# Atmospheric Čerenkov Radiation from Cosmic-Ray Air Showers

FORREST I. BOLEY*

*National Center for Atmospheric Research, Boulder, Colorado*

## I. INTRODUCTION

The electronic component of extensive cosmic-ray air showers radiates Čerenkov light in easily detected amounts. This paper is a review of observational and theoretical studies of this radiation. The various types of atmospheric Čerenkov-light detectors are described. Measurements of the lateral and longitudinal distributions, the angular spread, the height of production, and the fluctuations in the observed light are compared with theoretical expectations. The possibility of using the light, which is radiated over a wide range of heights, to aid in explicating the shower development is discussed. The tantalizing possibility that the relatively-narrow angular spread of the radiated light could provide a means to search for cosmic sources of high-energy gamma rays is considered.

The highest energy primary cosmic rays generate extensive cascades of particles and photons as they interact with the earth's atmosphere. From an astrophysical viewpoint the properties of these cascade-initiating primary particles are of great importance. Given the primary particle identity, energy, and direction of travel, one has some hope of relating this information to characteristics of their places of origin and to properties of the intervening regions. However, in order to extrapolate back to most of these primary properties, it is necessary to understand the very complex processes that constitute the showers they produce.

This article does not discuss at any length the literature pertaining to the detailed description of all the various shower processes. Reviews of this material are readily available.[1,2] This paper reviews the growing but largely uncorrelated and occasionally not readily available literature pertaining to a particular aspect of the extensive cosmic-ray air shower process: namely, the Čerenkov radiation generated in the earth's atmosphere by the passage of the electronic component of the shower. To place the main part of this discussion in proper perspective, however, it is necessary to mention certain aspects of the present understanding of extensive air showers (EAS).

The main components of the primary cosmic-ray flux are thought to be protons, with a small admixture of alpha particles and an even smaller contribution from heavier nuclei. In the energy range from $10^{10}$ to $10^{13}$ eV, nuclear emulsions carried by very high-flying balloons have established the relative abundances of these components. For the present discussion, protons having energies in excess of $10^{12}$ eV are considered to be the main component of the primary flux producing EAS although photons in this energy range are also mentioned.

The incoming primary particle interacts at great height with the nucleus of an atmospheric atom and produces a compact "core" of mesons and nucleons that proceed very nearly in the original direction of the initiating particle. These secondary mesons and nucleons further interact with the nuclei of other atmospheric atoms at lower levels producing a shower of particles that is referred to as the nucleon cascade.

Some of the mesons produced in the nucleon interactions are neutral $\pi$-mesons. These $\pi^0$-mesons decay over a wide range of elevation into high-energy gamma rays; these gamma rays initiate photon-electron cascades that propagate and decay primarily by the processes of positron-electron pair production, Compton scattering, bremsstrahlung, and ionization. Some of the charged $\pi$-mesons that are also produced in the nucleon interactions decay into $\mu$-mesons that can penetrate to great depths.

Thus the EAS consists of a large number of cascades incorporating a central core of high-energy nucleons, mesons, and electrons surrounded by a more highly scattered electron–photon component that is continuously nourished by decaying $\pi^0$-mesons. Due to their high energy, all the shower components descend in a more or less well-defined clump through the atmosphere approximately along an extension of the primary particle trajectory at very nearly the speed of light. This article is concerned primarily with the electron–photon component of the EAS since, as is seen presently, it is the electrons that contribute by far the largest quantity of Čerenkov radiation.

The number of electrons participating in the electron–photon cascade as a function of the primary particle energy $E_0$ for various thicknesses of atmospheric absorber $t$ has been calculated. Figure 1 is a plot of results by Snyder[3] as presented by Greisen.[4] Shower electron

* Present address: Department of Physics, Dartmouth College, Hanover, New Hampshire.

[1] K. Greisen, Ann. Rev. Nucl. Sci. **10**, 63 (1960).

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

[3] H. S. Snyder, Phys. Rev. **76**, 1563 (1949).

[4] K. Greisen, *Progress in Cosmic Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1956), Vol. III.

densities are seen to increase to a maximum then decrease as they penetrate further into the earth's atmosphere.

Blackett[5] in 1948 suggested that Čerenkov radiation is emitted on passage of cosmic-ray particles through the atmosphere. To be sure, the refractive index of air at sea level is only slightly larger than unity. Nevertheless, he calculated that the contribution might be $10^{-4}$ of the total intensity due to starlight. For such low intensity, detection appeared feasible only in EAS where large numbers of electrons with velocities near to that of light arrive simultaneously at ground level. In a later section the question of possible contamination of the Čerenkov radiation by other light-producing processes such as bremsstrahlung and recombination is discussed.

The pulses of Čerenkov radiation associated with EAS are easily detected. Thus they provide an alternative method to direct particle detection for investigating the properties of EAS and, thereby, the properties of the initiating primaries. Although a detailed discussion is deferred, the possible advantages derivable from observation of the radiated Čerenkov light are mentioned here.

A most desirable and unique aspect of the Čerenkov light is that it may provide information concerning the history of the shower electrons. The received light is not, as with direct particle detection, simply a measure of the local particle density. The radiation is produced along those portions of the electron paths during which the electron velocities exceed the local phase velocity of light. In general, the light arriving at ground-level first has been produced earlier in the shower development since Coulomb scattering of the electrons delays their longitudinal progress relative to the Čerenkov photons. Thus the time dependence of the arriving photons is seen to bear some correspondence to the longitudinal development of the shower. In addition, if the inverse-square decrease of light intensity with height is roughly compensated by the increase of the shower area included within the detector acceptance cone, the total light may be at least an approximation to an integral over the paths of the shower particles.

A second advantage accrues from the fact that the Čerenkov photons are generated at all levels in the shower development by electrons moving over a wide angular spread with respect to the core direction. Thus the Čerenkov photons have a much greater lateral spread than the particles on reaching ground level. This increased spread facilitates shower detection.

The ratio of $4.1\times10^5$ Čerenkov photons per electron reaching sea level is estimated in a later section. Even when this ratio is reduced by the relative efficiencies of photon and particle detection, there remains a detection efficiency advantage for the photons over the particles that may be as large as 10 to 1. Aside from increased ease of shower detection the large Čerenkov photon yield of EAS provides an additional possibility for determining the core direction by optical telescope techniques. Experiments attempting to utilize this possibility are described.

[5] P. M. Blackett, Phys. Abstr. **52**, 4347 (1949).

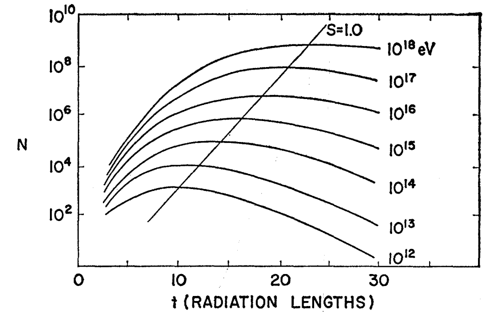


FIG. 1. Electron number as a function of depth in the atmosphere for primary energies from $10^{12}$ to $10^{18}$ eV. The straight line $s=1.0$ is the locus of shower maxima.

Of course, a prime disadvantage associated with the Čerenkov radiation is its removal, by one additional process, from the principal workings of the shower. In many circumstances this removal can make the analysis of the observations very complex. Another serious obstacle to work with the Čerenkov component is that observations must be carried out on clear, moonless nights at a location adequately removed from city lights.

In spite of these disadvantages, information concerning EAS development that is unobtainable by other techniques can in principle be deduced.

This paper reviews in detail the investigations that have been made of the atmospheric Čerenkov radiation generated by EAS. The discussion begins with a theoretical description of Čerenkov-light production by single particles and is then extended to the radiation emitted by unscattered and by Coulomb-scattered shower electrons. The lateral light distribution on the observing plane is deduced for both vertical and inclined showers. The detectors used for observing the Čerenkov light are described. The angular spread, production height, lateral distribution, zenith-angle distribution, fluctuations, and longitudinal distribution of the detected radiation are discussed in that order. A section is devoted to the possible detection of point sources of cosmic radiation.

## II. THEORETICAL CONSIDERATIONS

The theoretical aspects of Čerenkov-light production by the electrons of an EAS are now considered. First, Čerenkov radiation by a single particle is discussed. These considerations are then extended to EAS electrons in vertically incident showers first omitting then

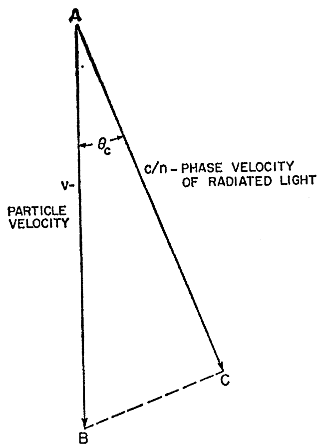


FIG. 2. Velocity diagram for Čerenkov light ($c/n$) radiated by a charged particle ($v$) and displaying coherence along BC for the condition $\cos\theta_c = 1/\beta n$.

including Coulomb scattering effects. A discussion of nonvertical showers concludes this section.

### Single Particle Radiation

Čerenkov radiation is emitted by a charged particle on passage through a dielectric medium if

$$\beta n > 1. \tag{1}$$

Here $\beta = v/c$, the particle velocity with respect to that of light, and $n$ is the refractive index of the dielectric medium. The radiation is emitted at an angle $\theta$ with respect to the direction of motion of the charged particle. The requirement for coherence of the radiated light emitted along the particle path AB in Fig. 2 is

$$\cos\theta_c = \frac{c/n}{v} = \frac{1}{\beta n}. \tag{2}$$

For $\beta = 1$ the maximum angle of light emission is given by

$$\cos\theta_c(\max) = 1/n. \tag{3}$$

The light wavefront has a conical form that propagates at velocity $c/n$ as shown in Fig. 3. The light emitted at height $h$ along a vertical segment $dh$ of an electron path illuminates a ring on the earth's surface of mean radius $h\theta_c$ and of width $\theta_c\, dh$. The radiation is polarized as shown with the electric vector **E** perpendicular to the direction of propagation and the magnetic field **H** tangential to the conical surface.

For the atmosphere the angle $\theta$ shown in Figs. 2 and 3 has been considerably exaggerated. At sea level (STP) the refractive index of air is $n = 1.00029$ and $\theta_c(\max) = 1.3°$. Thus the radiated light is quite closely directionally related to the radiating particle path. From Eq. (1) the threshold energies for Čerenkov-light emission in air by various shower particles may be calculated. For electrons the energy is 21 MeV, for $\mu$-mesons $4.4 \times 10^3$ MeV and for protons $39 \times 10^3$ MeV. From these energies and the number spectra of the various particles it is easily concluded that the primary contribution to the Čerenkov light from EAS is from the electrons. Therefore, the only shower particles with which this article is henceforth specifically concerned are the electrons. At sea level about 85% of the shower electrons have energies above the 21 MeV threshold and averaged over the entire shower about 36% have energies above 50 MeV.[6] A large fraction of all shower electrons have energies in the range 20–300 MeV. Since the threshold energy $E_t = 21$ MeV is large compared to the electron-rest mass energy 0.51 MeV, $\beta = 1$ for all shower electrons of interest for Čerenkov light production by EAS. Thus $\theta_c = \theta_c(\max)$.

These radiating electrons are Coulomb scattered during their passage through the atmosphere. Thus the light radiated by a single shower electron consists of a sequence of light emissions radiated at angles $\theta_c = \theta_c(\max)$ between consecutive Coulomb scattering events. And the total light radiated by all shower electrons is the sum of such contributions. The Čerenkov light detected at the ground is therefore a complex sum of contributions of all those electrons that, at one time or another in their participation in shower development and decay, radiate light into the acceptance solid angle of the detector. The calculation of this sum for arbitrary angle of shower incidence and for arbitrary detector solid angle is quite involved.

### Radiation by Unscattered Shower Electrons

In order to simplify the first calculations concerning the radiative processes, Coulomb scattering events are

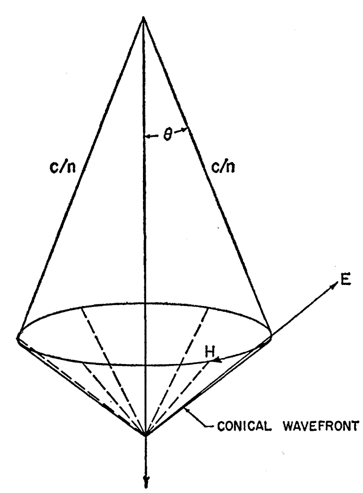


FIG. 3. The conical wavefront propagating at velocity $c/n$ with electric (E) and magnetic (H) fields as shown.

[6] J. A. Richards and L. W. Nordheim, Phys. Rev. **74**, 1106 (1948).

neglected. To begin, the light intensity at ground level from a single electron is calculated. This treatment follows closely those given by Galbraith[2] and by Goldanskii and Zhdanov[7] and is limited to consideration of particles with vertical incidence.

From Frank and Tamm[8] the loss of energy $E$ per unit path length by a particle of change $e$ and velocity $\beta$ to Čerenkov radiation of wavelength between $\lambda$ and $\lambda+d\lambda$ is

$$\frac{dE}{dh}=4\pi^2e^2\int\left(1-\frac{1}{\beta^2n^2}\right)\frac{d\lambda}{\lambda^3}. \qquad (4)$$

Now $n-1=0.00029$ at sea level varies by approximately 2.5% over the visible spectrum from 4000 Å–7000 Å. Thus $n$ is taken as a constant and

$$\frac{dE}{dh}=4\pi^2e^2\left(1-\frac{1}{\beta^2n^2}\right)I, \quad \text{where } I \text{ is } \int_{4000}^{7000}\frac{d\lambda}{\lambda^3}. \qquad (5)$$

The relative velocity $\beta=v/c$ can be written

$$\beta^2=1-m_0c^2/E^2\equiv1-\epsilon^2, \qquad (6)$$

where $\epsilon$ is the ratio of the particle rest mass energy $m_0c^2$ to total energy $E$. The refractive index is written

$$n=1+\eta; \qquad \eta\ll1. \qquad (7)$$

Then since from Eq. (1) the threshold velocity is $\beta_t^2=1/n^2$

$$\frac{dE}{dh}=8\pi^2e^2\eta\left(1-\frac{\epsilon^2}{\epsilon_t^2}\right)I. \qquad (8)$$

Here from Eq. (6) $\epsilon_t^2=1-\beta_t^2$. For high-electron energies such that $\epsilon^2/\epsilon_t^2\ll1$

$$dE/dh=3.8\times10^{-9}\eta \text{ erg/cm} \qquad (9)$$

for electrons. At STP $\eta=0.00029$ and $dE/dh=1.1\times 10^{-12}$ erg/cm which is approximately 0.7 eV/cm. This energy loss is equivalent to about 0.3 photons/cm or about $8.2\times10^3$ photons/radiation length at 4000 Å. Since for each electron reaching sea level there are of the order of 100 radiation lengths of electron path in the atmosphere, there are of the order $8.2\times10^5$ Čerenkov photons for each electron reaching sea level. Actually, since the approximation leading to Eq. (9) may yield a $dE/dh$ that is too large by a factor two, a better estimate may be $4.1\times10^5$ photons per electron reaching sea level. The advantage of this large factor for shower detection was mentioned above and has been pointed out by Greisen.[1]

The variation of $dE/dh$ with altitude $h$ is carried by $\eta$, which for an isothermal atmosphere may be written

$$\eta=\eta_0(\rho/\rho_0)=0.00029 \exp(-h/h_0). \qquad (10)$$

[7] V. I. Goldanskii and G. B. Zhdanov, Zh. Eksperim. i Teor. Fiz. **26**, 405 (1954).
[8] I. Frank and I. Tamm, C. R. Acad. Sci. URSS **14**, 109 (1937).

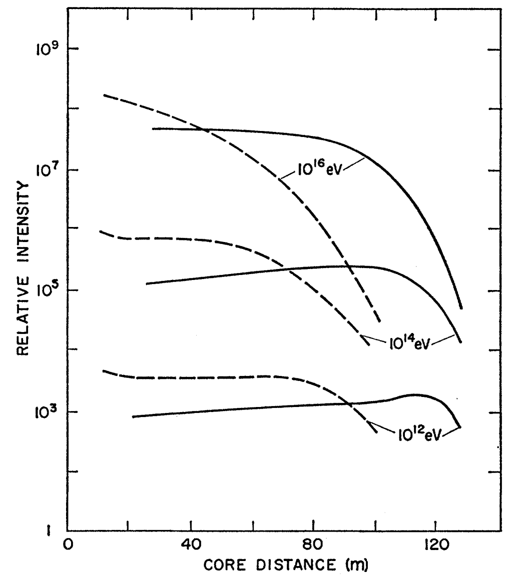


Fig. 4. Relative Čerenkov-light intensity calculated by Jelley and Galbraith to be emitted by EAS as a function of distance from the shower axis. The energies given pertain to that of the initiating primary for detector located at sea level (solid curves) and at 2860 m (dashed curves).

Here $\rho$ and $\rho_0$ are the atmospheric densities at height $h$ and at sea level, respectively, and $h_0=7.1$ km is the scale height of the atmosphere.

The light intensity $\Phi(R)$ at ground level on the basis of this calculation is

$$\Phi(R)=dE/2\pi R\,dR, \qquad (11)$$

between $R$ and $R+dR$ from the intersection of the particle path with the ground. Combining Eqs. (9) and (11)

$$\Phi(R)=4.7R^{-1}\exp(-h/2h_0) \text{ eV/cm}^2 \text{ per cm of path}. \qquad (12)$$

The problem remains to incorporate the result given by Eq. (12) for a single-shower particle into the development of a shower. A relatively crude attempt was made by Jelley and Galbraith[9] who calculated the lateral distribution of the light from an EAS based upon Eq. (12) and the nucleon-cascade model for vertical showers incident on a zenith-directed detector neglecting Coulomb scattering. The electron populations with energies greater than 50 MeV were determined at different altitudes for primary particles of selected energies. The light at ground level was then calculated by multiplying these electron populations by Eq. (12).

Figure 4 gives the results of the Jelley and Galbraith calculation for primary energies of $10^{12}$ eV, $10^{14}$ eV,

[9] J. V. Jelley and W. Galbraith, J. Atmospheric Terrest. Phys. **6**, 304 (1955).

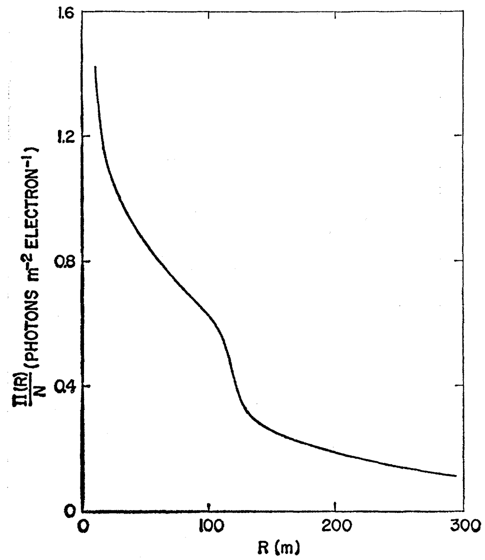


FIG. 5. Lateral variation of the Čerenkov-light intensity per shower electron at sea level as deduced by Goldanskii and Zhdanov.

and $10^{16}$ eV both at sea level and at 2860 m. These results are interesting in that the intensity appears to be relatively constant across the light front, particularly at sea level. At $10^{12}$ eV the intensity is nearly constant out to 120 m. However, it is clear that these results may bear little resemblance to the actual lateral light distributions produced by EAS since Coulomb scattering of the generating electrons is omitted.

### Radiation by Coulomb Scattered Shower Electrons

An estimate of the magnitude of the Coulomb scattering is easily made. The scattering probability for electrons of energy $E \gg m_0c^2$ at an angle $\theta_s$ into a solid angle $d\Omega$ on traversing a scattering distance $dt$ is given by the Rutherford scattering equation

$$P(\theta)d\Omega\, dt = 4Z^2e^4 \frac{N}{A}\frac{1}{E^2}\frac{d\Omega}{\theta_s^4}dt. \tag{13}$$

$N/A$ is the number of atoms per unit mass of the medium through which the particle is moving and $Z$ is the charge number of that medium. The mean-square scattering angle from Eq. (13) is

$$(\theta_s^2)_{\text{Av}} = (E_s/E)^2\, dt/X_0. \tag{14}$$

$E_s = 21$ MeV and $X_0$ is the radiation length, 274 m at sea level; for one radiation length of scattering medium $dt/X_0 = 1$. For shower electrons with energies of 100 MeV undergoing one radiation length of scattering, $\theta_s(\text{rms}) \approx 0.21$ rad $= 12°$, an order of magnitude larger than the Čerenkov-emission angle.

The work of Goldanskii and Zhdanov[7] largely overcomes the absence of Coulomb scattering from the foregoing calculation.[10] Starting with the more exact form for $dE/dh$ given by Eq. (8), they make the following assumptions regarding the electron population.

(1) The differential equilibrium electron spectrum is assumed to be

$$F(E)\, dE = (0.2E_c/E^2)\, dE. \tag{15}$$

Here $E_c$ is the critical energy for air, taken by Goldanskii and Zhdanov as 72 MeV.

(2) The lateral distribution of the electrons at a given height and energy in terms of a mean-square radius is taken as

$$(r^2)_{\text{Av}} \approx (E_s/E)^2 X_0^2 (P_0/P_h)^2. \tag{16}$$

$P_0$ and $P_h$ are air pressures at the observation level and at height $h$, respectively. $X_0 = 274$ m when $P_0 = 1$ atm.

(3) The mean-square angle of the Coulomb-scattered electrons of energy $E_0$ is assumed to be

$$(\theta_s^2)_{\text{Av}} = 0.62(E_s/E)^2. \tag{17}$$

(4) The total electron number $N$ at height $h$ up to $h = 8$ km where $N$ reaches a maximum is taken to be

$$N(h) = N(0) \exp[(P_0 - P_h)/P], \tag{18}$$

where $\Lambda = 195$ g/cm$^2$. $N(h > 8\text{ km})$ is assumed to be zero.

Goldanskii and Zhdanov then deduce the number of light quanta produced by electrons of energy $E$ and height $h$ incident on an optical system located a distance $R$ from the axis of the shower. This number is then integrated over all energies and heights to yield the total light intensity $\Pi(R)$ at $R$. Figure 5 is a plot of their results. The ordinate is the light intensity per shower electron at sea level.

In order to simplify this calculation, the total light is approximated by the sum of two contributions. One contribution arises when $\theta_c > \theta_s$ which implies that $E/E_s \gtrsim 3$. The other comes when $\theta_s > \theta_c$.

This type of approximation is avoided by the work of Zatsepin and Chudakov[11] who make a more detailed analysis of the role of shower and detector geometry upon the received light. They also treat only vertical showers, but take explicit account of the radial and angular variation of the electron population. In Fig. 6, OO′ is taken as the shower axis. The light intensity is deduced at $D$ a distance $R$ removed from the shower axis and generated by electrons of energy $E$ to $E+dE$ contained in the volume element $dV$ at A′ a height $h$ above the observation level. In Fig. 6, O′A′BO lie in

[10] An approximate calculation has also been made by Polikarov, C. R. Acad. Bulgare Sci. **7**, 29 (1954).

[11] V. I. Zatsepin and A. E. Chudakov, Zh. Eksperim. i. Teor. Fiz. **42**, 1622 (1962) [English transl.: Soviet Phys.—JETP **15**, 1126 (1962)].

a plane perpendicular to the observation plane in which lie OBCD. The direction of electron motion at the moment of Čerenkov-light emission is A′C. The light generated by an electron motion $dh$ illuminates the observation plane in a ring of mean radius $r_c(E, h) = h\theta_c$ and width $\theta_c\, dh$. Here $\theta_c\, dh$ is assumed to be much less than $l$, the characteristic linear dimension of the detector. Also it is assumed that $dh \approx d(\text{A}'\text{C})$ for purposes of calculating the light emission. The detector at D receives light from those electrons in dV for which the axes of the light cones intersect the observation plane within the ring of mean radius $r_c(E, h)$ and width $l \gg \theta_c\, dh$. The number of light cones from dV that intersect the observation plane within the area $r_c(E, h) l\, d\varphi$ centered at C is

$$dn_c = N(E_0, E, h, r) f(\theta, E) r_c(E, h)\, d\varphi h^{-2}\, dh\, dEr\, d\varphi\, dr. \tag{19}$$

Here $f(\theta, E)$ is the angular distribution of electrons about the direction A′B determined by an average electron direction angle $\bar{\theta}(r) = r/(t_0/\rho)$, where $t_0 = 34.2$ g/cm$^2$ is the area density per radiation length in air and $\rho$ is the air density at height $h$. $N(E_0, E, h, r)$ is the density of electrons with energy $E$ and position $h, r$ in a shower of primary energy $E_0$.

Since only a fraction $l/2\pi r_c$ of the emitted light illuminates the detector, the total incident number of photons per unit area at D is

$$\Phi(R) = \int \frac{dn_c}{l^2} g(E, h) \left(\frac{l}{2\pi r_c}\right). \tag{20}$$

The integral is taken over all pertinent values of $E$, $h$, $r$, $\alpha$, and $\varphi$. Here $g(E, h)$ is the number of photons within observable wavelength limits emitted by electrons of energy $E$ at height $h$ along one g/cm$^2$ of path.

The integral in Eq. (20) can be done once the functions $N(E_0, E, h, r)$, $f(\theta, E)$, and $g(E, h)$ are determined. The following assumptions are made concerning these functions.

The product of the electron density and angular distribution functions is assumed to be given by

$$N(E_0, E, h, r) f(\theta, E) = N(E_0, h) F(E) B \exp(-r^2/r_0^2) C \exp(-\theta^2/\theta_0^2). \tag{21}$$

Note the specific radial and angular dependences used for the electron distribution. Here $N(E_0, h)$ is the total electron number at height $h$ in a shower of primary energy $E_0$. Plots of $N(E_0, h)$ are shown in Fig. 1. The differential energy spectrum $F(E)$ is assumed (1) independent of the shower path traversed; i.e., independent of shower age, (2) to vanish outside the energy range 20 to 300 MeV, and (3) to be specifically

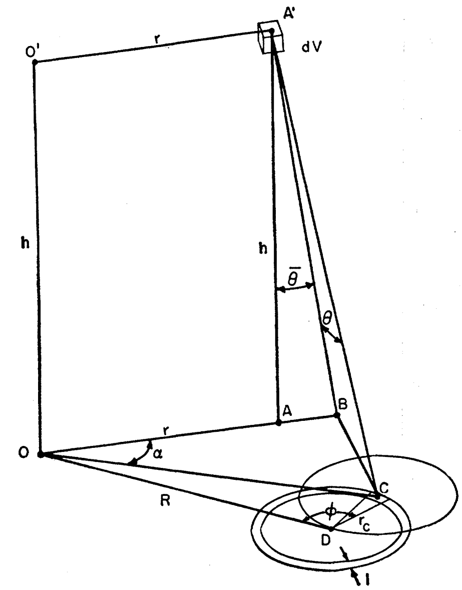


FIG. 6. Geometry used by Zatsepin and Chudakov for calculation of the lateral distribution of the intensity of Čerenkov radiation from extensive air showers. See text for full description.

given by

$$F(E)dE = \frac{1.73}{E_c} \frac{dE}{(1+2.3E/E_c)^2}, \qquad E_c = 72 \text{ MeV} \tag{22}$$

within that range. This spectrum is seen to differ, although not radically, from that used by Goldanskii and Zhdanov (Eq. 15). The radial and angular constants in Eq. (21) are assumed to be

$$\theta_0^2(E) = \frac{0.545}{(1+2.3E/E_c)^2} \left(\frac{2.3E_s}{E_c}\right)^2,$$

$$r_0^2(E, h) = \theta_0^2(E) (t_0/\rho)^2, \tag{23}$$

where $E_s = 21$ MeV and $(t_0/\rho)$ is defined following Eq. (19). $g(E, h)$ is taken as a constant 354 photons/g cm$^2$ and the lower limit of the $E$ integration in Eq. (20) is suitably adjusted to provide conservation of total light output. A model atmosphere is assumed according to the temperature distribution

$$T(h) = 288°\text{K} - bh \qquad 0 \le h \le 11 \text{ km},$$

$$= 218°\text{K} \qquad 11 \le h \le 30 \text{ km},$$

$$b = 6.3°\text{K/km}. \tag{24}$$

Zatsepin and Chudakov integrated Eq. (20) using the above assumptions and obtained, for proton initiated showers, the plot of lateral photon distribution per shower electron between 3000 Å–6000 Å given in

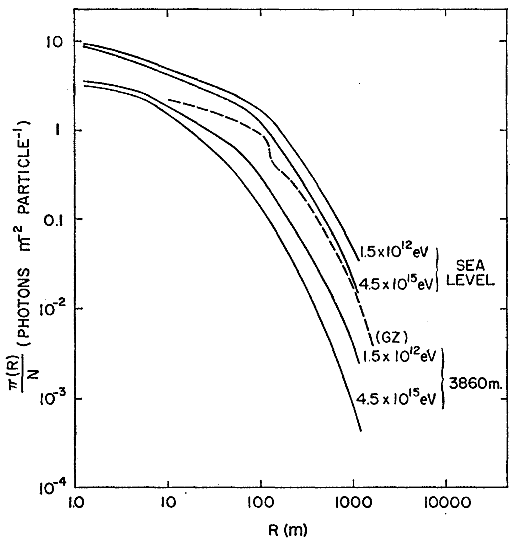


Fig. 7. Lateral variation of the Čerenkov radiation intensity per shower electron from EAS as calculated by Zatsepin and Chudakov. Results are shown for showers of initiating proton energy $E_0=1.5\times10^{12}$ eV and $4.5\times10^{15}$ eV at sea level and at 3860 m. Results due to Goldanskii and Zhdanov (GZ) are also shown for comparison.

Fig. 7. Also included for comparison is the lateral distribution calculated by Goldanskii and Zhdanov. Comparisons between these calculations and observations at the two elevations are shown in the next section.

The calculations of both Goldanskii and Zhdanov, and Zatsepin and Chudakov show that the radial dependence of the light intensity is much more marked than is deduced in the very simplified theory of Jelley and Galbraith.

### Light from Nonvertical Showers

The above calculations do not contain provisions for nonvertical showers. Due to the appreciable acceptance angle of some light receivers used, it is prudent to examine the possible influence of inclined showers upon the observed light distribution. A calculation of these effects has been made by Sitte[12] and is outlined here.

Sitte assumes the more detailed Nishimura–Kamata approximation for the radial distribution of particles with age parameter $s=1.3$, a constant. This approximation is given by Greisen[4] and has the form

$$f(r/r_0)\,\alpha(N/r_0^2)\,(r/r_0)^{2-s}(1+r/r_0)^{s-4.5}, \qquad (25)$$

where $r/r_0$ is the distance from the core in Moliere units, $r_0=79$ m at sea level. The angular distribution of shower particles of energy $E$ is assumed to be

$$g(\theta)=(1/\pi)\,(E/E_s)^2\exp\left[-(E/E_s)^2\theta^2\right] \qquad (26)$$

[12] K. Sitte, Nuovo Cimento **25**, 86 (1962).

so that on average the particles travel parallel to the shower axis. This explicit form of $g(\theta)$ is not far different from that used by Zatsepin and Chudakov. The energy spectrum is taken as

$$F(E)dE\,\alpha(E/E_s)^{-\delta}\,dE, \qquad (27)$$

with $\delta=(2-r/r_0)/(1-r/r_0)$ in order to force

$$\bar{E}_r=E_c/(r/r_0). \qquad (28)$$

The longitudinal development is handled in much greater detail than other Čerenkov light calculations by using the graphical and tabular material of Greisen[4] for $E_0=10^{15}$ eV. The zenith-angle distribution of showers is approximated as

$$F(\psi)=(9/2\pi)\,\cos^8\psi. \qquad (29)$$

The inclusion of this dependence is a most significant contribution of the Sitte calculation. The atmosphere is assumed isothermal and thus the threshold energy $E_t(h)$ is

$$E_t(h)=21.1\,\exp\,(h/2h_0)\ \text{MeV}. \qquad (30)$$

An appropriate geometrical construction is used to describe a shower incident at zenith angle $\psi$ and azimuth $\theta$, a distance $d$ from the Čerenkov detector. Corrections due to the field of view of the detector and the limited radiating area of the shower that effect the treatment at small angles and altitudes are added. Then Sitte is able to calculate the lateral distribution for Čerenkov light from showers as a function of detector aperture for a wide range of zenith and azimuth angles. Figure 8 shows the type of results obtained from this calculation.

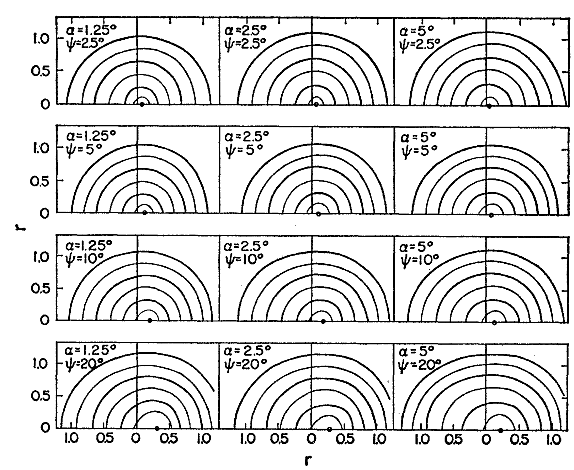


Fig. 8. Lateral light distribution in the observing plane for various zenith angles $\psi$ and apertures $\alpha$ as deduced by Sitte for $E_0=10^{15}$ eV. Each line corresponds to an intensity decrease by $e^{-1}$.

Figure 8 shows lines of constant intensity (decreased by factors of $e^{-\frac{1}{2}}$) in the plane of observation for various detector apertures and zenith angles. The position of maximum light does not correspond to the core location and the distributions are appreciably asymmetric. Displacements of the maximum light from the core locations by 20 m are not uncommon.

Sitte also produced plots of the relative contribution to the light output of the shower from various heights. These results suggest that at least roughly qualitatively the maximum contribution to the received light comes from those regions where the shower core is within the acceptance cone of the detector. Results very similar to these on altitude dependence were suggested earlier by Brennan *et al.*[13] and were worked through in some detail by Malos *et al.*[14] This question is discussed further in the next section.

Sitte has stated that in spite of some inaccuracies in his model, he believes the following findings are unaffected in any gross way by them: (1) No universal "structure function" for the lateral distribution of the light can be defined. (2) An eccentricity and shift of light maximum does occur for inclined showers. (3) Most observed parameters depend upon the acceptance aperture of the light receiver.

The theoretical framework outlined in this section is used to base the discussion of the observational results reviewed in the succeeding sections.

## III. OBSERVATIONS OF ATMOSPHERIC ČERENKOV RADIATION

The following qualitative picture may be made of the Čerenkov radiation that is generated by the shower electrons of an EAS. Bassi, Clark, and Rossi[15] have shown that the shower electrons arrive at sea level in a disk of a few meters thickness and very large radius of curvature. To a reasonable approximation we may expect the Čerenkov photons to be similarly disposed although as pointed out earlier they are distributed over a wider area, have a somewhat modified longitudinal structure, and have a much higher number density. Thus a first-approximation model of the Čerenkov photons from an EAS is that they form a very nearly plane disk a few meters in thickness. This model is useful in considering the various detector arrangements that have been used. The more detailed conclusions presented in the preceding section are of course necessary in interpreting the actual observations discussed in the latter portions of the present section.

### Light Detectors

The observations of Čerenkov radiation generated in the atmsophere by EAS have been made using a number of relatively simple detector arrangements. Perhaps the most common consists of a high-gain, end-window photomultiplier tube placed at the focus of a parabolic mirror of rather low ratio of focal length to mirror diameter. Figure 9 is a typical example of this arrangement. The mirror allows the collection of larger numbers of photons than would be incident on a photomultiplier tube of moderate photocathode diameter; a 25-cm-diam mirror allows detection of a few photons/cm² per flash. The photocathode limits the solid angle from which light is collected.

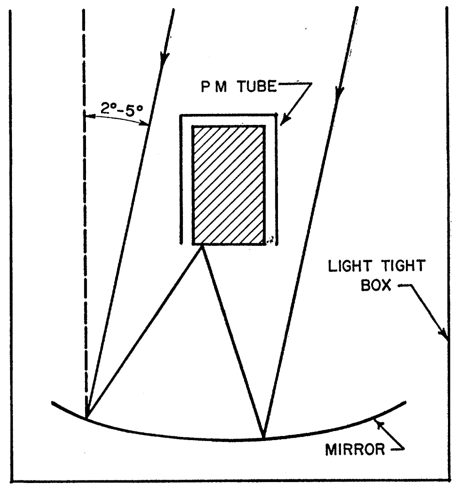


FIG. 9. Detector used for the observation of Čerenkov light associated with EAS. The parabolic mirror might be from 25 cm to 100 cm in diameter with a focal ratio of the order of 0.5. The half-angle of the acceptance solid angle is commonly a few degrees.

A second, even simpler, detector arrangement consists of omitting the parabolic mirror and pointing the photomultiplier tube upward thereby allowing the light to impinge directly on the photocathode. In this case, limiting apertures are ordinarily inserted in front of the photocathode to define the angular acceptance.

A modification of the arrangement shown in Fig. 9, employing a matrix of photomultiplier tubes at the focal surface of the parabolic mirror, has been used to obtain photon arrival direction information. Figure 10 shows an example of this arrangement in which 19 photomultiplier tubes are used with a 30-cm-diam, 120-cm focal-length mirror.

A considerable improvement in the optical detail, which can be obtained from such a telescope arrangement, is provided by substituting an image intensifier system for the matrix of photomultiplier tubes. A Schmidt mirror of 30-cm-diam, a 12.5-cm photocathode image intensifier optically coupled to a 3-stage intensifier, and an intensifier orthicon with kinescope display, makes it possible to photograph a Čerenkov-light flash of 10–50 photons/cm².[16,17]

[13] M. H. Brennan, J. Malos, D. D. Millar, and C. S. Wallace, Nature 182, 973 (1958).
[14] J. Malos, D. D. Millar, and C. S. Wallace, J. Phys. Soc. Japan 17, 114 (1962), Suppl. A-III.
[15] P. Bassi, G. Clark, and B. Rossi, Phys. Rev. 92, 441 (1953).
[16] D. A. Hill and N. A. Porter, Nature 191, 690 (1961).
[17] N. A. Porter and D. A. Hill, J. Phys. Soc. Japan 17, 112 (1962), Suppl. A-III.

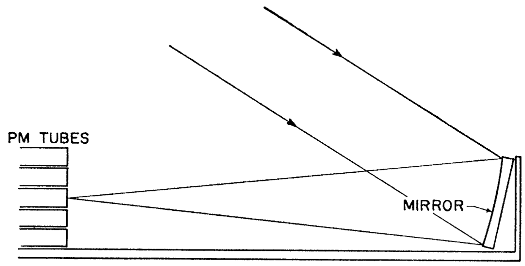


FIG. 10. Detector telescope used by Boley and Macoy for studies of the angular spread of Čerenkov photons from EAS. The 30-cm-diam mirror has a focal length of 120 cm and 19 one-inch-diameter photocathodes are located at the focal surface.

**Identification of the Radiation**

The first observations of light flashes associated with cosmic rays were reported by Galbraith and Jelley.[18,19] The light was detected by use of a photomultiplier tube and parabolic mirror arranged as shown in Fig. 9. This light detector was used in conjunction with a 180-m square array of 16 Geiger counters to search for coincidences between the light and the cosmic-ray particles. In approximately 44% of the cases in which light flashes above the general night sky illumination were observed, coincident particles were detected by the counter array. In this early experiment the number of detected coincident particles per light flash was so low (seldom more than one Geiger tube fired) that it was by no means clear that the flashes were correlated with EAS. Nor, of course, was the light shown to be of Čerenkov origin.

However, a subsidiary experiment to determine the relative production of Čerenkov radiation and isotropic radiation (due to ionization) from single $\mu$-mesons in air was performed by Barclay and Jelley.[20] This experiment is pertinent since the ionization-associated radiation from $\mu$-mesons and electrons should be comparable. The experiment showed that for $\mu$-mesons in air, the production of light associated with ionization is less than $10^{-2}$ of that for Čerenkov radiation, or less than $4\times10^{-6}$ of the rate of energy loss by ionization for relativistic $\mu$-mesons.

In addition to ionization processes, bremsstrahlung might contribute light that could be confused with Čerenkov radiation. However, Galbraith and Jelley,[21] using Heitler's spectral and angular distributions, have calculated the relative production rates for light in the wavelength range from 4000–5000 Å to be of the order of $10^{-7}$ bremsstrahlung photons per Čerenkov photon in air at STP. From these two findings it would appear that Čerenkov radiation should be the dominant photon feature of EAS in the wavelength range to which photomultiplier tubes are sensitive. To support this conclusion, Galbraith and Jelley carried out observations of the polarization, the directional properties, and the color of the light.

To observe the polarization it is necessary, as is evident from Fig. 3, to determine the trajectories of the generating electrons. Then the observed **E** field should be directed radially from the electron paths. Since a large fraction of the electrons travel reasonably near the shower core, the integrated **E** field over all shower electrons should be approximately radial to the core. Galbraith and Jelley arranged a set of Geiger counters along a 73-m horizontal line and placed a light detector of the type shown in Fig. 9 at one end of the line. A Polaroid filter covered the photocathode so that **E** fields parallel and perpendicular to the line of Geiger counters could be selected. Since the counters should be preferentially sensitive to the shower core, a higher coincidence rate between light detector and counters should occur for Čerenkov light for **E** parallel to the detector line. (Bremsstrahlung should show similar polarization to Čerenkov radiation but, as already mentioned, its intensity is expected to be very low.) Single counter discharges were not considered very sensitive to core location, so attention was concentrated on the coincident discharge of two counters. Triple the coincidence rate between the light detector and the discharge of two counters was observed for **E** parallel to the counter line than for **E** perpendicular. Thus the polarization is appropriate to Čerenkov radiation.

To observe the directional properties of the light, two detectors of the type shown in Fig. 9 were mounted so that the angle between their optic axes could be varied. Then the coincidence rate between the two detectors was measured as a function of the angle between the optic axes. Figure 11 is a plot of their results for detectors with half acceptance angles of 2.2°. The dashed curves are calculated for recombination and Čerenkov light neglecting Coulomb scattering in both instances. It is clear that the observed angular

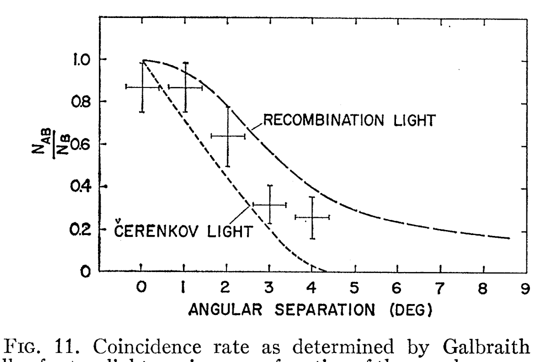


FIG. 11. Coincidence rate as determined by Galbraith and Jelley for two light receivers as a function of the angular separation of their optic axes. The dashed curves are calculated for recombination and Čerenkov light.

[18] W. Galbraith and J. V. Jelley, Nature **171**, 349 (1953).
[19] J. V. Jelley and W. Galbraith, Phil. Mag. **44**, 619 (1953).
[20] F. R. Barclay and J. V. Jelley, Nuovo Cimento **2**, 27 (1955).
[21] W. Galbraith and J. V. Jelley, J. Atmospheric Terrest. Phys. **6**, 250 (1955).

dependence is flatter than expected for non-Coulomb scattered electrons generating Čerenkov light, but is still not flat enough for recombination radiation.

Galbraith and Jelley also performed a color experiment with light filters and found the ratio of blue to green light to be that expected for Čerenkov radiation although no great accuracy was claimed.

None of these direct observations seem to give conclusive evidence of the Čerenkov nature of the light. But taken together with the Barclay and Jelley $\mu$-meson experiment and the aforementioned bremsstrahlung calculation, the evidence seems to be quite conclusive for the Čerenkov character of the light.

### Angular Spread of the Light

Independent measurements of the angular spread of the observed light have been made. Boley and Macoy,[22] using a 19-photomultiplier array in conjunction with a parabolic mirror, determined that over an average of 31 showers, 75% of the light fell within a half-angle of 2.3°, and 41% within 0.6°. In six of the 31 showers the only light detected was within a half-angle of 0.6°.

Porter and Hill[17] have utilized in series two image intensifiers and an intensifier orthicon with kinescope display to produce photographs of the Čerenkov light. The photographs show bright spots 2–5° in diameter. Some of the spots are circular; some have appreciable ellipticity. Typically elongated images are 3–5° in length by 0.5° wide and contain a bright portion about 0.5° in diameter. The system resolution was about 0.2°.

In spite of these relatively narrow angular spreads, it is possible to detect Čerenkov radiation at large angles with respect to the core direction. Brennan, Malos, Millar, and Wallace[23] operated a light receiver with seven photomultipliers at the focal surface of a 110-cm-diam, 46.5-cm focal-length parabolic mirror. The acceptance half angle of each photomultiplier was about 3°. One phototube was directed vertically, the others clustered about the vertical one were each 7° off vertical. The receiver was located near the end of an EAS array designed to observe showers of $10^5$–$10^7$ particles and with cores falling from 0 to 60 m from the light receiver.

When three of the photomultiplier tubes were operated, coincidences between two and three were sometimes observed thus indicating angular spreads of at least as much as 7°.

A somewhat different measure of the angular light distribution was also made by these workers. Using the EAS array to determine shower size, core location, and direction, the incidence of light from within 3° of the zenith was measured with the vertically oriented photomultiplier tube. Of ten showers in which the skew distance between the shower axis and the detector light acceptance cone axis was less that 20 m, light was observed at an angle greater than 30° with respect to the shower axis in one shower and between 20° and 30° in another shower. This observation shows that Coulomb scattering certainly plays a significant role in distributing the light over wide angles.

However, these last results should not be taken as contradictory to those obtained by the other methods described above. Since the contribution to the total light drops off with distance from the shower axis, the average distance from the core for detected showers should be less than the average distance of the light spread. Thus the telescope-like observations are expected to be predominantly influenced by the photons emitted at small angles even though detectable numbers of photons may be observed at large angles. Of course, the work of Sitte[12] indicates that the highest intensity still does not exactly correspond to the shower axis direction in nonvertically incident showers.

### Height from Which Light is Detected

An important question, which is closely related to one of the possible advantages for the observation of the Čerenkov light over particle detection, is the height of emission of the detected light. If light is received only from the last few hundred meters of the shower above the detector, little advantage is gained over particle detection except for higher detection efficiency and for the possibility of using optical techniques. On the other hand, if light is received from an extensive portion of the shower height, then the light arrival time and the lateral spread can contain information on shower history.

The direct evidence on this question is scanty and indirect conclusions remain somewhat difficult. The earliest evidence was obtained by Galbraith and Jelley.[18] They found that the rate of incidence of shower flashes above threshold in a receiver of the type shown in Fig. 9 was halved when a cloud cover occurred between 1300 and 3000 m. This result was confirmed by Nesterova and Chudakov[24] who observed the same decrease for cloud cover at 2000 m above similar type detectors.

Using very wide-angle detectors (1.7 sr solid angle) and filters to limit the wavelength range to 3100–4800 Å, White, Porter, and Long[25] found the detection rate reduced to 72% by cloud cover at 300–800 m. This implies for the observed integral pulse height distribution: $N(>H)\alpha H^{-1.6\pm0.1}$, that only about 20% of the light observed at sea level comes from heights greater than 800 m. Although this result is quite at

[22] F. I. Boley and N. H. Macoy, Rev. Sci. Instr. **32,** 1359 (1961).

[23] M. H. Brennan, J. Malos, D. D. Millar, and C. S. Wallace, Nuovo Cimento (Suppl.) **8,** 662 (1958).

[24] N. M. Nesterova and A. E. Chudakov, Zh. Eksperim. i Teor. **28,** 384 (1955) [English transl.: Soviet Phys.—JETP **1,** 388 (1955)].

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

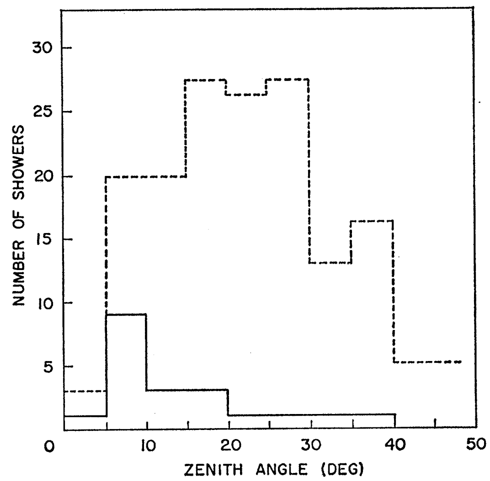


FIG. 12. Zenith angle distribution of 157 showers detected by an EAS array (dotted line) and of the 20 of those showers accompanied by a pulse in a vertically directed light receiver (full line). Data were obtained by Brennan *et al.*

variance with the others, it is likely entirely due to the large solid angle of the receivers used.

A calculation made by Malos, Millar, and Wallace[14] is pertinent to this point. For a receiver of 3° half-angle directed vertically, they calculate the amount of light received as a function of height above the detector for showers with different angles of incidence and cores falling 30 m from the light receiver. They assume that the angular distribution of the light does not vary over the shower front and that the shower-structure function

$$f(r)=\frac{N}{2\pi r_0}\frac{\exp(-r/r_0)}{(r+1)} \tag{31}$$

does not vary with height. Here $r_0=79$ m. They find that except for showers of near vertical (less than 5 deg) incidence most of the light received comes from elevations less than 1000 m. Rather similar results deduced by Sitte[12] were mentioned earlier. This calculation suggests that receivers of the type shown in Fig. 9 and used by Galbraith and Jelley and by Chudakov *et al.* may be particularly sensitive to vertical showers since they do appear to receive substantial amounts of light from above 1000–2000 m.

High-vertical sensitivity is particularly evident when several vertically directed detectors are operated in coincidence. Boley *et al.*[26] used four such detectors in coincidence in a roughly square array of approximately 65 m sides. For showers satisfying a $10^{-7}s$, fourfold coincidence requirement, less than 5% made an angle greater than 5° to the vertical.

However, even for a simple vertically directed, small acceptance angle light receiver, the increased efficiency for detection of vertical showers is evident. Brennan *et al.*[13] analyzed 157 showers for arrival direction by use of their EAS array and compared the distribution of these arrival directions with those 20 of the 157 showers accompanied by light received by their vertical detector. The angular distributions of the 157 showers and of the 20 shower subgroup are shown in Fig. 12. The requirement that a Čerenkov pulse be recorded clearly introduces a bias toward vertically incident showers.

The observations thus indicate that wide angle detectors are much more sensitive to light coming from lower levels than are those of narrow acceptance angle, particularly if some coincidence requirement is made on the latter. These observations are further supported by the conclusions of Sitte.[12]

### Lateral Light Distribution

Perhaps the most direct test of the understanding of the light production process of a shower is the measurement of the lateral spread of the emitted light. If for particular detector arrangements the lateral distribution can be correlated with the details of shower development processes, then the distribution can be expected to yield substantive information about those processes.

A number of qualitative and semiquantitative lateral distribution measurements have been made. In addition, absolute measures of photon distribution have been obtained; most attention in this section is devoted to these data. However, the earlier qualitative results of Jelley and Galbraith[9] are of some interest and are mentioned here. Using their simple linear EAS array they found the light-particle coincidence rate to drop monotonically with increasing separation distance, thus implying a drop in light intensity with distance from the shower axis. With the more elaborate Culham array they were able to show that the light extends well beyond the maximum radius expected for showers in which electron scattering does not play a role.[27]

The remainder of this discussion on lateral distribution is devoted almost entirely to the results obtained from two separate setups by the Soviet group although results from the Israeli group is also included and is

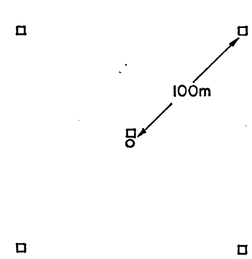


FIG. 13. Detector arrangement used by Chudakov and Nesterova to investigate the lateral distribution of Čerenkov light from EAS. The □ represents Geiger counter detectors and the ○ represents a Čerenkov-light detector. Additional details of the detectors are given in the text.

[26] F. I. Boley, J. H. Baum, J. A. Palsedge, and J. H. Pereue, Phys. Rev. **124**, 1205 (1961).

[27] F. R. Barclay and J. V. Jelley, Oxford Conference on Extensive Air Showers (London, 1956).

seen to bear upon the resultant views of the lateral light distribution.

An early detector arrangement used by Chudakov and Nesterova[28] to study the lateral light distribution is shown in Fig. 13. Five 96-counter particle detectors were placed at the center and vertices of a square array of 100 m radial extent. The light receiver consisted of eight separate photomultiplier tube-parabolic mirror detectors located at the center of the array. The light detectors all subtended a solid angle of 1/40 sr. Two of the light detectors were directed vertically. The other six were placed about the center two at about 2 m separation and were inclined toward the center by 5° to increase their sensitivity to inclination of the light. Only those showers for which the light amplitude into a vertical detector equaled or exceeded that into any of the inclined ones were selected for observation. This criteria was estimated to exclude all showers inclined more than $\frac{3}{4}°$ to the vertical. All but about 4% of the selected showers showed particle array outputs and about 10% of the selected showers gave adequate information for analysis. Analysis could be performed for core positions and size such that $R<150$ m for $N<10^6$ and $R<250$ m for $N>10^6$ particles.

Showers were recorded in the range from $10^5$ and $10^7$ particles and with core location from 0 to 200 m from the light detectors. Due to the above requirements for shower selection, the large particle number showers correspond to large core-distance showers. Thus showers for which $R<30$ m have $N<3\times10^5$ and for 30 m$<R<$100 m, $N>3\times10^5$ to $3\times10^6$.

If the form of the radial distribution $\Phi(R)$ is independent of $N$ and the light intensity $\Pi(R, N)$ is proportional to $N$

$$\Pi(R, N)=N\Phi(R). \tag{32}$$

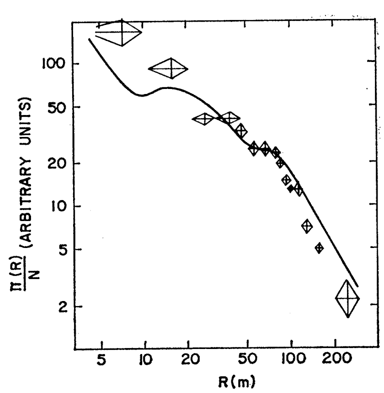


FIG. 14. Light intensity per shower particle as a function of radial distance of shower core from light receiver. The data were obtained by Chudakov *et al.* and the solid curve is deduced by them from theoretical considerations.

[28] A. E. Chudakov and N. M. Nesterova, Nuovo Cimento (Suppl.) **8**, 606 (1958).

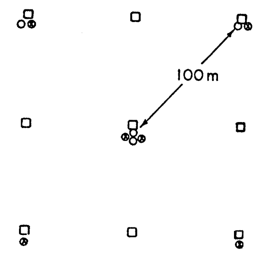


FIG. 15. Second extended array used by Chudakov *et al.* The □ denotes Geiger counters, the ○ denotes light detectors of the tube-parabolic mirror type, and the ⊗ denotes light detectors without mirrors and of 50° acceptance half-angles.

Then the ratio $\Pi/N$ may be plotted against $R$ as in Fig. 14. Although this presentation technique does not entirely remove the dependence upon shower size, it remains useful nevertheless. Since an absolute photon calibration was not obtained in this set of observations, $\Pi/N$ is in arbitrary units. The solid curve is the result of a calculation of the type made by Zatsepin and Chudakov[11] with the electron spectrum assumed constant with height. The correspondence between the observed data and the theory is most striking. The large scatter of the data for $R<50$ m was attributed by Chudakov and Nesterova to fluctuations in height of shower origin and in shower development. These and other observations of fluctuations are discussed presently.

A second set of observations by Chudakov *et al.*[29] was made by extending the array shown in Fig. 13 to that in Fig. 15. The detected showers satisfied an amplitude requirement on two of the central light detectors. An absolute photon calibration was made from $\mu$-mesons in Plexiglass. The absolute light flux was thus determined at five locations. The shower size and core location and direction ($\pm3$ deg) were recorded for showers in the range $2\times10^4$–$1.3\times10^7$ particles.

Figure 16 shows the lateral distribution of the photon flux per particle for showers of average size $\bar{N}=4\times10^5$ at sea level and $\bar{N}=1.1\times10^5$ and $\bar{N}=1.4\times10^6$ at 3860 m. The solid curves are constructed from the theory of Zatsepin and Chudakov for electromagnetic cascades starting at zero atmospheric depth. The $10^{15}$ eV curve is seen to correspond much more closely with the $\bar{N}=1.4\times10^6$ than the $\bar{N}=1.1\times10^5$ data. The correspondence between the $\bar{N}=4\times10^5$ sea level data and the $10^{14}$-eV curve is not unreasonable although these data are not as statistically firm as are those at 3860 m. The general degree of fit with the experimental data especially beyond 30 m indicates that most of the essential aspects of the problem of lateral distribution of near-vertical showers have been included in the theoretical development. The lack of fit below 30 m

[29] A. E. Chudakov, N. M. Nesterova, V. I. Zatsepin, and E. I. Tukish, *Proceedings Moscow Cosmic Ray Conference* (Moscow, 1960), Vol. II, p. 50.

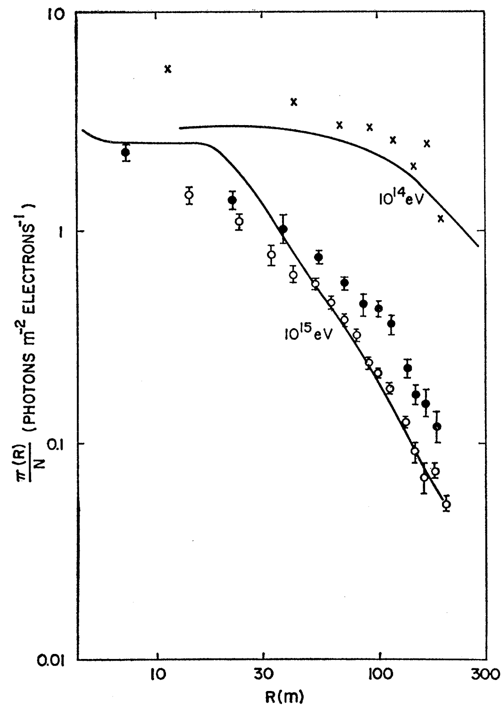


FIG. 16. Lateral dependence of Čerenkov radiation intensity per incident shower particle measured by Chudakov *et al.* The (**x**) denote showers of size $N \geq 4\times10^5$ at sea level and $\psi \leq 25°$. The closed circles (●) are for showers of size $N \geq 1.1\times10^6$ at 3860 m. The open circles (○) are for $N=1.4\times10^6$ at 3860 m. Solid curves are for electromagnetic cascades of $10^{14}$ eV observed at sea level and of $10^{15}$ eV observed at 3860 m.

is not resolved but may be connected with a finding at 20 m by Kasha *et al.*, to be mentioned later. It must be added, of course, that compensating changes in the depth of origin and of the primary energy can be introduced with little change in the solid curves shown.

Greisen[1] has pointed out that integration of the light over radius for shower size $N=1.4\times10^6$ yields $1.2\times10^5$ photons per electron at 3860 m and approximately an order of magnitude less at sea level. From these figures, the primary energy can be calculated. To yield $1.2\times10^5$ photons the track length in the atmosphere must be 45 radiation lengths using the $3\times10^5$ photons per 100 radiation lengths calculated by Greisen rather than the $4.1\times10^5$ from Eq. 8. The energy dissipation is $3.8\times10^9$ eV per electron in showers of this size at 3860 m. Greisen estimates the additional local energy in all shower components to be $0.8\times10^9$ eV thus giving a primary energy of $4.6\times10^9$ eV per electron or $6.5\times10^{15}$ eV.

The two 3860-m curves in Fig. 16 show that the average primary energy per local electron is higher in smaller $N$ showers. This effect can be understood by supposing that the smaller showers are further beyond their maximum when observed and that the large showers did not just begin lower in the atmosphere but are themselves well beyond their maximum development. Equal primary energies appear to produce comparable amounts of light although the number of electrons drops with increased atmospheric depth.

Kasha *et al.*[30] using combined EAS particle array and light detectors, have observed an interesting effect. They find that for all shower sizes, the intensity of the Čerenkov light has a maximum not at the shower core but at about 20 m from the axis. They point out how tempting it would be to attribute this shift of maximum intensity to zenith-angle variation as calculated by Sitte,[12] but they feel that for the showers they detected the zenith angles were too small to account for the observed shift. They believe the most likely explanation of the effect is an angular divergence of the shower particles that increases with increasing distance from the shower axis. An examination of the theory in such a way as not to restrict the average electron direction to the shower axis direction is clearly in order.

Kasha *et al.* point out that the failure of earlier observers of the lateral distribution to detect this effect may have been due to poor control of the zenith angles and shower sizes for events recorded at different distances from the axis. This criticism as applied to the first observation of Chudakov *et al.*[28] may be somewhat weak. Nevertheless, there are discrepancies between observations and between observations and theory.

### Zenith-Angle Distribution of the Light

Several measurements of the zenith-angle dependence of the incident light have been made. Since shower arrival direction information is included in this measurement, the results are not useful to a discussion of the angular spread of the light. However, in discussing the fluctuations in detected light intensity from showers of given energy, the role of the zenith-angle distributions is important. The measurements have been made by Jelley and Galbraith[9] and by Chudakov *et al.*[29] using detectors of the photomultiplier tube-parabolic mirror type. The results of the latter are for showers of accurately determined size range ($6\times10^5 \leq N \leq 8\times10^6$) and give for the zenith-angle distribution $F(\psi)=\cos^p \psi$ where $p=3.2\pm0.8$. A similar result on less-well analyzed showers was reported by Galbraith and Jelley with $p=2$–$3$.

White, Porter, and Long[25] using timing measurements with their very wide angle (1.7 sr) receivers stated agreement with Galbraith and Jelley and with the electron results of Clark *et al.*[31] The latter agreement, especially for very wide-angle detectors, is ex-

[30] H. Kasha, C. Leibovitz, Y. Oren, B. Reuter, and K. Sitte (unpublished).

[31] G. Clark, J. Earl, W. Kraushaar, J. Linsley, B. Rossi, and F. Scherb, Nature **180**, 353, 406 (1957).

pected since they appear to sample closely the local electron density.

### Fluctuations

Observational evidence of the possible role of fluctuations in showers as indicated by the amount of Čerenkov radiation detected from a given size shower was first shown by Brennan *et al.*[23] By plotting the ratio of the light pulse amplitude to the shower size as a function of distance from the shower core, they observed no correlation between the ratio and the distance although they found the maximum ratio to decrease with distance. Roughly similar results were obtained by Kasha, Oren, and Sitte,[32] although the decrease with distance of the maximum ratio was not apparent. At 3860 m similar but more extensive results were obtained by Chudakov *et al.*[29]

Brennan *et al.*[13] have pointed out that the fluctuations they observe are expected due to the variable zenith angle of the detected showers. They argue that (1) if the light distribution is approximately that of the electrons $f(\theta, r)$, (2) if the light emission $g$ is taken independent of altitude, and (3) if the electron density can be approximated by an average $[\rho(h)]_{Av}$, then the total photons detected are approximately

$$\Phi(R) = C\int_0^\infty [\rho(h)]_{Av}\, dh. \tag{33}$$

Here $C = gf(\theta, R)A\pi\alpha^2$, where $f(\theta, r)$ is taken to equal $f(\theta, R)$ at the detector position $R$; $A$ and $\alpha^2$ are the detector sensitive area and acceptance half angle, respectively. They thus argue that the number of photons received is determined approximately by the average electron density within the detector acceptance cone and that variously inclined showers thereby cause differing electron numbers to lie within that cone.

A plot of 60 showers observed by Chudakov *et al.* for $N > 8\times10^5$ and $\psi$ from 0 to 30 deg is shown in Fig. 17. It is apparent that the fluctuations are quite large, amounting to 40–50%. Chudakov *et al.* claim their experimental errors from shower-axis location, shower size, and light-intensity determinations amount to approximately 40%. Thus they imply that fluctuations do not play a large role in shower development at 3860 m, although they allow an upper limit of 40% from their data.

Kasha, Oren, and Sitte[32] state that the fluctuations they observe at sea level exceed those reported at 3860 m for two shower size groups: $7\times10^4$–$1.5\times10^5$. and $5\times10^5$–$10^6$. They observe greater fluctuations in the larger showers and attribute this to the larger zenith-angle interval over which the larger showers produce greater than minimum, although highly differing, amounts of light. No estimate of errors is given for these observations.

[32] H. Kasha, Y. Oren, and K. Sitte, J. Phys. Soc. Japan **17**, 108 (1962), Suppl. A-III.

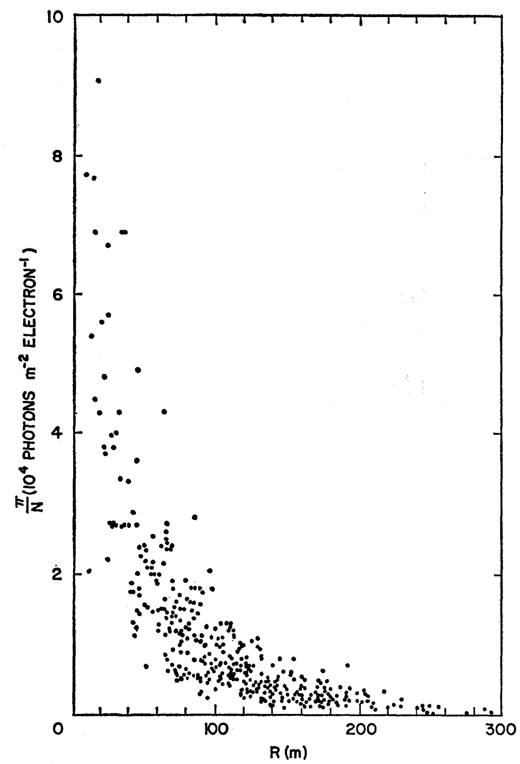


FIG. 17. Photons per cm²-particle observed as a function of $R$ for shower size $N > 8\times10^5$ and zenith angle between 0 and 30°. (From Chudakov *et al.*)

The result due to Chudakov *et al.*[1,29] that equal primary energies produce equal amounts of light in spite of the decrease of electron number with increased atmospheric depth would seem to argue that if fluctuations play a role at sea level, they must be comparably important at 3860 m.

More careful data to pinpoint the various specific functional dependences of the possible fluctuations is required before any conclusion can be reached on these points. In particular, the zenith angle must be accurately known if any correlation is attempted between detected light amplitude and shower size.

### Longitudinal Light Distribution

Just as Coulomb scattering of the electrons is an important process in the lateral development of the shower, so also this process is a determining factor in the longitudinal distribution of the light. In so far as the light detector simply measures the local electron density, the light should be distributed longitudinally at any instant in just the same manner as the particles. Thus with wide-angle light receivers the electron disk thickness measurements of Bassi, Clark, and Rossi[15] should be reproduced. However, with narrow-angle re-

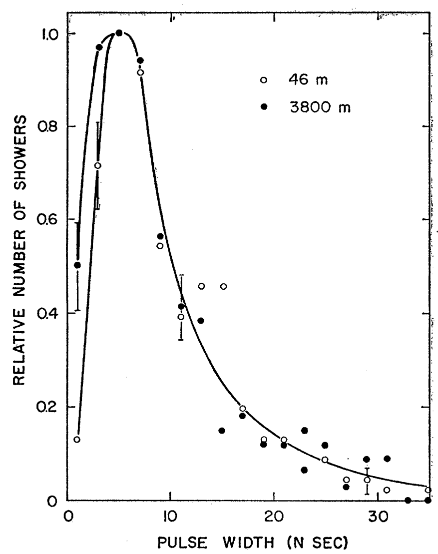


FIG. 18. Relative number of EAS producing Čerenkov light pulses of various widths at −46-m and 3801-m elevation.

ceivers of high sensitivity to near-vertical showers only, the longitudinal light distribution should be influenced by the electron paths over a wide range of heights.

To study the longitudinal light distribution, Boley *et al.*[26] measured the light intensity as a function of time using a photomultiplier of low-transit-time spread and fast oscilloscope display. The showers studied were selected to be vertically incident with axis positions within 10 m of a fast photomultiplier-parabolic mirror receiver. Shower direction and axis location were determined by timing of the light arrival at four receivers of the same general type placed at the vertices of a 65 m square around the primary receiver.

A first set of measurements was made at 2070 m. The observed disk thickness distributions for showers of energy $E_0 \gtrsim 10^{15}$ eV were not significantly different from those produced by a Monte Carlo calculation in which all scattering occurred in the last 2–3 radiation lengths. This result is surprising for vertically selected showers incident on such a detector; from what has been said to this point, greater dependence upon scattering at greater heights is expected.

The results of a second set of measurements[33] taken at −46 m and at 3801 m are shown in Fig. 18. The curves represent the relative rate of occurrence of showers with light pulse widths at half-maximum as shown. The two curves are normalized to give equal maxima. An increase in the number of showers with Čerenkov light thicknesses less than $5\times10^{-9}s$ at the higher elevations is apparent; otherwise the two distributions are very similar. Boley *et al.* conjecture that perhaps the effect upon the thinner light disks at higher elevations is caused by those showers containing relatively larger contributions from levels where Coulomb scattering is small. Thus, although much of the longitudinal spread can be accounted for by the scattering in the last few radiation lengths, there is some evidence of a dependence upon shower history. It is apparent that more detailed theoretical work is required to place these results in proper perspective.

### Detection of Sources of Cosmic Rays

The results reported by Galbraith and Jelley,[21] by Boley and Macoy,[22] and by Porter and Hill[17] on the relatively narrow angular spread of Čerenkov light produced by EAS has made the possibility of detecting point sources of the primary cosmic rays more attractive. This possibility was first explored by Jelley and Galbraith[9] who used photomultiplier tube-parabolic mirror detectors of 8.5, 4.7, and 2.2° acceptance half-angles. Observations of the plane of the Galaxy of Cassiopeia A, of Cygnus A, and of the Andromeda nebula gave no increase in flux from these objects for detector levels set to include showers with energy $E_0 \gtrsim 3\times10^{14}$ eV.

Since these early measurements, interest has grown in the suggestion of Morrison[34] that primary cosmic gamma rays should yield astrophysical information of importance since, for one thing, gamma rays are insensitive to magnetic fields intervening between their places of origin and of observation. Although Morrison's original idea related mostly to lower energy gamma rays, much interest is evident in the gamma rays produced in astronomical objects by the neutral $\pi^0$ decay, $\pi^0 \rightarrow 2\gamma$. It is supposed that the energy transferred to the photons in this decay equals that to the electrons in the $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ decay. Then since the electron energy associated with cyclotron radiation from radio sources such as the Crab nebula is about $10^{12}$ eV, the $\pi^0 \rightarrow 2\gamma$ photon energies should be comparable. Zatsepin[35] has estimated that the resulting $10^{12}$ eV photon flux from the Crab might amount to about 10% of the background cosmic ray flux in $10^{-3}$ sr.

On this basis, Chudakov *et al.*[35] have made a search for discrete sources of cosmic photons with energy of $10^{12}$–$10^{13}$ eV by looking for the Čerenkov radiation from the EAS these primary photons are expected to produce. Four single photomultiplier tube telescopes were used with 150-cm-diam mirrors and 6-cm photocathodes to form a receiver with about 1-deg angular acceptance. The effective recording area was estimated to be $10^5$ m$^2$ at $10^{13}$ eV. Figure 19 shows the histograms derived from passage of Cygnus A, Cas-

[33] F. I. Boley, J. A. Palsedge, and J. H. Baum, Phys. Rev. **126**, 734 (1962).

[34] P. Morrison, Nuovo Cimento **7**, 858 (1958).

[35] A. E. Chudakov, V. I. Zatsepin, N. M. Nesterova, and V. L. Dadykin, J. Phys. Soc. Japan **17**, 106 (1962), Suppl. A-III.

siopeia A, and Taurus A through the 1° field of view. Only Cygnus A shows an appreciable increase above background and this rise amounts to only 2.7±1.0%. For these histograms the counting rate was from 100–200 counts per minute and only those observations within 30° of zenith are included. These observers did not claim significance for the Cygnus A result. Further data concerning these observations have been given.[36] Nevertheless, additional investigation of arrival directions is in order. The photographic techniques of Porter and Hill, when extended to the greater sensitivity required for $10^{12}$–$10^{13}$ eV showers, should be of great utility.[37] The use of optical delay techniques to improve the signal-to-noise ratio in image intensifier systems has also been reported.[38]

Meanwhile, Maze and his co-workers[39,40] have argued that the EAS generated by photons and by protons should show differing ratios of electronic to penetrating components. By providing detection equipment that is sensitive to this ratio, they calculate an admixutre of one photon-initiated shower per $10^4$ proton-initiated showers to be detectable. Measurements carried out by this group suggest the presence of 0.3% of showers that may result from photon primaries.

Lateral distribution curves for the accompanying Čerenkov radiation were also given by Zatsepin and Cudakov[11] for photon-initiated EAS. Since these distributions differ from those due to proton initiation, another possible means of distinguishing the two is thereby provided.

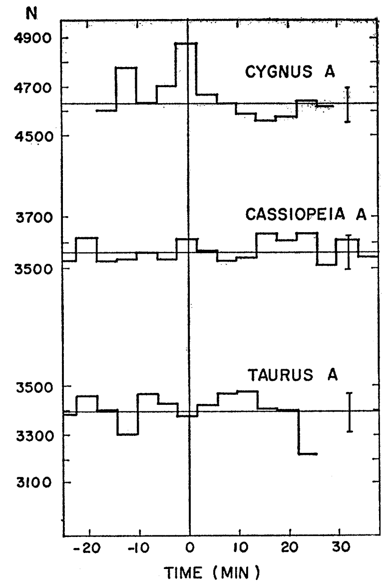


Fig. 19. Histograms of the passage of Cygnus A, Cassiopeia A, and Taurus A through the 1° field of view of the Čerenkov telescope used by Chudakov *et al.*

## IV. DISCUSSION

It should be clear that the combined complexities of the EAS, of the Čerenkov light generation by EAS, and of the detection geometries of the light make for a difficult theoretical and observational problem. However, much progress is evident.

A general, and in some instances a very detailed, view of the properties of the light has been provided by the various observers. The identification of the Čerenkov origin of the flashes is clear. With some reservations, the observational situation with respect to the lateral and longitudinal light distribution is in order. The small angular spread of the light makes it most interesting as a carrier of arrival direction information.

The theoretical work has made clear the crucial role of Coulomb scattering and has pointed up the questions pertaining to the treatment of inclined showers. A noteworthy achievement is the close agreement between the theoretical and observational determinations by the Soviet group of the lateral distribution of the light at distances beyond 30 m from the core.

A number of points obviously need further study. On the theoretical side it is clear that a detailed accounting of the development of the shower with depth in the atmosphere including the lateral density and angular distribution functions must be given. Results[30] have been obtained that suggest that the Nishimura–Kamata model is not adequate for describing the Čerenkov light emitting electrons in EAS. It seems clear that the Čerenkov light is not always, and perhaps is never, an approximation to an integral over the path length of the shower particle.

A further resolution of the effects of the angular spread of the light as it pertains to the lateral distributions at the observing plane and to the light as it appears in a telescope of finite aperture are important theoretically and observationally. In particular, the simultaneous observation of the lateral light distribution and the telescopic light image should yield useful information. These effects must be understood in detail before telescopes can be used with confidence in searches for sources of cosmic rays.

The discrepancies need to be reconsidered between the various measurements of the lateral light distribution particularly as these are reflected in shifts of the maximum intensity from the shower axis for near-

[36] A. E. Chudakov, Proceedings of the Fifth Inter-American Seminar on Cosmic Rays, La Paz, 1962 (unpublished).
[37] D. A. Hill and J. W. Overbeck, Proceedings of the Fifth Inter-American Seminar on Cosmic Rays, La Paz, 1962 (unpublished).
[38] J. V. Jelley and N. A. Porter, Quart. J. Roy. Astron. Soc. **4**, 275 (1963).
[39] R. Maze and A. Zawadzki, Nuovo Cimento **17**, 625 (1960).
[40] R. Firkowski, J. Gawin, A. Zawadzki, and R. Maze, J. Phys. Soc. Japan **17**, 123 (1962), Suppl. A-III.

vertical showers. Great care must be used in comparing results obtained from differing shower and detector geometries; both of these quantities require careful measurement in most observations.

There exist differing views of the role of fluctuations in EAS and the light produced. More detailed observations are required to clarify this question.

More measurements of the longitudinal light distribution coupled with a theoretical analysis of the contribution that various heights of the shower make to the time dependence of the received light would greatly supplement the shower development information obtained from lateral distributions. A direct comparison of the time distribution and amplitude of the light as detected by receivers of differing solid angle could provide additional information concerning longitudinal development.

## ACKNOWLEDGMENTS

The assistance provided by other workers in this field of research in the way of comments, and of reprints and preprints of their work is gratefully acknowledged.

Many thanks and much appreciation are extended to Walter O. Roberts and other members of the NCAR staff for their hospitality during the author's visit from the University of California, Lawrence Radiation Laboratory, Berkeley.