Measurement of Light Emission from Remote Cosmic-Ray Air Showers

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Extensive air-shower trajectories and sizes (numbers of charged particles) have been measured using an optical detection system at Volcano Ranch Station near Albuquerque, New Mexico. Light produced by atmospheric scintillation and Cherenkov emission by shower particles was measured at distances of 0.7 to ~10 km. The shower sizes determined by the optical measurements are in satisfactory agreement (an average of 10% higher) with measurements by the ground-level scintillation-counter array at Volcano Ranch.

Ultrahigh-energy (>10^{16} eV) cosmic rays are potentially useful for studying high-energy nuclear interactions. Up to now, the combination of small incident flux and limited detector size has prevented the full exploitation of this potential. In 1965, Greisen[1] described the possibility of detection of remote air showers by optical methods, a scheme which would enable a detector to have an effective viewing volume of ~10^{13} m^3, but subsequent attempts[2-4] to use this method were unsuccessful. In this Letter we report measurements of light production by distant air showers, using an optical system consisting of three "mirror units" described below. A system consisting of 67 such units, having a full-sky field of view (about 6 sr), is being constructed near Dugway, Utah.[5]

Remote optical detection of air showers is possible because shower particles (primarily $e^{\pm}$) excite nitrogen molecules which subsequently emit light isotropically. Although the energy loss per meter in air increases with increased pressure, deexcitation by molecular collisions rather than scintillation also increases with pressure. As a result, the light production per meter per particle is almost (within ~10%) independent of pressure.[6] Shower particles travel in a relatively small "packet" at practically the speed of light, thus forming well-defined trajectories. Consequently, shower distances and sizes can be found without undue reliance on calculations based on models.

In this experiment an optical system consisting of three 1.5-m-diameter $f/1.0$ mirrors and 36 photomultiplier tubes (12 per mirror) was positioned 1.53 km from the center of the ground-level scintillation-counter array (hereafter denoted SA) at Volcano Ranch, New Mexico.[7] The optical system was pointed toward the SA so that its field of view passed just above the ground-level counters as shown in Fig. 1. Hence, most

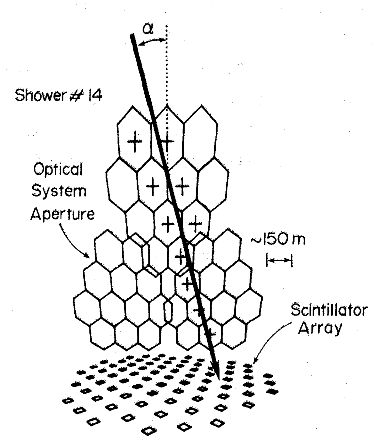

FIG. 1. Projection of the aperture of the optical detector onto a vertical plane above the center of the Volcano Ranch scintillator array. A reconstructed shower trajectory is indicated by the heavy line. Crosses denote phototube apertures in which a signal was detected.

air showers falling within the SA passed through the aperture of the optical system. The optical system was operated in coincidence with the SA in order to determine (1) whether remote optical sensing of air showers is possible, and if so, (2) whether the optical signals agree with expectations based on shower sizes and trajectories obtained with a conventional counter array.

The spherical mirrors were aluminized on the front surface. In each mirror's focal plane a cluster of twelve aluminized-plastic, hexagonal-faced funnels helped gather light onto the uv-sensitive, 90-mm-diam cathodes of EMI 9861 B photomultiplier tubes. The maximum angle subtended by a funnel-phototube combination was 5.8°. Before and after the experiment the cathode efficiencies (~23% at 3900 Å) and gains of the phototubes were measured in the laboratory. During the experiment the optical sensitivities were monitored for each phototube using a single, stable light pulser coupled to the mirror units by optical-fiber cables. The integrated pulse heights and signal-arrival times were stored, and later printed, for all showers which triggered the SA and also the optical system.

A total of 44 showers was registered by both systems in twelve consecutive nights of operation (~100 h). Shower sizes and trajectories were calculated in the usual manner from data given by the SA.[7] The sizes ranged from 1.3×10^7 to 6.2×10^8 particles; the shower energies, from $\sim5\times10^6$ to 2.5×10^{18} eV. The apparent brightness of each shower was calculated directly from the optical-pulse integrals. However, the intrinsic brightness could be obtained only for 15 showers with signals well above threshold and tracks well within the apertures of the top mirror unit and one of the bottom ones (see Fig. 1). The determination of a shower trajectory from the optical data involved a two-step fitting procedure. First, the location of the shower-detector plane in space was determined by fitting a straight line to the phototube data of Fig. 1. Next, the shower's impact parameter R_p and ground impact angle ψ (see Fig. 2) were determined from the arrival-time measurements plotted in Fig. 3. In order to determine both R_p and ψ from the optical data it is necessary that there by significant curvature in the graph illustrated by Fig. 3. Since a given shower could pass through the aperture of no more than two of the three mirror units, the field of view was so small that little curvature was present; so fits were made possible by constraining the trajectories to pass through the point of impact of the shower core with the ground, as determined by the SA. Comparison of shower trajectories so obtained with those determined independently by the SA yielded average differences of magnitude 4.8° in the projected zenith angle α (see Fig. 1), and of magnitude 8.6° in the angle ψ. Both values are consistent with the estimated combined angular resolutions of the two systems.

After reconstruction of the trajectories, shower sizes were evaluated from the optical data and compared to the SA results. Because the shower tracks were often more than one phototube-aperture wide, the signals from adjacent phototubes were combined. The ratios of "optical size" to SA size are given in Fig. 4(a), assuming that light production is a constant, isotropic, 4.0 photons per meter per particle. Ratios above 1.0 imply that more light was received than was expected from atmospheric scintillation. The data of Fig. 4(a) determine a calibration curve for converting light measurements to shower sizes. The systematic errors of the SA size measurements

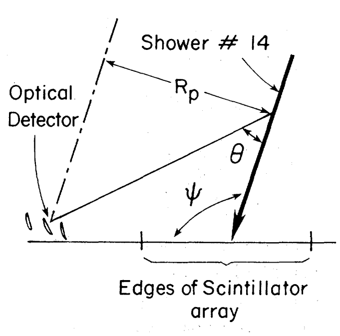

FIG. 2. View of the plane defined by a shower and the optical detector.

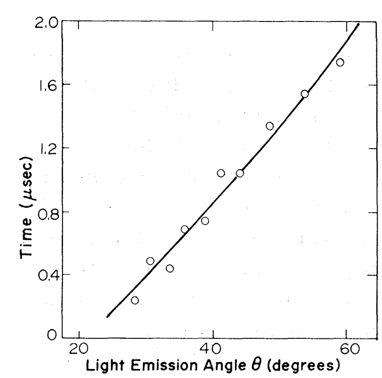

FIG. 3. Times at which phototubes triggered as shower No. 14 passed through the field of view. The curve shows the best fit to these data.

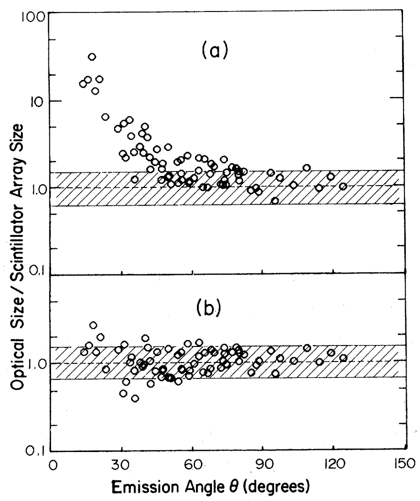

FIG. 4. Ratios of sizes obtained from the optical data to sizes measured by the Volcano Ranch array using (a) computed scintillation light only and (b) estimated light from all sources. Data are plotted for each phototube in all fifteen reconstructed showers. The shaded bands display the uncertainty due to systematic effects in both size measurements.

are ±20% and instrumental errors in the optical measurements are estimated to be ±30%. Such errors are mainly due to uncertainties in the phototube gains, cathode efficiencies, and the mirror and funnel reflectivities.

A shower-development calculation estimated the effects of both Cherenkov light received directly and of light which was received after scattering out of the accumulated Cherenkov-light beam by atmospheric aerosols and air molecules (Rayleigh scattering). It also estimated the effects of shower-size changes in the distance interval between the optical emission point and the SA observation point. The calculation indicated that on the average ~38% of the light reaching the detector was lost because phototube signals generated by the lateral edges of the showers were below threshold. The optical sizes of Fig. 4(b), which include corrections for those effects, show very little angular dependence. The large peak at $\theta < 30°$ in Fig. 4(a) was due to Cherenkov light scattered by aerosols as well as Cherenkov light received directly. The θ dependence of the direct Cherenkov light is caused primarily by the angular spread of the charged shower particles. In Fig. 4(b) the average ratio of the optical sizes to the SA sizes (1.10) changes by only ±0.07 as the atmospheric aerosol content is varied within the probable error estimates.[8] The rms deviation of the ratios about the average value is 0.39. The large corrections at small θ values are sensitive to shower-development fluctuations and errors in measurement of θ; hence, the data fluctuate more at the smaller angles.

A sample of twenty showers which triggered the SA but did not trigger the optical system was also analyzed. In seven cases, the trajectory was outside the optical aperture. In the remaining thirteen, the expected optical signals, as calculated from the SA size of each event and the geometry, were below threshold in all channels.

We have demonstrated the ability of an optical system to detect, reconstruct, and measure sizes of remote air showers. We estimate from these results that the 67-mirror assembly currently under construction near Dugway, Utah will detect about 10^6 showers per year within an area of about 10^4 km^2 and with energies greater than 10^{16} eV.

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