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LIGHT PULSES IN THE NIGHT SKY ASSOCIATED WITH EXTENSIVE COSMIC RAY AIR SHOWERS

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science

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Abstract.

Light pulses from the night sky have been detected at a maximum rate of 0.6 counts per minute, and have been shown to be associated with extensive cosmic ray air showers. An integral pulse height distribution has been found to be of the form $N(>H) \propto H^{-1.8}$. If the dependence of counting rate on zenith angle may be assumed to be of the form $\cos^n \theta$, the value for n for best fit is 3.7. The counting rate has been compared 'on' and 'off' three objects: the Large Magellanic Cloud, the Small Magellanic Cloud and looking out of the spiral arm of our galaxy in which our solar system is situated. No significant variation has been found.

CONTENTS.

C O N T E N T S. (Contd.)

PART II.

PART 1.

1. Introduction.

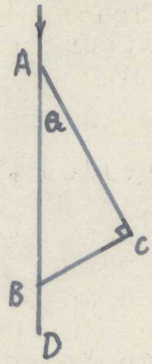
The present work on the detection of light pulses in the night sky associated with extensive cosmic ray air showers was undertaken at the suggestion of Dr. J. V. Jelley, who, with W. Galbraith, has pioneered the experimental work on this subject. Dr. Jelley has made available to us descriptions of his apparatus, and the apparatus in the present experiment is essentially the same as his.

Dr. Jelley has shown that the light flashes in the night sky are associated with extensive air showers, and most of the light detected is probably due to Čerenkov radiation from the electrons in these showers. I intend to anticipate this result by discussing the basic properties of Čerenkov radiation and some of the experimental results on extensive air showers, and the theories of distribution of Čerenkov light intensity from an extensive air shower on the ground. Two of Jelley's experiments to show that the light is largely due to Čerenkov radiation are interpreted by him on the basis of a light distribution theory which appears poor. These results are qualitatively discussed assuming another theory, which adds weight to the supposition that the light is predominantly Čerenkov radiation. Experimental work on the light flashes by various authors is discussed, and a brief survey of time variations of cosmic rays is given.

2. Čerenkov Radiation.

A. Theoretical Results of Frank and Tamm.

A charged particle traversing a medium at a constant velocity greater than the phase velocity of light in the medium emits electromagnetic radiation called Čerenkov radiation. This may be illustrated as in the figure.



AD is the path of the particle, and BC is the wavefront of the radiation. For other angles than θ, the radiated waves from all parts of the track interfere destructively.

If Δt is the time taken for the particle to travel from A to B, then AB $= \beta c \Delta t$, where βc is the velocity of the particle, and AC $= \frac{c}{n} \Delta t$, where n is the refractive index of the medium. θ_c, the angle at which the Čerenkov radiation is emitted to the path of the particle, is given by the relation

$$\cos\theta = \frac{1}{\beta n} \qquad \text{—(1)}$$

From the theory of FRANK and TAMM (1937), the energy E radiated per unit path as Čerenkov radiation is

$$\frac{dE}{dl} = \frac{e^2}{c^2}\int_{\beta n>1}\left(1-\frac{1}{\beta^2 n^2}\right)\omega\, d\omega \ \ \text{ergs/cm} \qquad \text{—(2)}$$

where e is the electronic charge, l the length of the path of the particle and $\frac{\omega}{2\pi}$ the frequency of the radiation.

These results have been experimentally confirmed in liquid and solid media by various authors e.g. ČERENKOV (1937) and COLLINS and REILING (1938).

B. Application of the Results of Frank and Tamm with the Medium Air.

For the purpose of the present work, the medium is the air of the earth's atmosphere. In this and subsequent sections of this thesis, the refractive index n and the Čerenkov angle θ_c will refer to the medium air. The following simplifications are made for equation (2) for air as the medium.

a/ Write $n = 1+\eta$ where $\eta = 2.9 \times 10^{-4}$ for air at N.T.P. and is small compared to one. The density of air is proportional to η and if η_H is the value of η at a height H above sea level and η_0 at sea lewel, then

$$\eta_H = \eta_0 e^{-2\alpha H} \qquad \text{—(3)}$$

where $2\alpha H$ is the exponent of the barometric pressure formula and $2\alpha \approx \frac{1}{8}$ km^{-1}

b/ The refractive index n is a function of ω, but in air over the wavelength range of interest in the present experiment, i.e. 3500-5500 A°, n is for practical purposes constant and independent of ω.

The total energy W of a particle of rest mass m_0 is given in terms of β by the relation.

$$\frac{W}{m_0c^2} = \frac{1}{(1-\beta^2)^{\frac{1}{2}}} \qquad \text{—(4)}$$

From the relations(1), (3) and (4), the Čerenkov angle θ_c for an electron in air is given by the relation:

$$\theta_c^2 \approx 2\eta_0 e^{-2\alpha H} - \left(\frac{m_0c^2}{W}\right)^2 \qquad -(5)$$

As W $\rightarrow \infty$, $\theta_c^2 \longrightarrow 2\eta_0 e^{-2\alpha H}$ and thus the maximum Čerenkov angle is 1·3° when H = 0.

Using the simplifications a/ and b/, equation (2) becomes:

$$\frac{dE}{dl} \approx \frac{e^2}{c^2}\left[2\eta_0 e^{-2\alpha H} - \left(\frac{m_0c^2}{W}\right)^2\right]\int_{\beta n>1} \omega\, d\omega \qquad -(6)$$

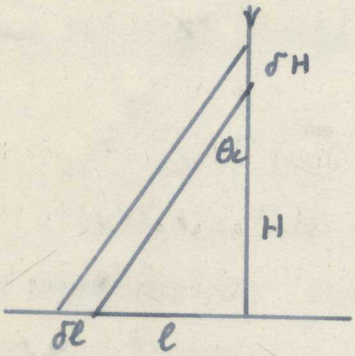
and from this may be obtained the number of photons emitted per cm. in air at N.T.P. between the wavelengths 3500 to 5500A° by an electron of energy W $\rightarrow \infty$. The number of photons is 0·25 /cm.

From the equation $\cos\theta_c = 1/\beta n$, the critical energy for emission of Čerenkov radiation occurs when $\beta = \frac{1}{n}$. Thus the critical energy W_c

$$W_c = 21 e^{\alpha H} \text{ MeV.}$$

3. Čerenkov Light Distribution from a Single Electron Travelling Vertically Through the Atmosphere.

The distribution of Čerenkov radiation on the ground from an electron travelling vertically through the atmosphere has been calculated by HOLDANSKY and ZHANDOV (1953) and JELLEY and GALBRAITH (1955). The type of distribution is simply indicated for an electron with $\beta=1$.



In the diagram it is seen that light falling at a distance between l and $l+\delta l$ comes from a height between H and $H+\delta H$ determined by the Čerenkov angle θ_c.

From the diagram

$$l = H\theta_c \qquad \text{—7 a.}$$

$$\delta l \approx \theta_c \delta H \qquad \text{b.}$$

for θ_c varies slowly with height. Substituting the value of θ_c as found in equation (5) in 7 (a),

$$l = H\theta_c$$

$$= \sqrt{2\eta_0}\, H e^{-\alpha H} \qquad \text{— (8)}$$

and by differentiating this equation the maximum value of l at sea level is 126m.

The energy emitted /cm. as Čerenkov radiation by an electron with $\beta = 1$ is obtained from (6)

i.e.

$$\frac{dE}{dH} \approx \frac{e^2}{c^2} 2 \eta_0 e^{-2\alpha H} \int_{\beta n > 1} \omega \, d\omega \qquad \text{—(9)}$$

The intensity $\phi(l)$ of Čerenkov radiation, falling at a distance l from the electron path is then

$$\phi(l) = \frac{dE}{2\pi l \, dl}$$

and from equations 7 (b), (8) and (9), and selecting light over the same range of wavelengths for all l

$$\therefore \phi(l) \propto \frac{1}{l} e^{-\alpha H} \qquad \text{— (10)}$$

$\alpha = \frac{1}{16}$ km^{-1}, thus the intensity of Čerenkov radiation falls off slightly more rapidly than l^{-1}.

4. __Extensive Air Showers__.

The following discussion is not given as a comprehensive survey of the subject, but an indication of results obtained. Extensive air showers are produced by the interaction of energetic primary cosmic rays on the earth's atmosphere. COCCONI (1946) terms a shower extensive for primary particle energies $\geq 10^{13}$ eV. The primary particles are ionised nuclei, and the ratio of protons: helium nuclei: heavy nuclei is approximately 100:10:1. This ratio and the flux are modified by the earth's magnetic field. Van ALLEN (1950) finds the flux of particles above an energy of 15 BeV. is 0.028 particles /cm^2 /sec./sterad. The integral energy spectrum of the primary particles is of the form

$$N(\geq E) = \frac{\text{constant}}{(1+E)^{\gamma}}$$

where the constant depends on the type of particle and γ is a slowly varying function of E, but seems to be independent of the type of primary particle (PETERS, 1952) The energy E is in BeV. The variation of γ with E is given by BARRETT et al. (1952), γ being approximately 1·1 for low energies and increasing to 1·7 for $E = 10^{15}$ eV. CRANSHAW AND GALBRAITH (1954) have found $\gamma = 1{\cdot}7$ over the range $10^{15}\,eV \leq E \leq 10^{17}\,eV$. The highest primary energy obtained is approximately 10^{19} eV, discovered by the Harwell team (results as yet not published).

Experimental results of COCCONI et al (1949) are typical of structure experiments on extensive air showers. Their apparatus consisted of a core selector, electron density detectors and a cloud chamber, and observations were made at a height of 3260m. Summarising the results:

a/ A unique correlation exists between the number of electrons at a distance r and r′ from the shower core, independent of the energy of the shower.

b/ The density of electrons at a distance r from the core agrees with the $\frac{1}{r}$ distribution as predicted by MOLIERE (1946) based on electron cascade theory.

c/ Approximately 2% of the total particles are penentrating particles (i.e. of mass heavier than that of the electron).

d/ The density of electrons at a distance 100m. from the core of a shower of energy $\sim 10^{17}$ eV. is approximately 500 electrons/m.^{2} .

e/ No evidence of multiple cores was detected. The arrangement would not detect multiple cores less than 5m. or greater than approximately 100m. apart.

HAZEN (1952,1954) has found multiple cores of estimated separation of the order of tens of cm.

An indication of the number of particles in an extensive air shower is given for an electron-photon cascade by BELENKII (1948). The number of electrons N_{max} at the shower maximum:

$$N_{max} = \frac{0.3}{\sqrt{\ln\left(\frac{W_o'}{72}\right)}} \frac{W_o'}{72}$$

where $W_o' = \frac{W_o}{2}$, where W_0 MeV. is the primary energy of the initiating particle and 50% of the energy is assumed given to the electron component. The number of electrons at a certain height above sea level in a shower varies with height, the number increasing with height to the height at which the maximum occurs. The number of electrons versus height is shown in curves given by BELENKII (1948) and MESSEL and JANOSSY (1951).

Theories of Distribution of Čerenkov Light from Extensive Air Showers on the Ground.

The average energy of electrons in extensive air showers is approximately 100 MeV., and since the critical energy for emission is 21 $e^{\alpha H}$ MeV. (see page 4.), most shower electrons do emit Čerenkov radiation. Čerenkov radiation from heavier particles than electrons may be neglected because:

(a) only 2·5% of the total number of particles are heavier particles (McCUSKER and MILLAR , 1951).

(b) The critical energy for emission of Čerenkov radiation for a particle of rest mass m_p is $\sim 21 . \frac{m_p}{m_e}$ MeV., where m_e is the rest mass of the electron, and thus only very high energy heavy particles emit Čerenkov radiation.

In the theories which follow, effects of dispersion, refraction and absorption of light are taken as neglible. The distribution of light on the earth's surface is calculated for a shower travelling vertically through the atmosphere, and the distance between the shower axis and the light detector is l.

A. JELLEY and GALBRAITH (1955).

The basic assumptions of this theory are:

(a) The Čerenkov angle θ_c is large compared to the angle of Coulomb scattering θ_P.

(b) The distance l from the light detector to the shower axis is large compared to the lateral displacement r of the shower electrons.

(c) $\beta \sim 1$ and only electrons of energy $\geq$ 100 MeV. are selected.

On the basis of these assumptions, the angle of scattering of the Čerenkov radiation is θ_c and r ≈ 0 . The intensity of the light at l will be the intensity of light due to a single electron travelling vertically through the atmosphere as found on page 6 multiplied by the number of electrons N_e^H at the height H as determined in equation 8.

i.e. $\phi(1) = \text{constant} \times N_e^H \times \frac{1}{l} e^{-\alpha H}$

Since N_e^H increases with height to the shower maximum, and the shower maximum occurs hight in the atmosphere, the intensity will fall off more slowly than $\frac{1}{l} e^{-\alpha H}$ as for a single electron.

Comments on basic assumptions:

a./ $\theta_c >> \theta_p$

From electron photon cascade theory as given by BELENKII (1948), the root mean square angle of Coulomb scattering of electrons is to a good approximation.

$$\sqrt{\overline{\theta_p^2}} = \frac{16.8}{W}$$

where W is the total electron energy in MeV. For $W = 100$ MeV.,

$\sqrt{\overline{\theta_p^2}} = 9.6°$. For $\theta_c = \sqrt{\overline{\theta_p^2}} = 1.3°$ for sea level and $\beta \sim 1$, as found on page 4, the value of W is 740 MeV. The integral energy spectrum of the shower electrons to a first approximation is given by BELENKII (1948) as

$$B(W) = \frac{14.4}{W} \quad \text{for air.}$$

Thus the number of electrons of energy $\geqslant$ 100 MeV which are scattered with $\sqrt{\overline{\theta_p^2}} \geqslant \theta_c$ is approximately 86% of the total number of electrons of energy $\geqslant$ 100 MeV. This first approximation of Jelley's is poor.

b/ $l >> r$

BELENKII (1948) gives the root mean square radius of lateral distribution of electrons of a given energy W:

$$\sqrt{\overline{r_W^2}} \approx \frac{6000}{W} e^{2\alpha H} \quad \text{metres}$$

For W = 100 MeV, $\sqrt{\bar{r}_W}$ = 60 $e^{2\alpha H}$ metres. The maximum value l at which light may be detected from Jelley's theory is 126 metres, from page 5 . This second approximation of Jelley's is also poor.

(c) For values of $W \geq 100$ MeV, the energy radiated as Čerenkov radiation is to a very good approximation the same as for $\beta = 1$. The probable reasons for selecting energies greater than 100 MeV are that

(i) higher energy electrons will be less scattered from the core and so $l \gg r$ is a better approximation.

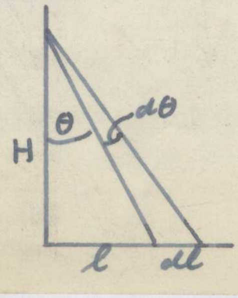
(ii) a theory is available for the N_e^H distribution based on nucleon-electron cascade theory for electrons of energy ≥ 100 MeV . Results of this theory are given by CRANSHAW and GALBRAITH (1953).

B. Radial Approximation Theory.

This theory has been worked out by various persons in the Sydney School of Physics, including Mr. B. Chatres, and Dr. E. P. George and myself.

The assumption $l \gg r$ and $\beta \sim 1$ are the same as for the previous theory. A Coulomb scattering function is taken from the electron cascade theory of MOLIERE (1946). The proportion of electrons at a height H directed between θ and $\theta + d\theta$ to the shower axis is

$$f(\theta)\,d\theta = \text{constant} \times e^{-7\theta}\,d\theta$$



This theory holds for distances $l >> r$, but this approximation is good for large distances since l is not limited as in the previous theory by θ_c . The light is assumed to be detected by a circular detector of area S and radius R. Values of l are taken greater than 126m., so the scattering angle is greater than the Čerenkov angle, which is assumed neglible.

The light detector is at a distance l from the core of the shower, and from the diagram, for detection of light

$$l = H\theta \qquad \text{—(13)}$$

Since θ_c is approximated to 0, the fraction of light detected from a height H emitted between angles θ and $\theta + d\theta$

$$= \frac{S}{2\pi l \cdot 2R}$$

The energy emitted as Čerenkov radiation is given in equation 6 for a height H, and so the intensity at l :

$$\phi(l) = \text{constant} \times \int_H N e^H \times e^{-2\alpha H} \times \frac{S}{2\pi l \cdot 2R} e^{-\tau\theta} d\theta \, dH$$

$$= \text{constant} \times \frac{S}{l} \int_H \frac{N e^H e^{-2\alpha H} e^{-\frac{\tau l}{H}}}{H} dH \qquad \text{— 14}$$

by substitution of equation (13) and $d\theta \approx \frac{2R}{H}$

The limits of H are determined by the detector. For a vertical detector of field of view determined by a cone of semiangle a , the lower limit of H is $\frac{l}{a}$. The upper limit of H is determined by when $N e^H e^{-2\alpha H}$ becomes small. This occurs for heights of H past the shower maximum.

The results of this theory are not shown because of the better theory C. The intensity at large values of l should be the same as for the Theory C.

C. HOLDANSKY and ZHANDOV (1953).

This theory is the first to take into account both the lateral and angular structure of extensive air showers. Although published in Russia in 1953, it was not noted by Western authors until after the other theories were made. I intend to discuss it in detail, because the interpretation of some of Jelley's experiments is modified because of it.

The theory is based on electron cascade theory, as given by BELENKII (1948).
The more difficult case of a nucleon-electron cascade has not been worked out. Approximations are made because of the not fully known angular and radial distribution of the particles in the shower.

The basic assumptions are:

(i) The integral energy spectrum of electrons B(W):

$B(W) = \frac{144}{W}$, where W is the total energy in MeV.

(ii) The root mean square radius of the lateral distribution of the electrons of a given energy W is

$\sqrt{\overline{r_W^2}} = \frac{6000}{W} \frac{P_0}{P_H}$ metre where P_0 and P_H are the atmospheric pressures at sea level and a height H respectively.

(iii) The root mean square angle of Coulomb scattering of the electrons

$$\sqrt{\overline{\theta_P^2}} = \frac{16.8}{W} \text{ radians}$$

(iv) For an extensive air shower, the number of electrons Ne^H at a height H is related to the number of electrons at sea level Ne^0 by the formula

$$Ne^H = Ne^0 \, e^{\frac{p_0 - p_H}{\Lambda}}$$ where Λ = constant,

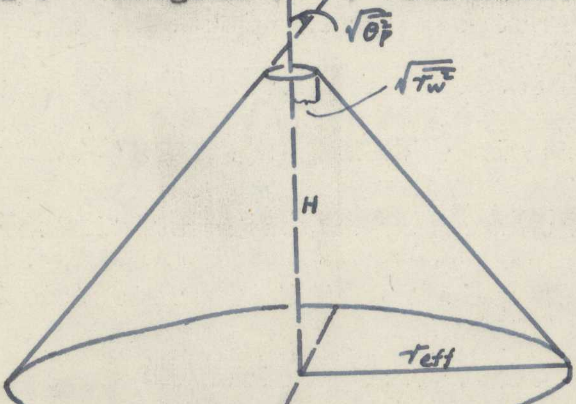
up to H = 8km., where Ne^H reaches a maximum.

At an arbitary height H all the electrons of a given energy W are proportionally distributed over a circle of area $\pi \overline{r_W^2}$. For scattering in which Coulomb scattering is predominant, the intensity of light from the height H will be equally spread over a circle of radius

$$r_{eff.} = \sqrt{\overline{r_W^2}} + H \tan \sqrt{\overline{\theta_p^2}}$$

For $\sqrt{\overline{r_W^2}} = 0$, 50% of the electrons will be directed through $\sqrt{\overline{\theta_p^2}}$, but for $\sqrt{\overline{r_W^2}} \neq 0$, 50-100% of the electrons will be directed through $\sqrt{\overline{\theta_p^2}}$, the percentage depending on $\sqrt{\overline{r_W^2}}$ and $\sqrt{\overline{\theta_p^2}}$. An arbitary value of 75% is taken as an approximation.

For scattering in which $\sqrt{\overline{\theta_p^2}}$ is predominant, a circle of radius r_{eff} is approximately proportionally illuminated. Diagram (i) illustrates this.



(i)

The number of light quanta collected by a circular detector of radius R and area S at a distance l from the shower axis is determined as follows. The detector 'sees' light emitted at a height H from electrons of energy W for values of W $\leq W_{max}$, where $W_{max.}$ is determined by l and H. The light from one height H is first determined by integrating over the energy W, and the total contribution from all heights by then integrating over all heights.

Case (A) $\sqrt{\overline{\theta_p^2}} \geq \theta_c$ and θ_c is neglected. The number of light quanta ($\lambda \sim 5500$ Å) emitted in 1 metre of path by an electron as Čerenkov radiation is

$$= 5.10^4 \sin^2\theta_c \approx 5.10^4 \theta_c^2$$ as calculated from eqn. (6) on page 4 .

From Equation (5) on page 4

$$\theta_c^2 \approx 2\eta_0 e^{-2\alpha H} - \left(\frac{m_0c^2}{W}\right)^2$$

Thus the number of quanta at a distance l from the axis of the shower is

$$\phi_1(l) = 5.10^4 \, N_e^0 \times 0.75\, S \int_0^{H_{max}} \exp.\left(\frac{P_0 - P_H}{\Lambda}\right) dH$$

$$\times \int_{W_{THR}}^{W_{max}} \theta_c^2 \, \frac{dB(W)}{dW} \times \frac{1}{\pi (r_{eff})^2} \, dW \qquad (15)$$

Now

$$r_{eff.} \approx \sqrt{\overline{r_W^2}} + H\sqrt{\overline{\theta_p^2}}$$

$$\approx \frac{6000\, e^{2\alpha H} + 16.8H}{W}$$

where $2\alpha H$ is the exponent of the barometric pressure

i.e. $P_H = P_0\, e^{-2\alpha H}$

Thus (15) becomes

$$\phi_1(l) = 5.10^4 \, N_e^0 \times 0.75 \frac{Sa}{\pi} \int_0^{H_{max}} \frac{\exp\left(\frac{P_0 - P_H}{\Lambda}\right) dH}{(6000\, e^{2\alpha H} + 16.8H)^2}$$

$$\times \int_{W_{THR}}^{W_{max}} \left[2\eta_0 e^{-2\alpha H} - \left(\frac{m_0c^2}{W}\right)^2\right] dW \qquad (16)$$

W_{THR} is the threshold energy for Čerenkov radiation i.e. 21 $e^{\alpha H}$ MeV. as found on page 4 .

W_{max} is determined by either (a) $r_{eff} = l$ or (b) $\sqrt{\overline{\theta_p^2}} = \theta_c$

The condition (a) when $r_{eff} < l$, the light is not 'seen', and (b) the scattering due to Čerenkov radiation predominates.

i.e. $$W'_{max} = \frac{6000 e^{2\alpha H} + 16.8 H}{l} \quad \text{for (a)}$$

and $$W''_{max.} = 700 e^{\alpha H} \quad \text{for (b)}$$

and the heights over which to be integrated are determined by these conditions.

Case B. $\theta_c \geq \sqrt{\overline{\theta_p^2}}$ and the Coulomb scattering is neglected. The minimum energy at which this occurs is 700 $e^{\alpha H}$ MeV . Holdansky determined the light distribution for energies $\geq 700 e^{\alpha H}$ MeV. by the same method as Jelley, described on page 9 . This assumes that $l \gg \sqrt{\overline{r_W^2}}$. The maximum radius of $\sqrt{\overline{r_W^2}}$ may be determined from page 13 , and $W_{min.} = 700 e^{\alpha H}$ MeV.

i.e. $$\sqrt{\overline{r_W^2}} = 8.6\, e^{\alpha H} \text{ metres}$$

This approximation is good for most values of l. The number of light quanta $\phi_2(l)$ (l) from electrons of energy $\geq 700 e^{\alpha H}$ MeV is

$$\phi_2(l) = 5.10^4 . N_e^0 \frac{Sa}{4\pi l R} \int e^{\frac{p_0 - p_H}{\Lambda}} dH \int_{700 e^{\alpha H}}^{\infty} \frac{\theta_c^2}{W^2} dW$$

$$= 5.10^4 N_e^0 \frac{Sa}{4\pi l R} \exp\left[\frac{p_0 - p_H}{\Lambda}\right] \frac{\Delta H \times 2 \eta_0 e^{-2\alpha H}}{700 e^{\alpha H}} \qquad (17)$$

The total number of light quanta at l is $\phi(l)$, where

$$\phi(l) = \phi_1(l) + \phi_2(l)$$

. This has been calculated by Holdansky and Zhandov for $S = 500\ cm^2$ and the light distribution is shown in the graph on page 17A. From equations (16) and (17) it is seen that $\phi_1(l) \propto S$ and $\phi_2(l) \propto \frac{S}{R}$. In table I I have calculated the values of $\phi_1(l)$, and $\phi_2(l)$ for $S = 2800cm^2$ as used in the present experiment. Thus

$$\phi(l) = \frac{S}{S_0}\,\phi_{1,0}(l) + \frac{R}{R_0}\,\phi_{2,0}(l)$$

where S_0 and R_0 refer to the original values, i.e. $S = 500cm^2$ and $\phi_{1,0}(l)$ and $\phi_{2,0}$ (l) are as calculated for the case $S = 500cm^2$.

T A B L E I.

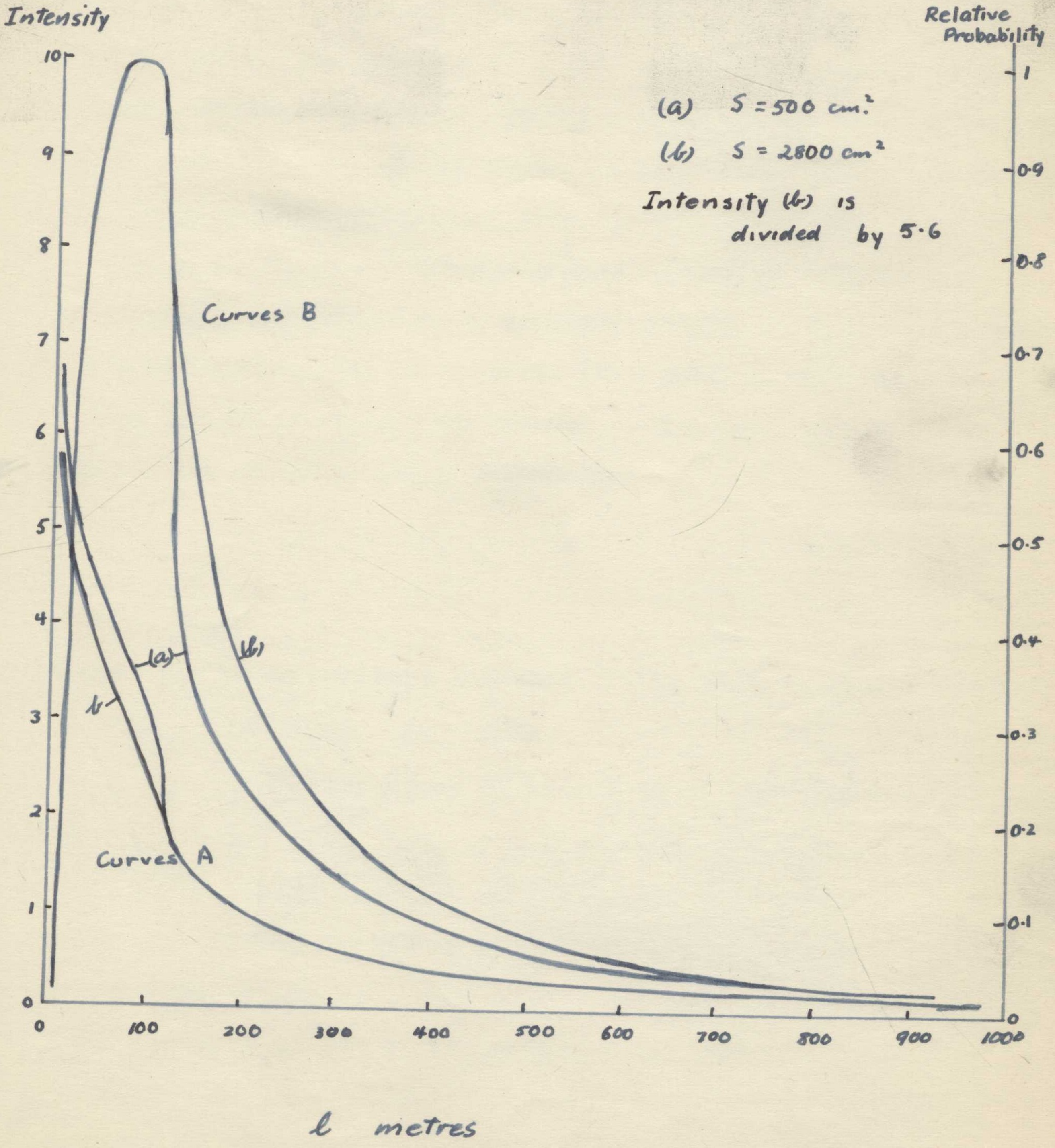
l metres	10	30	65	100	115	130	200	300	500	1000	2000
$\phi_1(l)$	262	212	154	119	104	90·4	54·2	31·6	14·1	4·0	·4
$\phi_2(l)$	59	30	27·6	24·5	18·7	0	0	0	0	0	0
$\phi(l)$	321	242	181·6	143·5	122·7	90·4	54·2	31·6	14·1	4·0	·4
$\frac{l}{l_0}\left(\frac{\phi}{\phi_0}\right)^{1.8}$	·43	·78	·985	1	·87	·56	·35	·21	·074	·016	

The amplitude of flashes are referred to one shower electron in units $\frac{\phi(l) \times 10^2}{N_e^0}$ of photons.

The relative probability of detection of an extensive air shower at a distance l from the receiver may be determined. The number of particles at the shower maximum is

ČERENKOV LIGHT INTENSITY Vs. l metres: CURVES A.

RELATIVE PROBABILITY OF RECORDING A ČERENKOV PULSE AT l Vs. l metres: CURVES B.



given by

BELENKII (1948) as

$$N_{max.} = \text{constant} \times \frac{W_0'}{\sqrt{\ln\left(\frac{W_0'}{72}\right)}}$$

where W_0' is in MeV. and W_0, the energy of the primary causing the shower, equals 2 W_0'. For a limited energy range N_{max} is approximately proportional to W_0. Thus if N_e^H is proportional to W_0 over all heights, then $\phi(l) \propto W_0$. Holdansky quotes the integral energy spectrum of the primaries as proportional to $W^{-1.8}$, and since the probability of a shower core falling at a distance l from the detector is proportional to l, then the relative probability of detecting a shower at l

$$= \frac{l}{l_0} \left[\frac{\phi(l)}{\phi(l_0)}\right]^{1.8} \qquad \text{—(19)}$$

where l_0 is an arbitary distance. (19) is plotted on the graph on page 17A for l_0 = 100m.

The frequency of detection of light pulses is then

$$f = 2\pi l_0 f_0 \int_0^\infty \frac{l}{l_0} \left[\frac{\phi(l)}{\phi(l_0)}\right]^{1.8} dl \qquad \text{—(20)}$$

where f_0 is the frequency of observation of flashes, appropriate to l_0.

Comments on Theory of Holdansky and Zhandov.

This light distribution theory may be regarded as only very approximate. An accurate theory would have to take into account the penetrating component, thus modifying the extensive air shower structure of a pure electron-photon cascade. The theory is based on many approximations e.g. (i), (ii), (iii) and (iv) on page 13, the assumption that 0·75 of all the electrons are directed into a circle of radius r_{eff} independent of τ_w and θ_p, and the assumption that for $\sqrt{\overline{\theta_p^2}} \leq \theta_c$, $\sqrt{\overline{\theta_p^2}}$ is taken as 0. Yet this is the first theory that takes into account both the angular and radial distribution of the shower, and I intend to discuss various experimental results of Čerenkov radiation to see if these results are generally in accord with the theory.

6. Nature of Light Flashes Associated with Extensive Air Showers.

In the previous section the various theories of the distribution of Čerenkov light intensity on the ground from an extensive air shower have been discussed. There are two other main processes which give rise to light pulses associated with showers:
Bremsstrahlung and the recombination radiation following ionisation. The table below compares some of the properties of the three processes.

Type of Radiation	Meanangle of emission for a 100 MeV. electron	Polarised	Spectrum
Bremsstrahlung	$\theta \sim \frac{mc^2}{E} \sim 0.3^\circ$	Yes	Continuous
Čerenkov	$\sim 0.9^\circ$	Yes	Continuous
Recombination Ionisation	isotropic	No	Line

From HEITLER (1949), assuming complete nuclear screening, and that the Bremsstrahlung spectral and angular distributions hold for the wavelengths 4000-8000 Å, the number of photons emitted per cm. track in air at N.T.P. is 6×10^{-6}, compared to 0·5 as Čerenkov radiation. The Bremsstrahlung may thus be neglected compared to Čerenkov radiation.

There seems to be little data on the intensity of radiation associated with recombination processes following ionisation. Since this process is possibly significant in light pulses from extensive air showers, Jelley (BARCLAY and JELLEY, 1955) has compared the light intensity scattered in a forward direction to that emitted isotropically for a μ meson in 6m. of air at atmospheric pressure. The forward directed light intensity is consistent with that of Čerenkov radiation as predicted by FRANK and TAMM (1937). The isotropic light was found to be less than 10^{-2} of the forward directed light.

Equal intensities of Čerenkov radiation are emitted by μ mesons and electrons of the same β (equation 2, page 2). Whether the light from recombination ionisation processes is approximately the same for μ mesons and electrons of the same β is difficult to predict. If this may be assumed, it is most probable that the light flashes from the night sky are due to the Čerenkov effect.

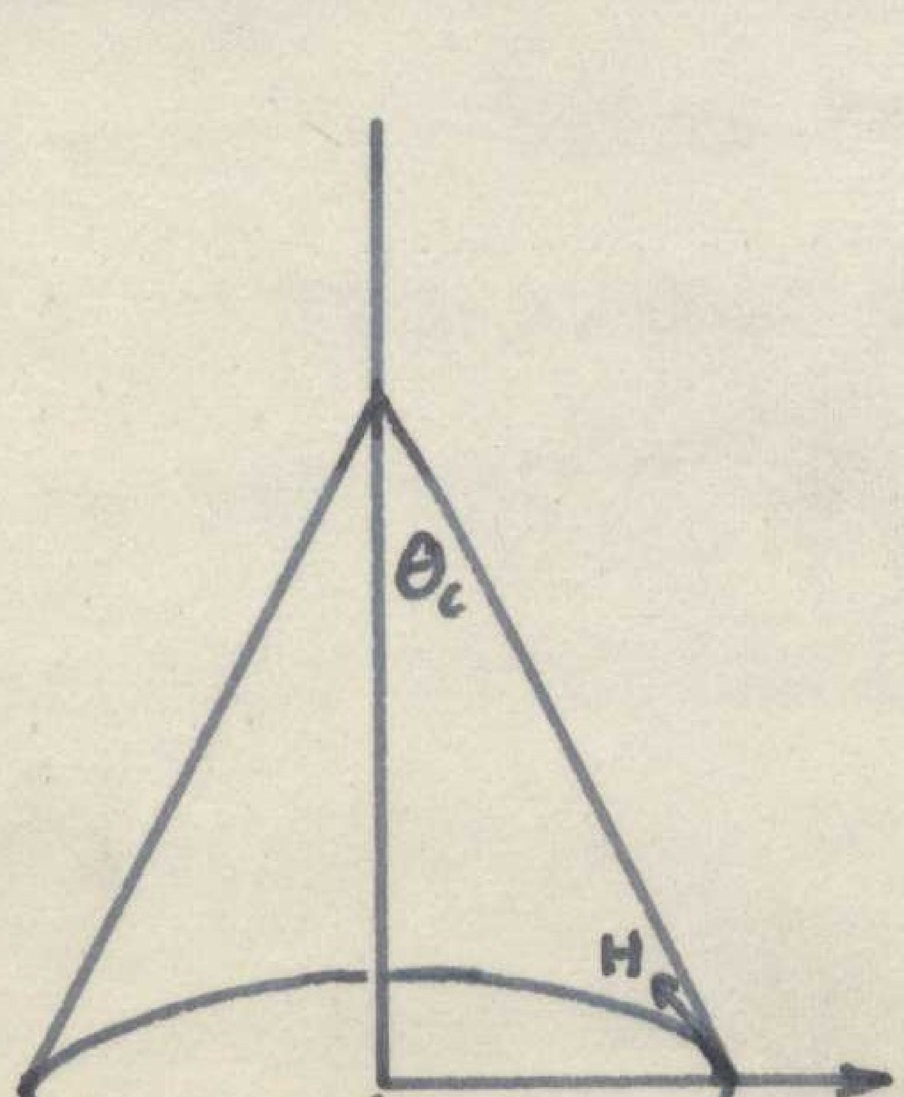
Experiments of JELLEY and GALBRAITH (1955).

The light detector used to detect the light pulses consists of a photomultiplier at the focus of a parabolic mirror and electrical pulses from the photomultiplier are amplified and put into a discriminator. A noise level is defined as that bias at which noise pulses are detected by the discriminator at one pulse per second. The discriminator is usually set at 2x. The noise level, and at this setting the noise pulse rate is neglible compared to the light pulse rate. By means of varying the intensity of an artificial light placed near the photomultiplier, the phototube current may be kept constant, and thus the noise level may be kept constant. This is done in all experiments in which a comparison of counting rates is made.

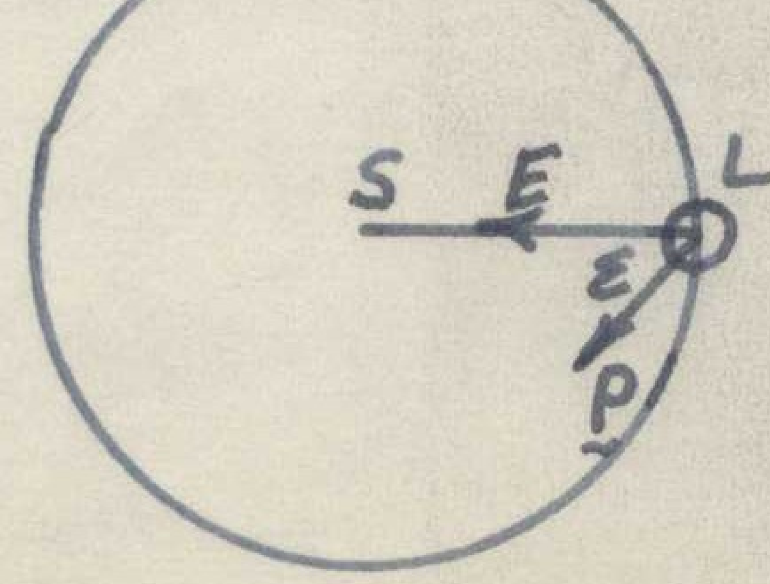
To determine the nature of the light, Jelley and Galbraith carried out the following experiments at the height 2860m.

(A) Polarisation Experiment.

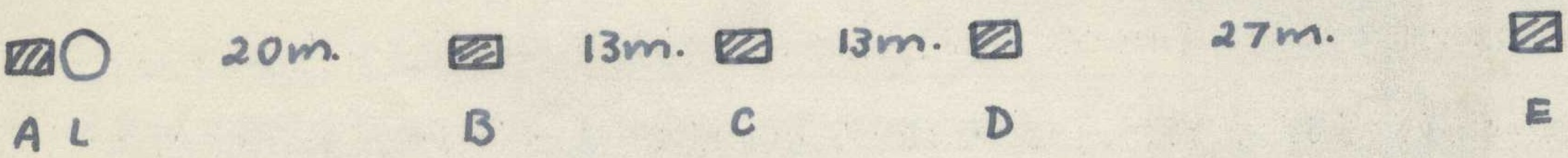
The polarisation of Čerenkov radiation is shown diagrammatically below in (i) where E and H are the electric and magnetic vectors respectively.



(i)



(ii)



(iii)

The experiment is designed to see if some of the light is polarised. Taking the Bremsstrahlung radiation as neglible compared to Čerenkov radiation in the range of wave-lengths 3500-5500A^{0}, a polarisation effect would indicaté at least some Čerenkov radiation present. In diagram (ii) S is the core of a vertical shower and L a light detector. A polariser is placed over the photocathode of the photomultiplier, and ε is the angle between SL and the plane of polarisation $\underset{\sim}{P}$. Assuming Jelley's theory of Čerenkov radiation, the Čerenkov light would be plane polarised along SL, and the intensity of Čerenkov light at a point on the circle described by SL will be proportional to $\cos^2 \varepsilon$.

In diagram (iii) L is a 61cm. diameter light detector with a field of view $\pm 18^{0}$ and A, B, C, D and E are geiger counter trays, each tray having an effective area of 800cm^2. The energy of the extensive air showers detected is approximately $3 \cdot 10^{14}$ eV, and the positions of the cores are defined only very approximately along the line AE. The polarisation effect is sought by comparing the counting rates for $\underset{\sim}{P}$ parallel and perpendicular to SL.

The results are summarised below.

	Coincidences between Čerenkov detector and					
Polaroid vector	one of trays A. -E	BC	CD	DE	BcD	CDE
Parallel to AE	195	46	48	27	26	9
Perpendicular to AE	185	19	12	9	22	10

There appears to be a significant effect for two fold geiger coincidences, but none for single and threefold geiger coincidences.

If the positions of the shower cores were accurately determined and Čerenkov radiation was the predominant radiation detected, then, assuming Jelley's theory, the polarisation effect would be very pronounced. Holdansky and Zhandov predict that much of the light is scattered at wide angles. The polarisation effect observed on the ground will be neglible. for light from angles $\sqrt{\overline{\theta_p^2}} > \theta_c$. For a 61cm. diameter light receiver at sea level, the number of light quanta received at a given value of l for the cases $\sqrt{\overline{\theta_p^2}} \geqslant \theta_c$ and $\theta_c \geqslant \sqrt{\overline{\theta_p^2}}$ is given in table I on page 17. The ratio of the number of light quanta from angles $\theta_c \geqslant \sqrt{\overline{\theta_p^2}}$ to the total number of quanta received at a given l varies from 0·12 to 0·18 for values of l between 10 and 115m. and is 0 for l $\geqslant$ 126m. A polarisation effect would be expected for light when $\theta_c > \sqrt{\overline{\theta_p^2}}$, being most pronounced when $\theta_c >> \sqrt{\overline{\theta_p^2}}$. The previous mentioned ratio will be different at the 2860m. height at which the experiment was carried out, but it is expected that the ratio will still be small.

The polarisation effect will depend on;

(a) The fraction of light which is Čerenkov radiation

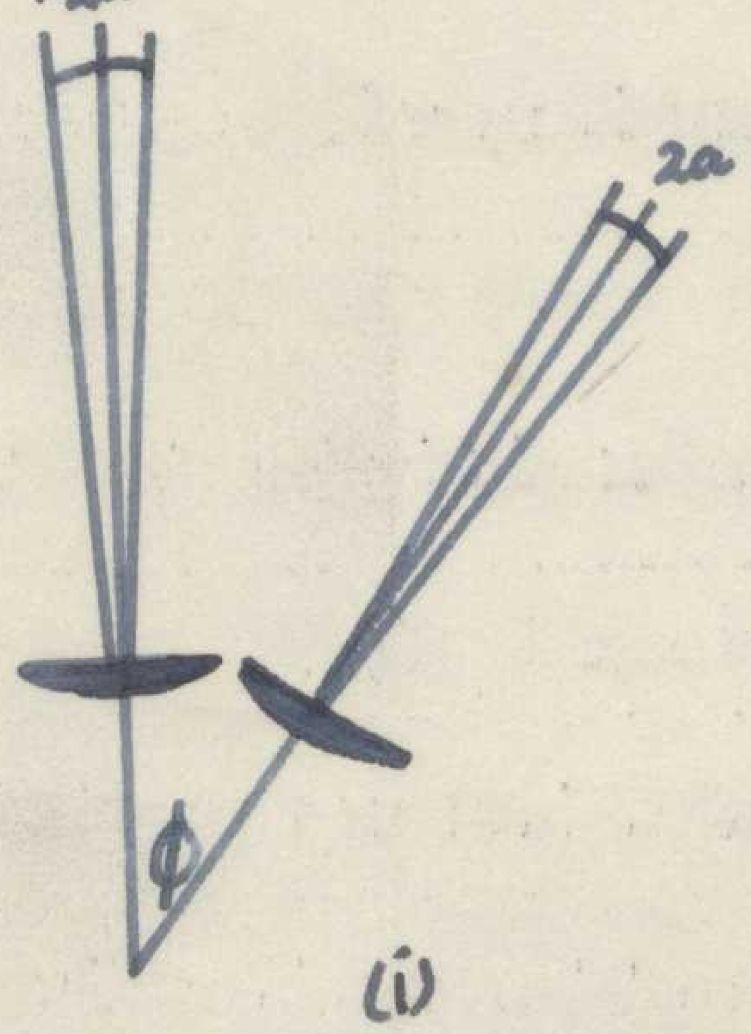
(b) The fraction of the Čerenkov light at a given l which is polarised in one direction and not in other directions.

(c) The accuracy of location of the shower cores by the geiger counters.

I think a quantitative discussion on the magnitude of the polarisation effect to be expected is impracticable until an accurate positioning of the shower cores is made at the same time as a polarisation effect sought. Jelley interpreted the polarisation effect being small because of inaccurate location of the shower cores. On the basis of the theory of Holdansky and Zhandov a polarisation effect would be small even with well located shower cores, and so the presence of a polarisation effect is strong evidence that the light is predominantly Čerenkov radiation. Thus, qualitatively, the light is most likely to be predominantly Čerenkov radiation. I cannot explain the absence of a threefold effect and the presence of a two fold effect.

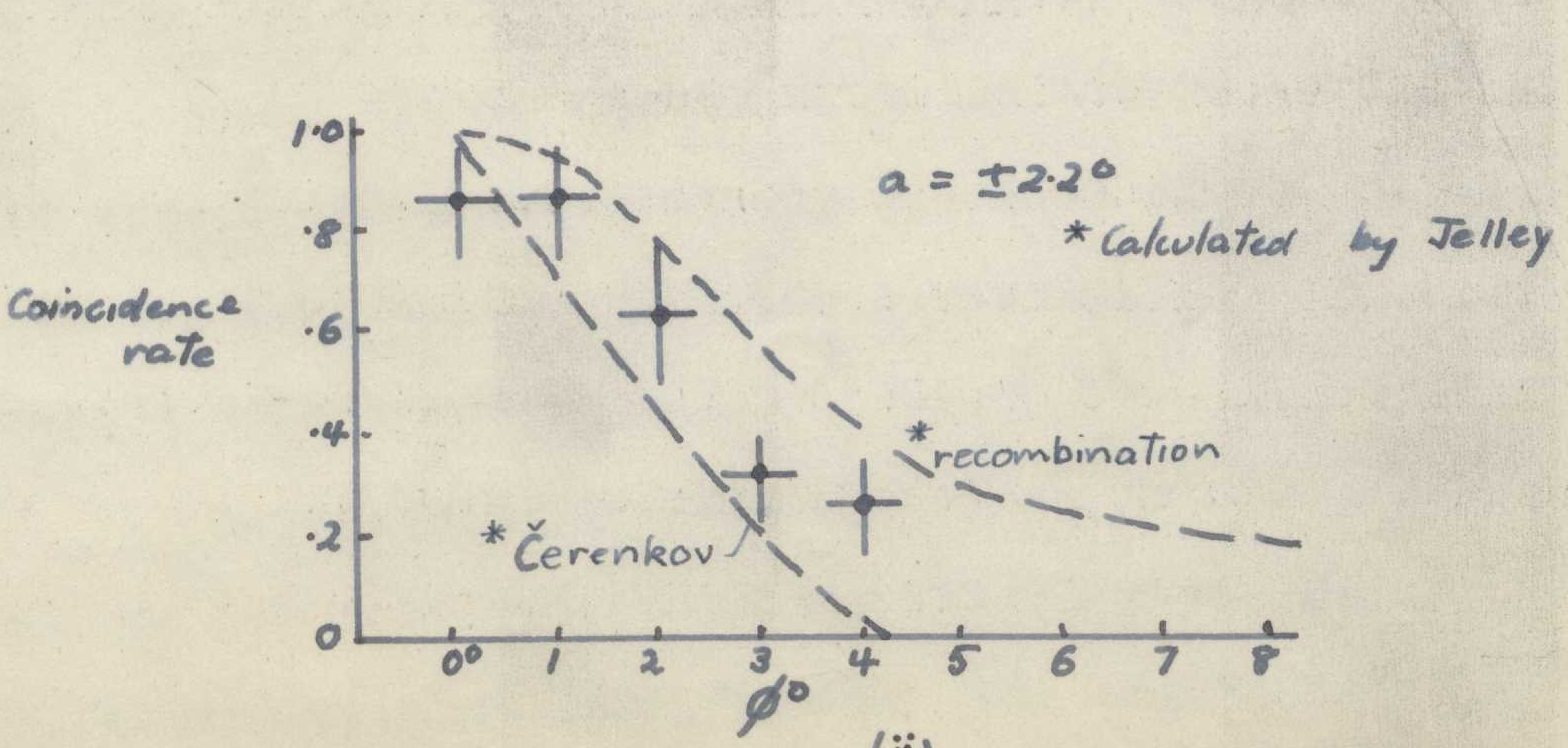
B. <u>Directional Property of the Light</u>.

The second experiment to determine the nature of the radiation, i.e. Čerenkov or recombination, is as follows. Two similar light detectors with a field of view a cone of semi-angle a are placed close to each other (~ 1 metre), but at directions at an angle ϕ to each other as shown in the diagram (i).



(i)

A shower triggers the vertical detector, and the coincidence counting rate of the two receivers is plotted as a function of ϕ for two values of a : $2{\cdot}2^{o}$ and $3{\cdot}6^{o}$. On the basis of Jelley's theory i.e. $l \gg r_W$ and $\theta_c \gg \sqrt{\bar{\theta}_p^2}$ and since $a > \theta_c$, the coincidence rate is zero when $\phi > 2a$. The coincidence rate for light produced by recombination ionisation will not be zero for $\phi > 2a$, because light is emitted isotropically and thus part of the shower core which is not 'seen' assuming $\theta_c > \sqrt{\bar{\theta}_p^2}$ is 'seen' for isotropic light. The graph as found by Jelley is given below. From this graph it would appear



(ii)

that there is in fact a recombination ionisation effect which is significant. Again a quantitative discussion is impracticable but qualitatively on the basis of Holdansky's and Zhandov's theory the coincidence counting rate will fall off more slowly than as predicted by Jelley because of large angle Coulomb scattering of the electrons. The results of the experiment are consistent with the light being predominantly Čerenkov radiation, which does not seem likely when based on Jelley's theory.

C. <u>Experiments with colour filters</u>.

A precise spectral distribution of the light is impracticable because of the low light intensity. Two colour filters, a blue and a green one, were used and the counting rate compared for a fixed bias level set on the discriminator. The response of the photo-multiplier with each of the filters over it was compared. The ratio of the counting rates of the blue and green filters was $4 \cdot 3 \pm 0 \cdot 4$ to 1. The expected ratio of the counting rates, found from the relative spectral responses of the filters over the photocathode and from an integral pulse height spectrum $N(>H) = \text{Const } H^{-1 \cdot 8 \pm 0 \cdot 2}$ and from the theoretical predictions of Čerenkov radiation is $4 \cdot 0 \pm 1 \cdot 0$., which agrees within the errors to that found. This experiment shows that the spectral distribution is at least consistent with Čerenkov radiation.

<u>Comments on Experiments</u>.

Experiments B and C do not conclusively show that the light is predominantly Čerenkov radiation, but do not contradict this supposition. The existance of a polarisation effect in experiment A gives the most definite indication that the light is predominantly Čerenkov radiation.

7. Counting Rates at Sea Level.

To discuss the counting rates at sea level it is necessary to indicate what determines the minimum light pulse detectable.

A. This minimum pulse is partly determined by the background intensity of light of the night sky, which consists of: (HULBERT, 1951)

(a) a great number of spectral lines, mainly emitted from heights between 50 and 200 km. by ionised gases, and comprising on the average, 4/5 of the total light intensity of the night sky.

(b) a continuous spectrum from stars, etc.

From calculation of the gain of the photomultiplier (see page 52) and taking the photocathode sensitivity as 20μamp/lumen (photomultiplier data sheets), the total photon flux between 3500 and 5500A^{o} as measured in the present experiment from dark regions in the sky is $2 \cdot 4 \times 10^{9}$ photons/cm.^{2} /sterad./ sec., accurate to an order of magnitude only because of a large possible error in the gain determination. This flux is increased by a factor of approximately two for brighter regions of the sky.

HULBERT (1951) reports that there is no indication of a latitude variation in the background intensity of the night sky, and for comparing counting rates the light intensity from the dark regions of the sky will be taken as the same.

B. The minimum light pulse detectable depends on the arbitary method of selecting noise pulses. JELLEY and GALBRAITH (1953) take the noise level as that bias of the discriminator at which noise counts are recorded at 1/sec. The Čerenkov pulse is then selected at a bias level at which noise pulses are neglible.

C. The method of taking the pulse from the photomultiplier also determines the minimum light pulse detectable. This is more fully discussed on page 59, but is not important for the comparison below since this apparatus is the same in both cases.

JELLEY and GALBRAITH (1953), using a light detector of $S = 500cm^2$ and field of view a cone of semi-angle $a = \pm 12^\circ$, obtained a counting rate at sea level of 60 per hour for an estimated light pulse of 1300 photons detected. Calculations by Holdansky and Zhandov for equation (20) show that the expected counting rate for a minimum number of 1300 photons is 70/hr., which closely agrees with the 60/hr. found.

An indication of the expected counting rate may be obtained for the present experiment, in which $S = 2800cm^2$, $a = \pm 5^\circ$ and the detector is at sea level. The background noise level is to a good approximation the same for both cases. The amount of background light detected is proportional to Sa^2 and $\frac{S_1 a_1^2}{S_2 a_2^2} \sim 1$ where the subscripts 1 and 2 refer to Jelley's and the present experiment respectively. The relative probability of detection of a shower at a given l is approximately the same for both cases, as seen in the graph on page 17A, and so the integral (20) is approximately the same. Although $\phi(l) = \frac{S}{S_0}\phi_1(l) + \frac{R}{R_0}\phi_2(l)$, to a good approximation $\phi(l) \propto S$ because $\phi_2(l) << \phi_1(l)$. Now the number of shower cores falling in a core of semi-angle a is proportional to a^2. In the present experiment an integral pulse height distribution $N(>H) \propto H^{-1.8}$ was found. Since similar photomultiplier circuits have been used in both cases, the expected counting rate for pulses greater than 3x noise as used in Jelley's experiment

$$= \left(\frac{S_2}{S_1}\right)^{1.8} \times \left(\frac{a_2}{a_1}\right)^2 \times 60 \approx 230/\text{hour}$$

In the present experiment pulses were selected at 2x 'noise' and so the expected counting rate for the present experiment is $\left(\frac{3}{2}\right)^{1.8} \times 230 \approx 480/\text{hour}$.

The counting rate calculated this way assumes that both detectors 'see' the same parts of the shower. For the detector with $a = \pm 5^\circ$

(a) only light scattered at angles less than 5° is detected from a vertical shower, i.e. light from only 10% of all the shower electrons, from approximations (i) and (ii) on page 13.

(b) the core of the shower will be seen above a certain height determined by a e.g. for a vertical shower with $l = 100$m. This height seen is above 1140m. compared to 480m. for a detector of $a = 12{\cdot}^\circ$.

The expected counting rate will be considerably reduced by these effects. Jelley predicted for this experiment a counting rate of the order of 240 per hour, while from the basis of Holdansky and Zhandov's theory and Jelley's experiment it is seen that a counting rate of considerably less than 480/hour is expected.

8. <u>Experimental Results on Čerenkov Radiation by various Authors.</u>

(a) JELLEY and GALBRAITH (1955) at Pic du Midi, height 2860m.

(i) The integral pulse height distribution found was

$$N(\geq H) \propto H^{-1.6\pm0.1}$$

The number of electrons at the shower maximum is given on page 8 as

$$N_{max} = \text{constant} \cdot \frac{W_0}{\sqrt{\ln \frac{W_0}{144}}}, \quad \text{where } W_0 \text{ is}$$

the shower energy in MeV. Over the range of H found in the present experiment

$$N_{max} \approx \text{constant} \times W_0$$

The number of electrons N_e'' will be approximately proportional to the primary energy, so one expects the power of H to be approximately the same as the power of W in the integral energy spectrum i.e. 1·7 as given by BARRETT et al (1952).

(ii) The dependence of counting rate with zenith angle was found to be approximately $\cos^{2.5}\theta$, and geiger counters in coincidence with the Čerenkov detector varied as approximately $\cos^{6}\theta$.

(b) NESTEROVA and CHUDAKOV (1955) at a height 3860m.

The Čerenkov detector has a field of view $\pm 10^{\circ}$, and the mirror is of diameter 30cm. The resolving time of the Čerenkov pulse is approximately 5×10^{-8} sec. A maximum counting rate of 1·5 per minute was obtained, and the power of the integral pulse height spectrum was found to be 1·5.

A core selector is placed a t a distance of 70m. from the detector, and the authors estimated that 80% of the showers recorded fall within a distance of 50m. from the centre of the core selector. The core selector consists of a large number of hodoscoped counters controlled by a system of multiple coincidences. Only 5% of the showers over the critical theshold to be detected by the light receiver are actually recorded. This is probably because most showers have shower axes not included in the field of view of the detector. 1/25 of the light flashes recorded have cores within 50m. of the core selector. This would indicate an effective radius of detection of light flashes as 250m.

These results have been stated only and the apparatus not described. The experiment has what I think is an essential to the preliminary experiments on Čerenkov radiation: a core selector. Knowing the position of the shower core reduces the number of uncertain factors, and an accurate light distribution versus 1 could be obtained experimentally.

9. <u>Theories of the Origin of Cosmic Rays</u>.

Theories of the origin of cosmic rays should explain the following observed facts.

1. An integral energy distribution proportional to $W^{-\gamma}$, where γ varies slowly with the energy of the particle, but seems independent of the type of particle.

2. Primary energies to 10^{17} eV, as observed at Harwell.

3. A directional isotropy to within 2% for 10^{16} EV. primaries.

4. Nuclei of primary particles, stripped of electrons.

5. The chemical proportions of primary cosmic rays approximately the same as for the galaxy.

6. The presence of the elements lithium, berrylium and boron amongst the primaries. These nuclei have very small binding energies.

Although it is not certain that cosmic rays originate in the galaxy or part of the galaxy, it is probable, and most theories assume this. If cosmic rays were equally dense in intergalactic space as detected in our solar system, the total energy of cosmic rays would be tremendous.

Some heavy primary cosmic rays have energies for exceeding their binding energies, and so it is improbable that the energy is gained by annihilation of matter. A slower acceleration mechanism is indicated, as an electromagnetic one. RICHTMEYER and TELLER (1949) and ALFVEN (1949) suggest that cosmic rays originate in the sun. The cosmic rays circulate in an extended solar magnetic field assumed to be 10^{-5} gauss, and become isotropic by circulating in this field for a period $10^{3} - 10^{8}$ years. The upper energy limit for protons would be 10^{14} eV, and so this theory does not explain very high energy cosmic rays.

It is possible that cosmic rays circulate in an extended galactic field. The galaxy is approximately an ellipsoid of revolution of dimension $10^{22} \times 10^{23}$ cm. The radius of curvature ρ cm. of a particle of energy EeV. in a field of H gauss is

$$\rho = \frac{E}{300H}$$

and thus a field of $3 \cdot 10^{-4}$ gauss is required to retain a particle of energy 10^{19} eV. HILTNER (1949) and HALL (1949(found that if starlight is reddened by passing through dust clouds, it is plane polarised proportional to the amount of reddening. Two interpretations of this effect are:

(a) SPITZER (1949): The light is plane polarised by orientated dust particles, and he calculated the orientation could be produced by a field of the order of 10^{-5} gauss.

(b) GOLD (1952): The crystals are orientated by cosmic gas clouds passing through the dust clouds, and thus the direction of orientation being along the direction of relative motion of the two clouds.

Thus there is no conclusive evidence that a galactic magnetic field exists. If a galactic field did exist, the cosmic rays would have long paths through interstellar matter, which would raise the proportion of lithium, berrylium and boron nuclei, because the radiation should hold an equilibrium content of breakup particles. These nuclei are observed, and this indicates they have long paths through interstellar matter. GREENSTEIN (1954) in a summary on work on interstellar matter, states that most astrophysicists now believe that either a galactic magnetic field or localised magnetic fields associated with dust clouds exists.

Two main theories of the origin of cosmic rays are given by FERMI (1949) and MORRISON et al (1954). Fermi postulates energy equipartition between protons and the magnetised gas clouds which wander through interstellar space. If the collisions are assumed elastic between light and heavy bodies, the energy gain $\frac{\Delta E}{E}$ for the proton when the cloud and proton approach can easily be shown to be $\frac{4V}{v}$, where V is the velocity of the gas cloud, and v of the proton. The proton energy increases for opposing collisions and decreases for overtaking collisions, but the probability of an opposing collision $\propto v+V$ and an overtaking collision $\propto v-V$, and thus there is an average energy gain of $\frac{4V^2}{v^2}$ per collision, or, if allowance is made for the random directions of motion, $\frac{V^2}{v^2}$. Morrison et al also assume thermal equilibrium between protons and gas clouds. The main difference between the two theories is the cause of 'death' of the cosmic ray. If cosmic rays circulate for an indefinite time in the galaxy they will eventually lose energy by nuclear collisions. The mean free path of nuclei of atomic weight A in a gas of density ρ gm/cc. is: $\frac{70}{\rho A^{2/3}}$

and since the density of interstellar space is of the order of 10^{-24} gm/cc. , the mean free path is $\frac{7 \cdot 10^{25}}{A^{2/3}}$.

Heavy nuclei will undergo nuclear collisions more often than light, and thus the energy spectrum will fall off more rapidly for heavy nuclei. This is at variance with observation, since γ seems to be independent of the nuclei. Morrison et al assume that cosmic rays escape from the galaxy, and that the time taken for escape is less than the time for nuclear collision. The energy spectrum for nuclei of Z of 10-30 has been partly measured and γ found the same as for protons, and thus the limit of the life of cosmic rays is $\sim 3 \times 10^6$ years. The galactic life time is estimated at 5×10^9 years.

<u>MORRISON et al Theory of Origin of Cosmic Rays</u>.

Morrison et al assume the galaxy is a squat disc of radius 5×10^4 L. Y. and length 10^3 L. Y. Let λ be the collision mean free path between the particles and the gas clouds, and assume the particles make many collisions in their lifetime. Let s be the total path length of a particle; L is the mean path length. From diffusion theory, the distribution $f(s)$ is

$$f(s) \propto e^{-s/L} \qquad \text{——} (1)$$

where $s = n\lambda$ and $L = n_L \lambda$ where n is the number of collisions in a path length s, and n_λ is the mean number of collisions.

The particle will be at a distance $\sqrt{n}\,\lambda$ from the source after n collisions. If the length of the galactic disc is $2h$, then $h = \sqrt{n_c}\,\lambda$

and so $n_c = h^2/\lambda^2$

and L $= n_c \lambda = \frac{h^2}{\lambda}$ —— (2)

The distribution is n from (1) is

$$f(n) \propto e^{-\frac{n\lambda}{L}} \qquad (3)$$

The mean energy the particle acquires/collision

$\frac{\Delta E}{E} = a = \frac{V^2}{c^2}$ as for the Fermi theory

and thus, after n collisions, the energy E, referred to the initial energy E_0, is

$$E = E_0 e^{an} \qquad (4)$$

and $\therefore \frac{dE}{dn} = aE$

Thus the distribution in E is, from (3)

$$f(E) = f(n) / \frac{dE}{dn} = \frac{e^{-\frac{n\lambda}{L}}}{aE}$$

From (4)

$$e^{-n} = \left(E/E_0\right)^{-\frac{1}{a}}$$

$$\text{and} \therefore e^{-\frac{n\lambda}{L}} = \left(E/E_0\right)^{\frac{-\lambda}{aL}}$$

$$\therefore f(E) = \frac{E_0^{\frac{\lambda}{aL}}}{aE.\, E^{\frac{\lambda}{aL}}}$$

$$= \text{constant } E^{-\gamma}$$

where $\gamma = 1 + \frac{\lambda}{aL}$ —— (5)

As mentioned previously, the mean path length L must be small compared to $\frac{70}{\rho A^{2/3}}$, and thus for Z = 10-30

This is $3 \cdot 10^6$ L.Y. i.e. from (2) $\lambda = \frac{h^2}{L} > \frac{10^6}{3.10^6} > \frac{1}{3}$ L.Y.

For many collisions of proton and gas clouds $\lambda << h$,
and an upper limit is set at approximately 200 L.Y.

Morrison et al take $\lambda = 1$, and from (5) and (2)

$$1 + \frac{\lambda}{aL} = 1 + \frac{\lambda^2}{ah^2} = 2 \cdot 5$$

and thus $a = \frac{V^2}{c^2} = \frac{1}{h^2}$

Thus the R.M.S velocity of the magnetised clouds is predicted to be 300 K.M./sec.

The value a determines the rate of gain of energy, and for this to exceed the rate of loss of energy due to ionisation, the injection energy E must be greater than 20 MeV for protons and 200 MeV for iron nuclei. These injection energies could probably be obtained from stars with extremely high surface magnetic fields, of the order of 1-10 Thousand gauss (BABCOCK, 1951).

THOMPSON (1954) says that the power law spectrum as predicted by the Morrison et al theory breaks down at 10^{15} e.V. for $\lambda = 1$ light year. Since it has been shown to hold for $E = 10^{16}$ eV. (CRANSHAW and GALBRAITH, 1954) a more efficient accelerating mechanism must be found. Thomson suggests that in the irregular magnetic field there are fluctuations, and these fluctuations enable the dust clouds to operate more effectively. He predicts the power law spectrum will fail at 10^{18} eV and thus extends the range to the limit of present experimental results.

<u>Time Variations of Cosmic Rays</u>. An apparent sideral variation will be detected if both a solar day and year variation exist e.g. if this variation may be represented by $A(1 + B\cos\frac{2\pi d}{365})\cos 2\pi d$ (A, B amplitudes, d time), the expansion contains terms $\cos 2\pi(d + \frac{d}{365})$ and $\cos 2\pi(d - \frac{d}{365})$.

Evidence of a diurnal variation of heavy primary particles at the top of the atmosphere has been reported by LORD and SCHEIN (1951), FREIER et al (1950) and NEY and THON (1951). No variation of heavy primary particles was found by FREIER et al (1951) in a subsequent experiment. These authors found no apparent variation of the primary proton flux, but it appears there is an actual diurnal variation of the heavy primaries, the magnitude of which has not yet been accurately ascertained.

Time variations of cosmic rays at sea level have to be corrected for the following effects: barometric pressure, temperature and the height of the 100 mb. layer. ELLIOT and DOLBEAR (1951) have arranged two geiger counter telescopes pointing at 45^{o} to the vertical, one facing north and the other south. The atmospheric effects should be the same for both telescopes, and no corrections need be made. Their results show an anisotropy in solar time of amplitude approximately 0·02%.

A maximum value which the solar magnetic field may have to fit in with observed experimental results is $\sim 10^{-5}$ gauss, e.g. ALFVEN (1949). A 10^{12} eV particle will have a radius of curvature of

$$\rho = \frac{E}{300H}$$ from page 33.

$$= 3 \cdot 10^{14} \text{ cm.}$$

The distance between the sun and the earth is $\sim 1{\cdot}5 \times 10^{13}$ cm. Thus primary particles, of energy greater than 10^{12} eV. are little effected by the magnetic fields of our solar system and so a possible sideral time variation may be detected. The time variations of high energy primary particles have been sought by time variations of μ mesons underground. COCCONI (1951), BARRETT and EISENBERG (1952), and SHERMAN (1953) find no time variation within the limits of statistical accuracy of 3%, 2% and 0·5% respectively for an estimated energy of the primary particle producing the μ mesons of $10^{13} - 10^{14}$ eV.

Experiments using arrays of geiger counters to detect high energy extensive cosmic ray air showers have been made.

The time variations have been tabulated below -

Author	Estimated Energy (eV)	Variation	Amplitude	Time of Maximum Amplitude
HODSON (1951)	5×10^{14}	Sideral	1.15±0.61%	2330H.L S.T
DAUDIN and DAUDIN (1953)	10^{15}	Sideral	2%	between 20 and 23 h.
CITRON (1952)	10^{15}	Solar	1%	
FARLEY and STOREY (1954)	$10^{13}-10^{14}$	Sideral	1.5±0.23%	1700 h.
CRANSHAW and GALBRAITH (1954)	10^{16}	None within 1% statistical accuracy.		
	2×10^{16}	Sideral	3.0% second harmonic	20-24 h L.S.T.
	5×10^{16}	Sideral	4.9% first harmonic	
	10^{17}	None with 10% significant level.		

From these results it seems that cosmic rays are isotropic within 2% up to an energy of 10^{16} eV., and considering the disagreement of the lower energy results insufficient experiments have been made for energies greater than 10^{16} eV.

Time Variations.

JELLEY and GALBRAITH (1955) have used the light detector to determine accurately the directions of the shower axes of the extensive air showers, and assume that the showers detected have axes directed within the limits $\pm a$ of the detector. An indication of how well defined the direction is may be seen in figure (ii) on page 25. For small angles e.g. $a = \pm$ 2.2° as used by Jelley in the direction finding experiment, the showers are not very well located within the cone (see figure (ii)) because only a fraction of the shower is seen. Take for example a vertical shower whose core falls at a distance 100m. from the detector. A vertical detector with a ±2.2° will see the core of the shower above 2600m. A detector with $\phi = 2a$ and directed towards the shower will 'see' the core between 800 and 2600m., over which range a substantial contribution to the total light intensity is emitted. For large angles of a the direction finding is more accurately determined within the limits $\pm a$.

Jelley has compared the counting rates 'on' and 'off' various objects in the northern sky. The background noise level is kept constant 'on' and 'off' the objects by means of an artificial light. The advantage of this method of searching for a time variation has over the others mentioned on page 39 is that the direction of the showers is accurately ascertained, while the energies detected are reasonably high e.g. ~ 3.10^{14} eV. at Pic du Midi. Jelley found no significant increase 'on' and 'off' various objects, the total counts 'on' and 'off' being approximately 70.

In the present experiment it was decided to compare the counting rates 'on' and 'off' three objects. The large and Small Magellanic Clouds were selected because these are the nearest galaxies to our own and it might be possible to detect cosmic rays 'escaping' from the galaxy. Morrison et al (1954) predict such an 'escape'. Looking out of the spiral arm in which our sun is situated was selected because of various theories predicting a flow of particles along the spiral arm.

Statement of Work Accomplished.

It has been found impracticable to separate some of the work done in my honours year from the subsequent work. The Čerenkov apparatus was built during the honours year, but subsequently the discriminator and the recording unit were completely redesigned, and the wide bandwidth amplifier modified. The lightning detector apparatus has been assembled and the experimental results obtained for the present thesis work.

Experimental Section.

1. General Description of Apparatus.

The Čerenkov detector consists of a back-silvered parabolic mirror, of diameter 60 cm. and focal length 30 cm., focussing on to an end window 6262 14 stage E.M.I. photomultiplier. A cylindrical bin, blackened on the inside, is placed about the mirror to shield the photomultiplier from stray lights. This bin is mounted on a crude alta-azimuth setting. A torch bulb is mounted at the edge of the mirror so that the photomultiplier may register a background from an artificial source.

Photographs of the Čerenkov detector are on page 45A.

Electrical pulses from the photomultiplier are put into a cathode follower which is immediately above the photomultiplier and amplified by a 5Mc/sec. bandwidth amplifier. The resultant signal pulse is discriminated against the background noise, and mechanically recorded.

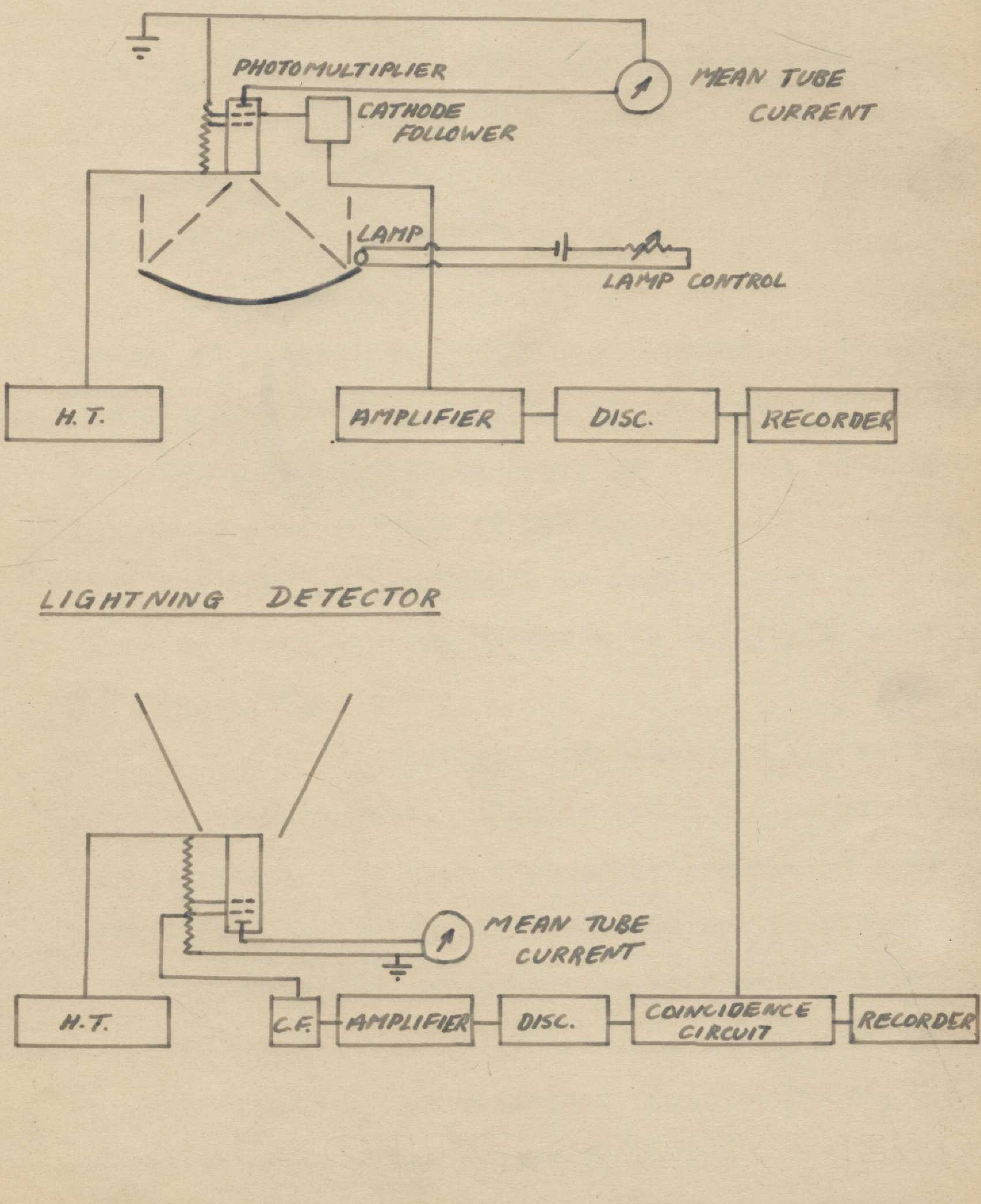
During the period of observations, lightning flashes were observed visually and were also recorded by the Čerenkov detector. A lightning detector was built, and is briefly described below. A fuller discussion of the lightning detector is given on page 48. A block diagram of the Čerenkov light detector and the lightning detector are shown on page 45B.

ČERENKOV LIGHT

DETECTOR

BLOCK DIAGRAM OF APPARATUS

ČERENKOV DETECTOR



The lightning detector is simply a 6262 14 stage E.M.I. photomultiplier, the cathode of which faces the sky. A light shield in the form of a cone of semi-angle 30° limits the area of sky which the detector views. Electrical signal pulses from the photomultiplier are put through a cathode follower, amplied by 80 kc./sec. band-width amplifier and discriminated against the background noise. The resultant pulse is put in coincidence with the pulses from the Čerenkov detector, and the coincidences are mechanically recorded.

The apparatus has been set up at Badgery's Creek, 30 miles from Sydney. A comparison of the back-ground light intensity in Sydney and Badgery's Creek was made using the lightning detector directed towards zenith. The anode tube current of the photomultiplier as measured from the roof of the School of Physics, was found to be six times as great as when measured at Badgery's Creek.

2. Weather Conditions.

The weather conditions for the experiment must be near perfect. Clouds lower the counting rate considerably. To have a reasonable counting rate the moon must be low in the sky or under the horizon, which, in practice, means the moon must be less than half full.

WOOD (1950) has made a seasonal survey of weather conditions in different parts of N.S.W. for astron-omical purposes. The survey shows that, for a ten year period the average number of nights per quarter with less than '2/10 cloud' in Sydney and Badgery's Creek are:

December, January, February; 14

March, April, May;	18
June, July, August;	24
September, October, November;	18·5

Less than '2/10 clouds' roughly corresponds to the requirements of this experiment. The number of possible observational nights per quarter should be halved for this experiment, since the moon must be less than half full.

This year has been a bad year to carry out the experiment. The average rainfall for the first four months of the year was the highest since 1890, and for the rest of the year considerably above average. The first night of the year that observations could be taken throughout the whole night was May 16th! Most of the results were obtained during the months July, August and September. During the winter months heavy mists, often rising at 1.00a.m., cut down the possible observation time. The mists are local to the Badgery's Creek area, and are probably due to Badgery's Creek and the small dams which are part of the irrigation system of the university farm.

I have emphasised the influence of the weather on the experiment because it in itself has been the major difficulty of the experiment.

Technique.

To distinguish between Čerenkov and noise pulses, the discriminator is set at an arbitary bias level at which level the counting rate of noise pulses is neglible compared to that of the Čerenkov pulses. The phototube current is accurately measured and kept constant during the experiment by varying the intensity of the artificial lamp, and by this means the noise level is kept constant. The arbitary level is chosen as 2x the bias level at which noise pulses are detected at one / second.

To test the stability of the apparatus a run is made with the lid of the detector on, and the intensity of the night sky approximated by the use of an artificial lamp. The run was made for a minimum of 15 minutes after each working night. If counts were recorded, the apparatus was regarded as unstable, and the observations of that night were wiped.

The detector was pointed at an object by means of the crude sights on the outside of the tin as may be seen in the photograph on page 45A. The reflection of bright stars may be seen on the photocathode of the photomultiplier, and if a bright star was near the object a more accurate 'sighting' was obtained.

4. Lightning.

A lightning detector originally was not thought necessary. Observations were to be made only on very fine nights. The Čerenkov counting rate for the nights of May and most of June were consistent with a steady rate of pulses, and no lightning flashes were observed visually. During the last two nights of the June period the counting rates rose by approximately

25%, and in July some sheet lightning flashes were observed visually. Most of these flashes came from somewhere over the eastern horizon (towards the ocean), although on some of these nights no clouds could be seen from Sydney out to sea. It seems probable that many of the flashes originated from an area at least 15 miles out to sea.

HAGENGUTH (1951) says that 50% of lightning flashes are visible for a length of time between 600 microseconds and 0.35 seconds. Čerenkov flashes and lightning flashes differ in three main aspects:

(a) Čerenkov flashes occur in approximately 10^{-8} seconds, while lightning flashes are longer.

(b) Lightning flashes are spread over a large area of sky compared to Čerenkov flashes.

(c) Lightning considerably effects wireless transmission.

Regarding (a), although the Čerenkov flash is of time-length of the order of 10^{-8} seconds, the electrical pulse from the photomultiplier and pulse shaping circuit is of the order 5×10^{-7} to 10^{-6} seconds. JELLEY (1955) has photographed the electrical pulses from the photomultiplier, and thus was able to distinguish lightning flashes from Čerenkov ones but this means using an oscilloscope with a high persistance cathode ray tube screen. Such an oscilloscope was not available for the experiment.

Detection of lightning by means of a wireless was tried. Lightning from local storms often causes a loud crackle over the loudspeaker. Three settings of the broadcast band were tried:

(i) off a station with the volume turned up on the local broadcast band

(ii) tuned on a station with the volume turned down so as just to hear the broadcast, on the local broadcast band

(iii) similar to (ii) but on the 10 Mc./sec. band.

The output of the wireless was connected to an oscilloscope to see if pulses occured when the Čerenkov recorder registered. The number of pulses observed was far too few to account for all the lightning pulses. The method of visual observation has the severe limitation that observable pulses must be fairly large compared to the background noise. Electrical coincidence would allow weaker wireless pulses to be detected. This was not tried.

The type of lightning detector tried and finally adopted, utilises two differences in the properties of the Čerenkov and lightning flashes. The detector views a large area of sky, preferably selecting flashes over the entire area, and the main amplifier of the lightning detector has a bandwidth of 80 kc/ sec. and thus amplifies lightning flashes more that the short time length Čerenkov pulses. The detector consists of a 6262 E.M.I. 14 stage photomultiplier whose photocathode faces the sky, and is surrounded by a cone which limits the view of the photomultiplier to a cone of semi-angle 30°. The electrical pulse taken from the photomultiplier is amplified by an amplifier of bandwidth of the order of 80 kc./sec., put into a discriminator, and the resultant pulse is put in electrical coincidence with the Čerenkov detector. The lightning pulse is only recorded if a pulse is also recorded by the Čerenkov detector.

The bias level of the discriminator of the lightning detector was set at $1^1/3$ times the voltage at which the background noise counts came through at approximately one per second. The anode tube current of the photomultiplier was found to remain fairly constant, and so no artificial light was used.

The highest lightning rate recorded was 50% of the Čerenkov rate. Since the lightning detector was installed, the Čerenkov counting rate has been consistent with a steady rate of Čerenkov flashes. The results in the following sections, except the integral pulse height distribution section, are those obtained using both Čerenkov and lightning detectors. The results for the integral pulse height spectrum were obtained in May before the lightning effect became appreciable, and the Čerenkov counting rate agrees well with that found later using both detectors.

Counting Rate.

The counting rate expected for the present experiment is fully discussed in section 7 on page 27, and this expected rate should be considerably less than 480/hour. The counting rate found is approximately 36/hour.

When the experiment was being planned Jelley predicted a counting rate of 240/hour. When the much lower counting rate of 36/hour was found, the electrical apparatus was extensively checked and two separate photomultipliers were used to check the original one. The bandwidth of the main amplifier was modified to 18 Mc./sec. There was no noticeable change in counting rate. Late in 1955 a Čerenkov detector similar to the one used in the present experiment was set up in Sydney by Messrs. Brennan and Wallace. After correcting for the greater background light intensity in Sydney, their results agree well with the present experiment.

It is difficult to measure the gain of the photomultiplier with the facilities available. BIRKS (1953) has measured the gain of several photomultipliers including the 6260 E.M.I. photomultiplier at different voltages per stage. The 6260 and 6262 photomultipliers are similarly constructed, and the difference in the tubes is that the 6262 has 3 more stages. Since the construction is similar, it is reasonable to assume that the gain per stage for the two photomultipliers will be approximately the same. The gains of various 6260 photomultipliers differ, but it is probable that the same class photomultiplers would agree within an order of magnitude. Taking the same gain per stage as found by Birks for the 6260 photomultiplier for the 6262 photomultiplier used in the present experiment, the total gain is found to be 1.3×10^5. The makers of the

E.M.I. photomultipliers quote a photocathode sensitivity of 20μ amps./lumen, and using the energy conversion factor of 685 lumen = 1 watt at 5560 A^o (LEVERENZ, 1950), this gives a cathode conversion efficiency of photons into electrons as 5%. The output capacity of the last dynode is taken as 15 p.F., and the minimum number of photons which may be detected is 1200. The minimum number of photons detected per cm.^{2} by the light detector is 0.43. This value gives an indication of the light pulse, and is probably accurate to an order of magnitude.

6. Pulse Height Distribution.

An integral pulse height distribution of both the Čerenkov and the noise pulses has been determined experimentally. The results are shown in the table below:

	Pulses	Number of Pulses	Time (minutes)
Noise	17.3	343	5
	18.6	248	10
	20.6	100	31.1
	22.7	20	42
Čerenkov	35	75	120
	42	15	51
	50	33	98
	60	19	75

Let N(>H) be the number of pulses per minute of height greater than H. A graph of $\log_{10}$ N(>H) Vs

$\log_{10}$ H has been plotted from the results of the above table, and is shown on page 54A. The Čerenkov pulse height distribution is best represented on this scale by

$$\log_{10}\left[N(>H)\right] = 2.58 - 1.8 \log_{10} H,$$

found by the method of least squares.

i.e. $(N(>H) = \text{constant} \times H^{-1.8 \pm 0.4}$

This agrees well with the distribution obtained by JELLEY (1955), at a height 2860 metres above sea level,

i.e. $N(>H) = \text{constant} \times H^{-1.6 \pm 0.1}$

Using the same notation but small letters, the background noise distrubition may be represented by

$$n(>h) = \text{constant} \times h^{-17.8}$$

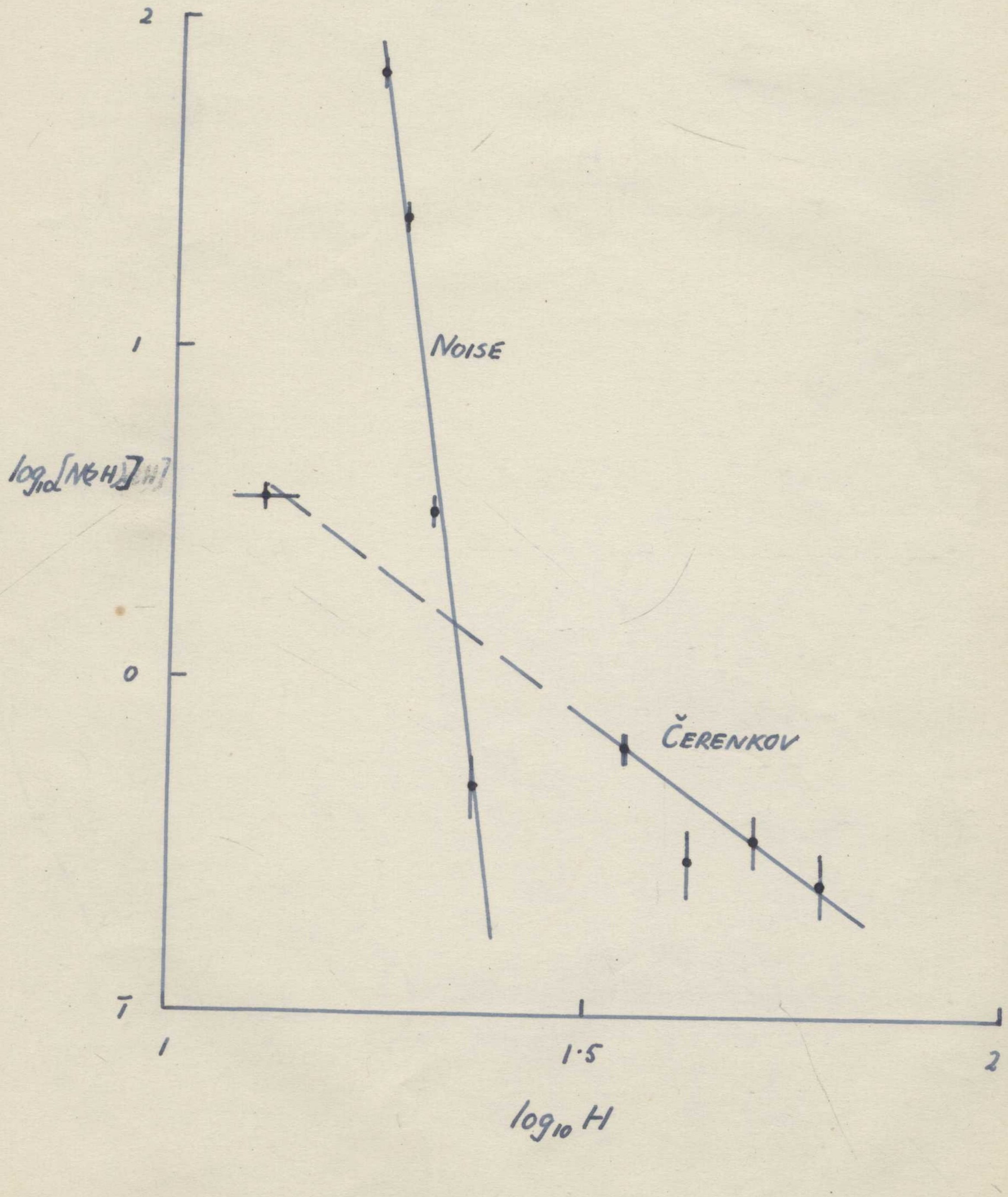
7. Variation of Counting Rate with Zenith Angles.

The variation of counting rate with zenith angle is shown in the graph on page 54B The counting rate at $\theta = 0^{o}$ is normalised to one, and if a $\cos^{n}\theta$ distribution may be assumed, the best fit of N is 3.7. The statistics are not good. JELLEY (1955) obtained n = 2.5 at 2860m. above sea level but there seem to be no published results for the variation at sea level.

8. Search for a Possible Localised Source of Cosmic Rays.

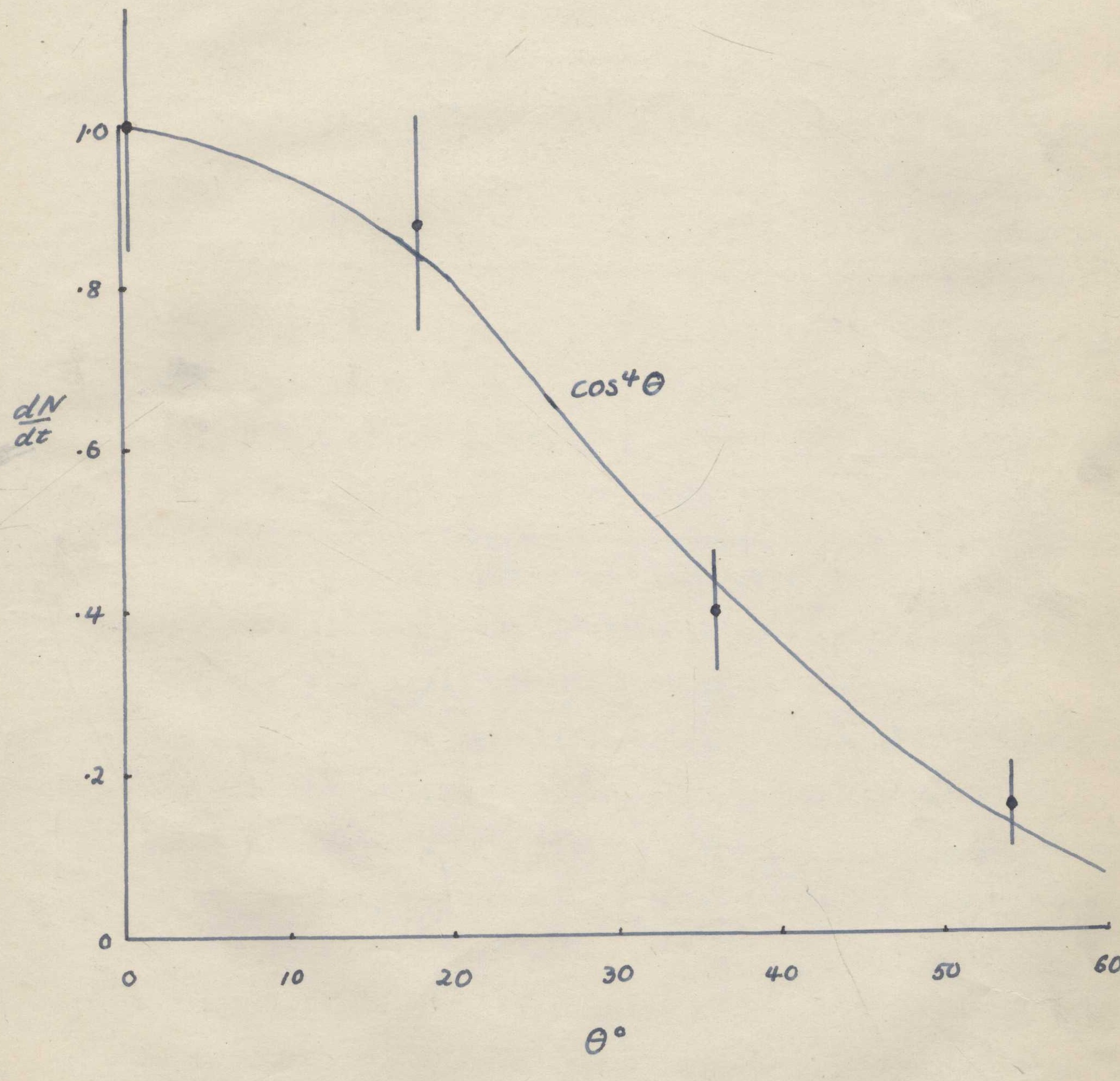
A search for a possible anisotrophy of the extensive air showers was made. To eliminate the necessity of corrections due to barometric pressure, zenith angle and possible fluctuations in the sensitivity of the equipment, the detector was pointed at the object ('on') for a half hour period, and then, keeping a constant zenith angle,

INTEGRAL PULSE HEIGHT SPECTRUM



COUNTING RATE vs. ZENITH ANGLE

The counting rate is normalised to 1 at $\theta = 0°$



and changing the azimuth by at least 30°, pointed off the object ('off') for half an hour. The mean photomultiplier tube current was kept constant during the comparisons.

The results are these observations are given in the table below. The average counting rate was approximately 0.2 per minute.

The total number of counts 'on' and 'off' an object is N, the mean N/2, and the standard deviation $\sqrt{N}$.

Object	On	Off	N	Mean	$\sqrt{N}$
Large Magellanic cloud	84	71	155	77.5	12.4
Small Magellanic cloud	108	126	234	117.0	15.3
Looking out of the Spiral Arm of our galany	90	77	167	83.5	12.9

The counts 'on' and 'off' lie well within $\sqrt{N}$ from the mean, and so there is no significant increase 'on' and 'off' these objects from these results.

The present experiment accurately determines the direction of the extensive air showers. It has the great disadvantage of a limited operating time determined by the weather, and because of this it is only practicable to select shower of energy of 10^{15} eV or less. Most large scale geiger counters experiments looking for an anisotrophy in extensive air showers accept showers from any zenith angle θ, although there are more small zenith angle showers because of the absorption of cosmic rays by the atmosphere. The present trend in anisotrophy experiments seems to be to to have some means of good direction detection (e.g. delays in pulses from scintillation counters as at M.I.T.) together with means of detecting very high energy showers, i.e. approximately 10^{18} eV. The Čerenkov detector in its present form is not practical for these experiments because ofits limited operating time.

9. Fast Counting Rate.

Late in 1955 Messrs. M. Brennan and C. Wallace developed a circuit about the photomultiplier which considerably attenuates most of the noise pulses but only slightly attenuates the signal pulses. The circuits used by Jelley and in the present experiment, and the newly developed one, are shown on page 61A.

The new circuit was set up at Badgery's Creek and a maximum counting rate of 3.5 counts per minute was obtained.

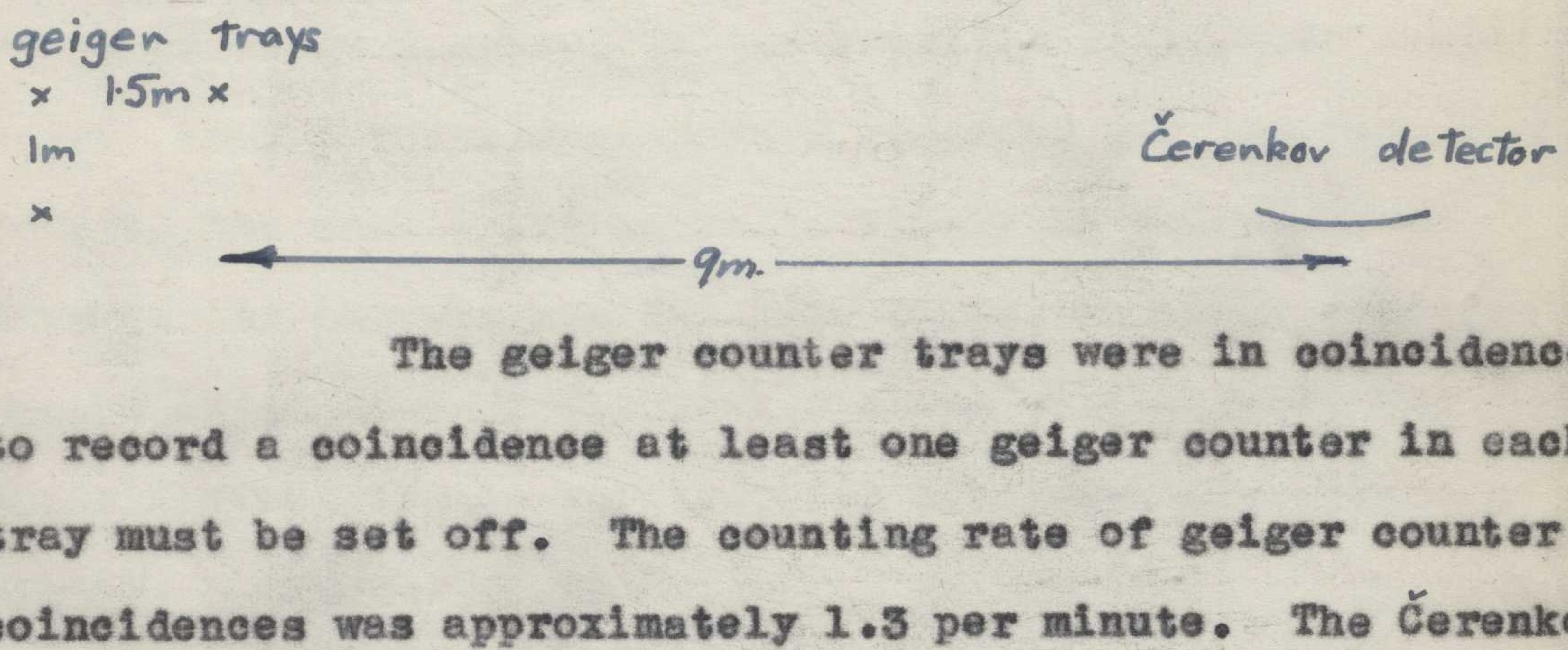
Another experimental point may be added to the integral pulse height distribution on page 54A, i.e. with $N(>H)$ = 3.5 counts per minute. For both experiments the same voltage per stage is used for the photomultiplier, and the gain per stage is $\sqrt[14]{(\text{total gain})}$ i.e. 2.32 from page 52. In the first experiment pulses were taken off the last dynode, and using the new circuit off the anode of the photomultiplier. Thus the light pulse sizes may be compared and the minimum number of photons which can be detected with the new circuit is 438. Thus the point $N(>H) = 3.5$ counts/minute and H = 12.9 volts is plotted on page 54A, and is seen to be in good agreement with $N(>H) \propto H^{-1.8}$

A 10% allowance for error in H is made, because of uncertainity in the gain measurements.

10. <u>Geiger Counters in Coincidence with Čerenkov Dectector.</u>

It was originally planned to put the Čerenkov detector with the extensive air shower experiment, and so not to have to construct counters and electrical apparatus for the Čerenkov experiment above. Late in the year, after the extensive air shower experiment had been discontinued, Mr. C. Wallace loaned apparatus for this experiment.

The geiger counter tray consisted of ten geiger counters each of approximate area 215 sq.cm., and each spaced at a distance of 0.7 cm. apart. The diagram below shows the layout of the apparatus.



The geiger counter trays were in coincidence; to record a coincidence at least one geiger counter in each tray must be set off. The counting rate of geiger counter coincidences was approximately 1.3 per minute. The Čerenkov detector, using the new photomultiplier circuit, was placed in electrical coincidence with the triple geiger coincidences.

The following results were obtained, and although the number of Čerenkov - geiger counter coincidences is small, it is well above the probable chance rate and gives an order of magnitude for expected coincidences.

In a period of 4 hours, there were 3

coincidences between the three geiger trays and the Čerenkov detector, During this time 552 Čerenkov and 310 geiger counts were recorded.

The resolving time of the coincidence circuit is ~ 1 μ seconds. If N_1 and N_2 are the counting rate of Čerenkov pulses and geiger counters respectively, and τ is the resolving time of the coincidence circuit, then the accidental coincidence rate A_{12} is

$$A_{12} = 2 N_1 N_2 \tau$$

Now N_1 = 138/hr. and N_2 = 77.5/hour. and since $\tau = 10^{-6}$ seconds

$$A_{12} = 2 \times 138 \times 77.5 \times 1 \times 10^{-6} \times \frac{1}{3600}$$

$$= 6 \times 10^{-6} \text{ /hour.}$$

The coincidence counting rate found is 0.75/hr. which is large compared to the expected accidental counting rate. Only 3 coincidences were recorded for 552 Čerenkov counts, but such a low value is likely to be expected because the showers are detected by the Čerenkov detector over a large area. The result shows that some of the light flashes are associated with extensive air showers.

11. Conclusion.

The results of the present experiment agree fairly well with those of Jelley and Galbraith. The integral pulse height distributions are essentially the same at 2860m. and at sea level. Both the zenith angle dependence at sea level and the comparison of the counting rate 'on' and 'off' various objects are new work.

Appendix.

Electronic Apparatus.

(a) Photomultiplier and Cathode Follower.

These circuits are shown on page 61A. Figure 1 on page 61A shows the circuit used for Jelley's and most of the present experiment, and figure 2 shows the one developed by Messrs. Brennan and Wallace.

The 6262 14 stage photomultplier was operated at approximately 63 volts per stage. The maximum safe tube current for the photomultipliers is 100μ amps, and so the high background intensity limits the volts per stage which may be used.

In the circuit shown in figure 1, positive pulses are taken off the last dynode. The Čerenkov flashes are of the order of 10^{-8} seconds long, and the resultant photomultiplier pulse is probably spread to approximately 5×10^{-8} seconds. Assuming the output capacity of the photomultiplier to be 15pF., then the positive pulse will have a fast rise time, and decay with a time constant of 0.75μ seconds. This pulse is then put into a 6AK5 cathode follower connected as a triode, and the resultant pulse passes through a 71 ohm coaxial cable to the main amplifier.

In the circuit in figure 2, negative pulses from the anode of the photomultiplier are immediately differentiated with a time constant of approximately 0.15μ seconds. The leading edge of the resulting pulse passes through a germanium diode OA-72, which has a high back resistance of 2 megohms.

If the input capacity of the 6AU6 is 3 pF., then the pulse decays with a time constant of 3 μ seconds. This pulse is then amplified, put into a cathode follower and the resultant pulse passes through a 71 ohm coaxial cable to the main amplifier.

The essential difference of the two circuits is that in the second circuit the noise and Čerenkov pulses are differentiated with a time constant of 0.15 μ seconds, while in the first circuit the time constant is 3.5 μ seconds.

(b) Amplifier.

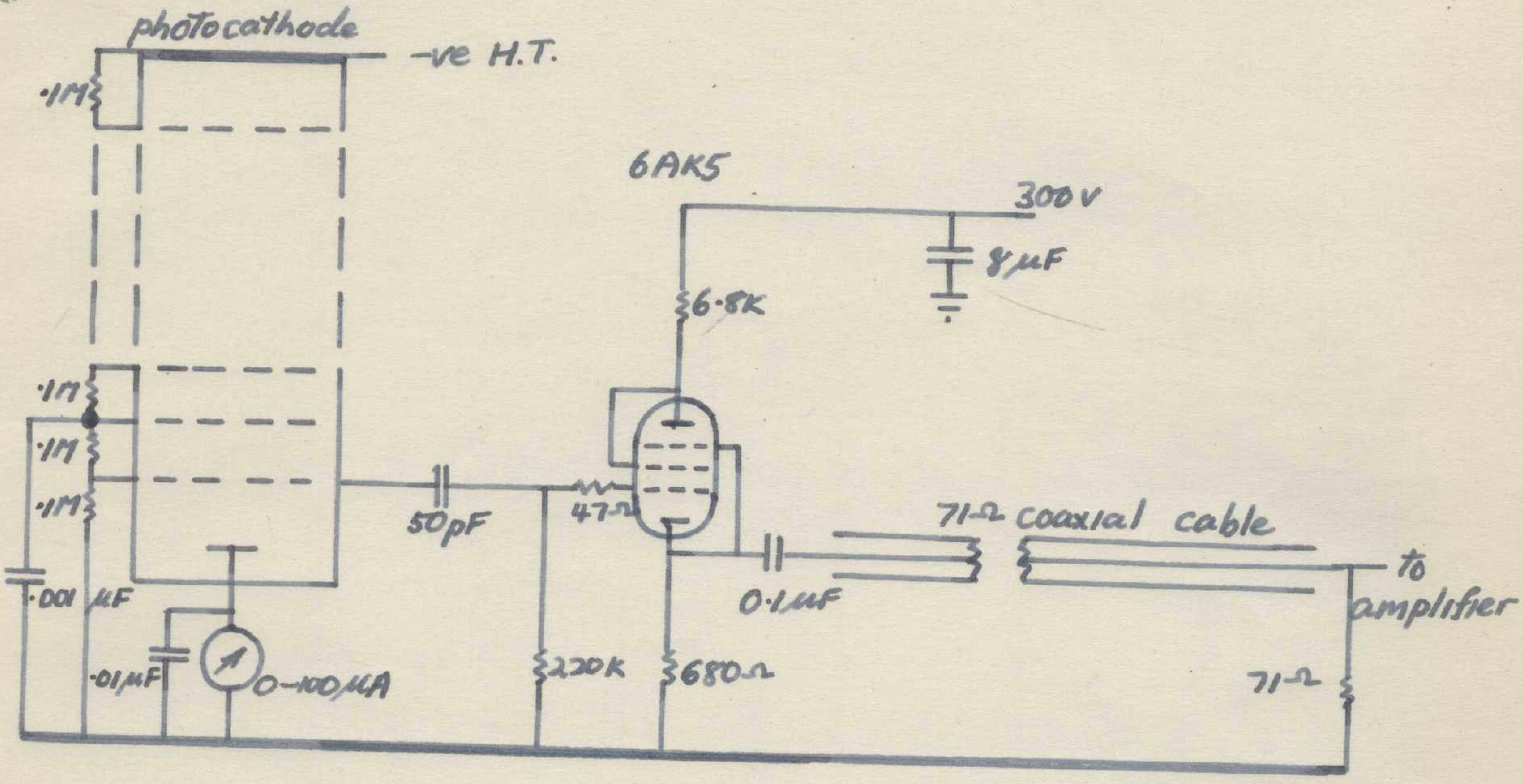
The amplifier originally was of 5 Mc./sec. bandwidth and amplification factor 250. Later in the year it was modified to a 18 Mc./sec. bandwidth and amplification factor 120. The amplifier is built into an oscilloscope, the fastest timebase sweep of which is approximately 100 μ seconds. The timebase and cathode ray tube are not at all suitable for this experiment. It was quite impossible to see the Čerenkov pulses on the screen. What was needed for the experiment was a good oscilloscope with a high persistance cathode ray tube screen, and a timebase with a sweep of 5 μ seconds per centimetre.

(c) Discriminator and recording equipment.

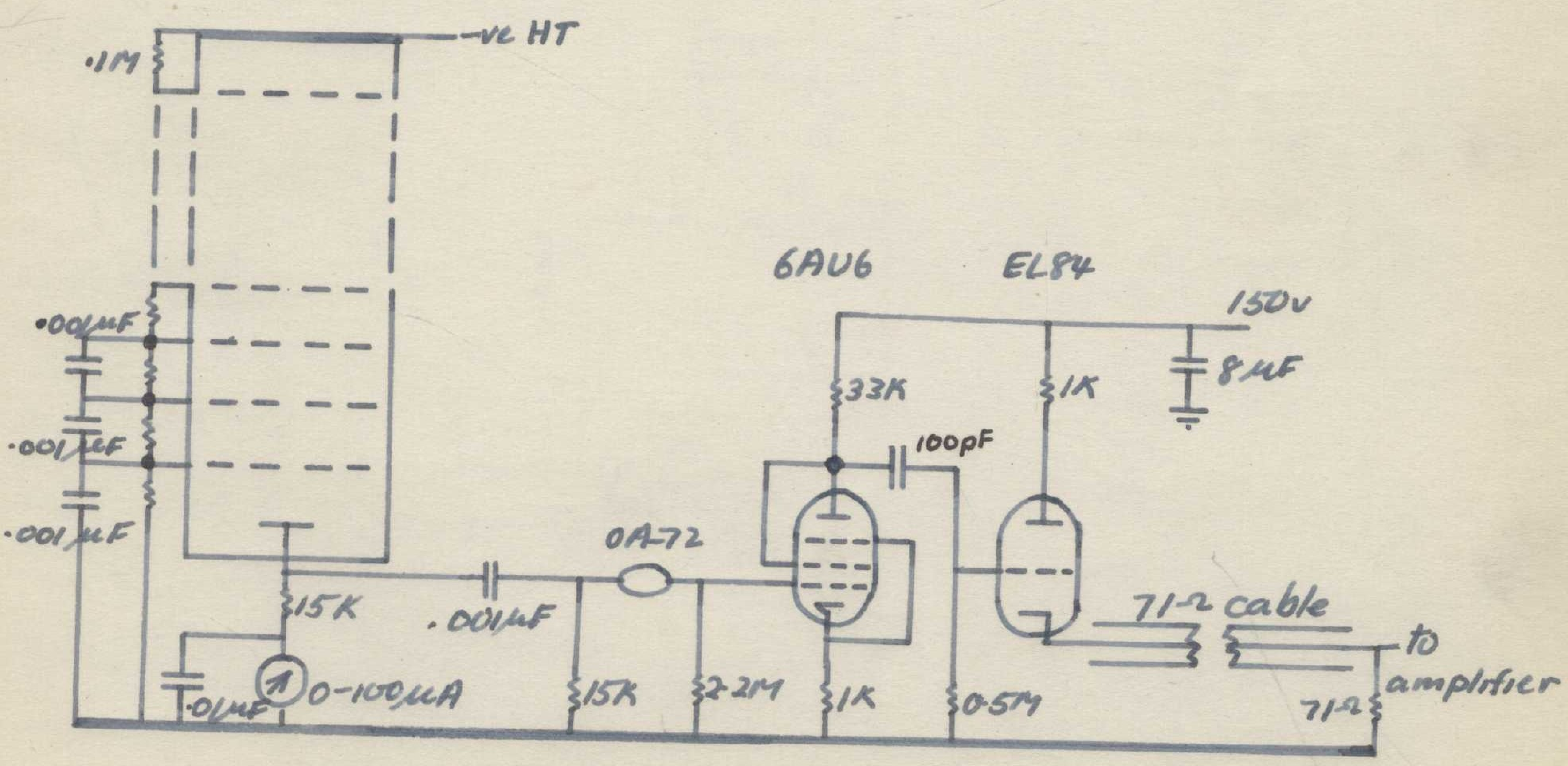
The two circuits, one for the Čerenkov pulses and the other for the lightning pulses, are shown on page 61B. The Čerenkov circuit consists of a fast discriminator, of the Schmitt trigger type, a pulse lengthener, phase inverter, univibrator and a power rube to drive a mechanical recorder. The lightning detector has a slower Schmitt trigger type discriminator, univibrator, coincidence circuit and recorder.

ELECTRONIC CIRCUITS ABOUT PHOTOMULTIPLIER

(1)

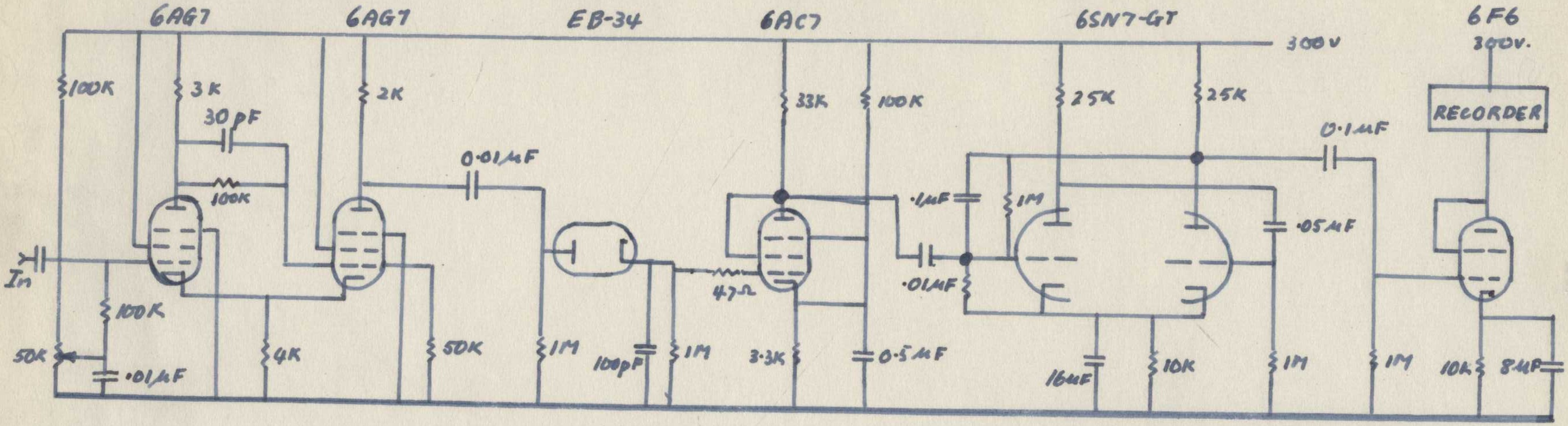


(2)

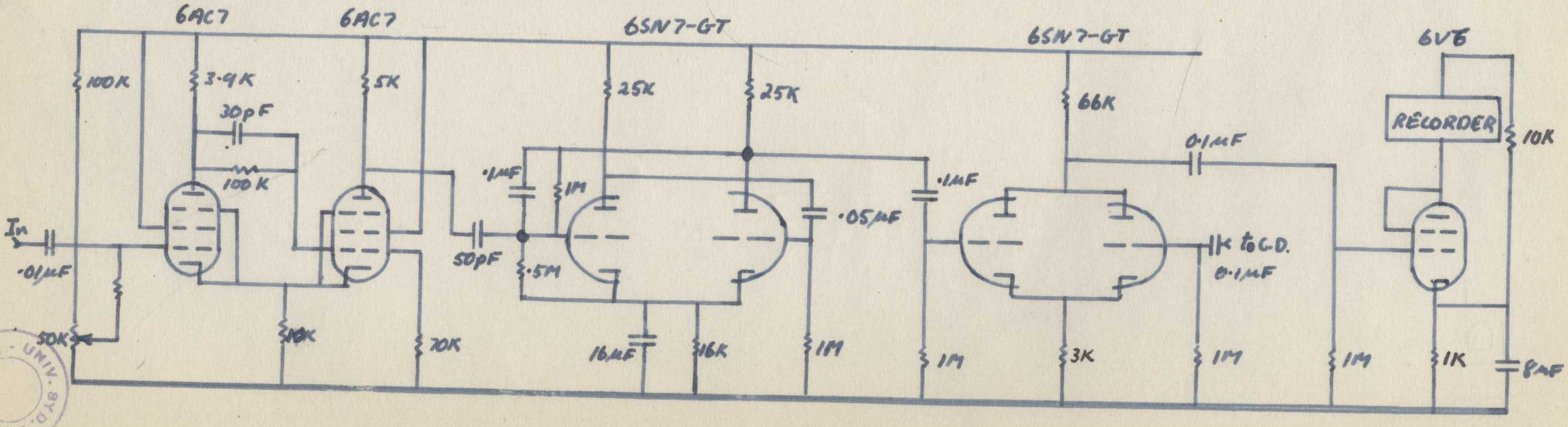


DISCRIMINATOR and RECORDING APPARATUS

(a) for ČERENKOV DETECTOR



(b) for LIGHTNING DETECTOR



Acknowledgements.

I wish to express my thanks to Professor H. Messel for allowing me to undertake this work and the Nuclear Research Foundation for supplying a grant for the purpose. I especially wish to thank Dr. E.P. George for his continued interest in the work, and for the advice and encouragement he has given me. My thanks to Mr. C. Wallace for the loan of the geiger counter apparatus.

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