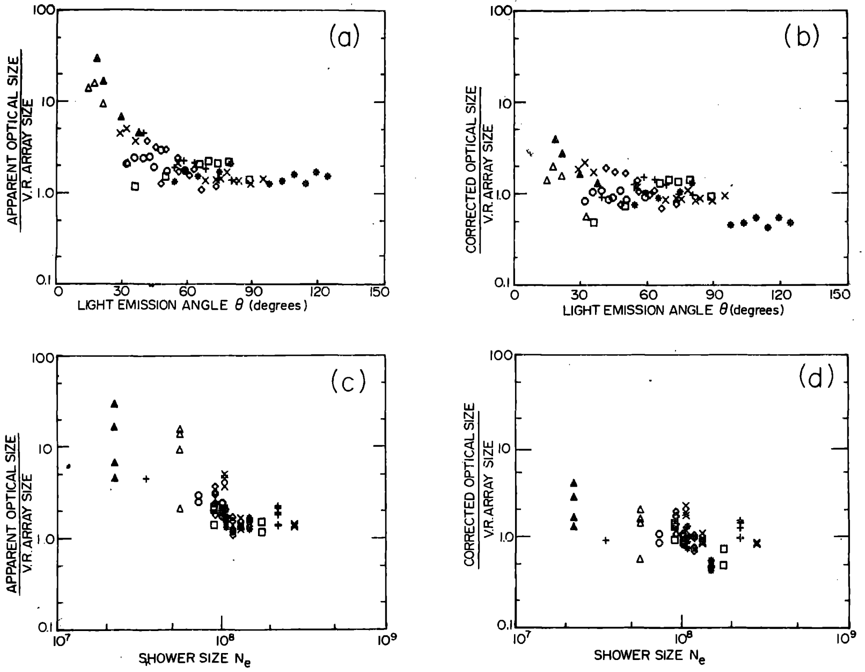

Fig. 2. Comparison of sizes from the optical shower detector to those from the Volcano Ranch Array for 15 showers. The dependence on the light emission angle is shown in a and b, and the dependence on the VRA sizes is shown in c and d. Optical results are converted to shower sizes in a and c using scintillation light only (apparent optical size) and in b and d using both scintillation light and estimated Cherenkov light (corrected optical size).

Thus, knowledge of the light emission angle and the apparent optical size can be used to determine the VRA size reasonably well.

The distribution is approximately independent of angle for angles above 45°. This supports the expectation that direct Cherenkov light is not significant in this angular region. A large peak is observed in the light production at angles less than 30°, presumably due to Cherenkov light. Beyond 45°, ratios of apparent optical size to VRA size exceed 1.0. A possible cause of this discrepancy is indicated below.

A computer calculation has been done to evaluate the importance of the scintillation light, direct Cherenkov light, and Rayleigh-scattered Cherenkov light. Aerosol (Mie) scattering was neglected. The showers were assumed to vary in size with depth according to calculations using Feynman scaling and assuming the primary cosmic rays are iron nuclei. This assumption, together with the VRA measurements, completely specified the showers' development, neglecting fluctuations. Angular distributions of shower electrons were taken from the tables of Messel and Crawford (1970). The Rayleigh-scattered Cherenkov light was evaluated and found to yield a significant contribution to the total received light. For each observation in each shower, the absolute number of photoelectrons was calculated. The ratios of the observed number of photoelectrons to the calculated number are shown in Fig. 2b. The ratios are also equivalent to "corrected optical sizes" divided by VRA sizes. For intermediate angles, the ratios are clustered about 1.0. The drop in the ratios beyond 90° is due to measurements on a single event. This shower may represent a major fluctuation from average conditions rather than a downturn of the distribution in this angular region. Even after the estimated effects of Cherenkov light have been removed, extra light appears to have been received in 3 or 4 events at small light emission angles. This excess may be due to an underestimate of the angular width of the Cherenkov light, neglected aerosol scattering or other systematic effects.

Fig. 2c presents evidence of a bias in the event sample which was studied. The smaller size showers have a high ratio of the apparent optical size to the size measured by the VRA. Showers of a small size which otherwise might not produce a track in the optical system can be detected if they occur in the detector's aperture with small light emission angles. This is because of the large quantity of Cherenkov light occurring at small emission angles and because the electronic pulses are short in time but high in amplitude under these circumstances and these pulses are more likely to be above the voltage threshold required for detection. Thus the smaller showers tend to be detected at smaller light emission angles and at higher ratios of apparent optical size to VRA size. Because of the steeply falling primary cosmic ray spectrum, fluctuations of small showers which allow them to be detected may be important. The estimated effects of Cherenkov light (both direct and Rayleigh-scattered) have been removed in the results plotted in Fig. 4d.

## 4. Comparison of Observed and Missed Events

Another result of the measurements is the threshold light level, above which events are detected with high probability. The "detectability" of an event is approximately dependent on three parameters. These are the impact parameter of the shower, $R_p$, (i.e., the perpendicular distance from the detector to the shower axis), the size of the shower, $N_e$, and the emission angle, $\theta$, for light received from the shower. The charge, Q, produced by the photomultiplier tube is proportional to $N_e/R_p$ (see Cassiday et al. 1977). This charge is received in a time, T, proportional to $R_p/(1+\cos\theta)$. The pulse amplitude is proportional to the current Q/T and is therefore proportional to $N_e\ (1+\cos\theta)/R_p^2 \equiv D$. Thus, the quantity D is a rough gauge of the detectability of an event with a fixed threshold amplitude.

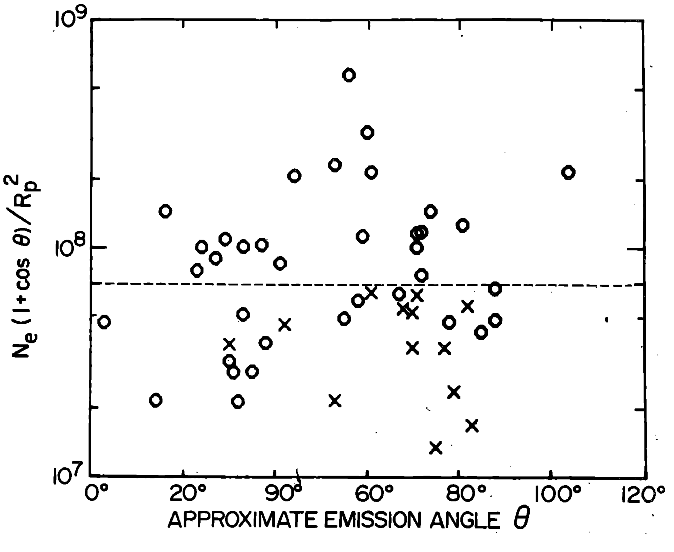

Fig. 3. Distribution of the approximate optical "detectability" of showers in this experiment. The symbols are defined in the text.

A sample of 20 events missed by the OSD were analyzed using the VRA data.

These appeared to be the most likely candidates for detection in the OSD based on measurement results from the VRA. Of these events 13 passed through the aperture of at least 2 photomultiplier tubes of the OSD and were candidates for triggering the OSD. The quantity D has been calculated for these events and the values are plotted as crosses in Fig. 3. Also plotted are the events which triggered the OSD and satisfied the aperture requirements. None of the missed events have $D > 7 \times 10^7$ km$^{-2}$. This value represents the level above which events are detected with high probability by the OSD.

It is useful to compare the value $D_o = 7 \times 10^7$ to the expected response of the system. The direct current levels in the photomultiplier tube correspond to about 6200 photoelectrons/μs due to the background light at Volcano Ranch. The time interval in which signals are integrated is about 1 μs so the r.m.s. noise level is about 80 photoelectrons. The value of $D_o$ corresponds to about 590 photoelectrons assuming 4 photons of light are produced per particle per meter. (In reality, the shower width reduces the received light in each tube and Cherenkov light increases it relative to 4γ/m.) The signal to noise ratio at this threshold is thus about 7. This is just somewhat above the signal-to-noise ratio of 5 that is required at threshold if the accidental coincidences in the mirrors are to be negligible. Thus the sensitivity of the Fly's Eye prototype is about what it would be expected to be for the measured background light levels.

## Conclusion

The results presented here demonstrate the capability of optical systems to detect, reconstruct, and measure the sizes of remote extensive air showers. The Fly's Eye system under construction is expected to greatly improve upon the capabilities demonstrated by the prototype. Note that the value $D_o$ is not the theoretical sensitivity limit for all locations or for all impact parameters. The light levels at Volcano Ranch are elevated due to the city lights of Albuquerque. Also, optimal threshold levels and light pulse integration times depend on the shower impact parameters and values of θ. In conclusion, the study of EAS by remote optical systems is very promising.

## Acknowledgements

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## References

Cassiday, G. L. et al. 1977, accompanying paper in these proceedings.
Mason, G. W. et al. 1977, accompanying paper in these proceedings.
Messel, H. and D. F. Crawford 1977, Electron-Photon Shower Distribution Function, Pergamon.