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CENTRAL INTELLIGENCE AGENCY

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(a) "Atmospheric Electricity Research in the Far East" by H. Hatakeyama

(b) "Report on Atmospheric Electricity in Central Europe 1959-62" by R Mühleisen

(c) "Atmospheric Electricity Research in Great Britain, Ireland, Africa and New Zealand" by W C A Hutchinson

(d) "Electromagnetic Energy Radiated From Lightning" by Atsushi Kimpara

(e) "The Concepts of Atmospheric Electricity as Applied to the Ionosphere" by K Maeda

(f) "Geoelektrische Probleme der Blitzforschung" by Volker Fritsch

(g) "Charge Generation in Thunderstorms" by J Alan Chalmers

(h) "Relations Between Lightning Discharges and Different Types of Musical Atmospherics" by Harald Norinder

(i) "Problems of Fair Weather Electricity; Introducing Remarks" by H Israël

(j) "Action of Radioactivity and of Pollution upon Parameters of Atmospheric Electricity" by J Bricard

(k) "Generation of Electric Charges Outside Thunderclouds" by J Alan Chalmers

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(l) "Charge Generation in Thunderstroms" by B J Mason

(m) "The Theory of Lightning" by D J Malan

(n) "Types of Lightning" by N Kitagawa

(o) "Lightning Protection" by D Müller-Hillebrand

(p) "Whistlers as a Phenomenon to Study Space Electricity"
by N D Clarence

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SESSION 1.1

Atmospheric Electricity Research in the Far East

H. Hatakeyama

1. Atmospheric electric observations in the upper atmosphere.

Observations of the electrical conductivity and the electric field in the upper atmosphere were made twice a day during the World Meteorological Intervals in the IGY and IGC at four stations in Japan--Sapporo (43° 03'N, 141° 20'E), Tateno (36° 03'N, 140° 08'E), Hachijojima (33° 07'N, 139° 47'E) and Kagoshima (31° 38'N, 130° 36'E).

The results of observations were discussed by K. Uchikawa (1961) and he shows that the mean vertical distribution of the conductivity obtained at respective stations are almost equal to each other from the ground up to 500 mb level and that the conductivity increases with the latitude in the upper troposphere and in the lower stratosphere as shown graphically in Fig. 1. This suggests that the conductivity in the free atmosphere is mainly under the control of cosmic ray intensity, because the total intensity of cosmic rays increases with the geomagnetic latitude.

Mean values of the potential gradient in the upper atmosphere obtained at four stations are shown in Fig. 2. Values of the potential gradient are large near the ground and decrease exponentially with an altitude. Above 100 mb level the value becomes lower than 5 V/m. However, as the accuracy of the measurement is ± 5 V/m, the electric field intensity above 100 mb level could not measured precisely.

When the exchange layer develops, as shown in Fig. 3, the sudden decrease in the atmospheric electric field and relatively small sudden increase in the electrical conductivity were observed at the top of the exchange layer as in other measurements in foreign countries. This marked decrease and increase disappear for several days after the low pressure or the cyclone passes through the observation point because the exchange layer fades away after the low pressure.

The conduction current in the exchange layer is about 1.3 times larger than that above the exchange layer. This means that the "Austausch" contributes to generate the conduction current in the exchange layer through the rapid production of ions.

Day to day variations of the electric field and the electrical conductivity in the upper troposphere were investigated. These variations are related to meteorological factors, such as the air mass, the upward or downward motion of the air, and the jet stream. For example the increasing rate of the electrical conductivity with respect to the latitude in case of a strong jet stream is larger than that in a weak jet.

The concentration of small ions was computed from the observed electrical conductivity. The vertical air currents in and around the jet stream were calculated using the time and space variation of the concentration of small ions. When the intensity of the jet stream is increasing, downward motions of the air predominate in and around the jet stream, only except the southern and lower part of it where upward motion exists. And vice versa when the intensity of the jet stream is decreasing. An example of which is shown in Fig. 4. These characteristics coincide qualitatively with those obtained thermodynamically from the time and space variations of the air temperature.

At Poona in India, observations of the potential gradient using radiosonde techniques have been made since 1953 and systematic observations were made during the IGY. The results of the observations were discussed by S. P. Venkiteshwaran and Anna Mani (1962).

During clear weather, in both winter and summer, the higher values of potential gradient are confined to a region extending from the ground to about 600-500 mb, above which height it either remains fairly constant, at about 20 V/m, or increase slightly with height. Within the exchange layer, there are appreciable diurnal variations in the potential gradient. They are at a minimum and almost constant during the hotter parts of the day and higher at other times.

The data obtained during the IGY 1957-59 have been classified into four groups, corresponding to the four main seasons -- (1) November-February (Winter), (2) March-May (Summer), (3) June-August (Monsoon season) and (4) September-October (when the monsoon is withdrawing and the skies are clear or partly covered with low clouds with a few thunderstorms). Examples of the results of observations are shown in Fig. 5.

In winter, high potential values are confined to a region from the ground up to about 600 mb (4.4 km), above which, which represents to the top of the austausch region, the potential gradient remains almost steady (about 10-40 V/m) with increasing height up to about 300 mb (9.7km). Above which it again increases up to the highest levels studied, -- 50 mb (19 km), suggesting an increase in the particle content of the atmosphere. The 300 mb region nearly corresponds to the altitude of the jet stream over India to the north of Poona. The increase in the potential gradient above 300 mb therefore suggests the existence of fine suspended particles, presumably of extra terrestrial origin, in a larger concentration just above the level where the extra-tropical stratosphere flows into the troposphere, through the region of the jet stream between the tropical and extra-tropical stratospheres.

The conditions over Poona in the summer season are as follows: (a) The austausch region extends up to 500 mb (5.8 km), about 1.4 km higher than in winter: (b) the region of maximum potential gradient lies very near the ground and the potential gradient generally decreases with height up to 500 mb: (c) above the austausch region, the potential gradient is quite steady at the 500 mb value up to 150 mb (14.2 km) or above: and (d) the potential gradient above 500 mb is of the order of 20-80 V/m compared to 10-40 V/m during winter.

The observations during the monsoon month are again markedly different from those observed in either winter or summer. The potential gradient attains its highest values between 800 and 600 mb, which is the region of maximum cloudiness during the season. The upper limit of the region of high potential gradient (500 mb) also represents roughly the top of the clouds during this season, The most important difference is the steady fall in the potential gradient above 500 mb, from 20-60 V/m to about 20-40 V/m at 200 mb, and decreasing to less than 10 V/m at about 100 mb.

September and October is a transition period when the monsoon is withdrawing and winter conditions are setting in. The potential gradient values are characteristic of both seasons.

T. Sekigawa (1960) observed and discussed the atmospheric electric potential gradient at the summit of Mt. Fuji (3,776 m). Results are shown graphically in Fig. 6. In summer months (May-August), the potential gradient is large in later afternoon hours and small at about midnight. On the contrary, in winter months (November-February) it is large in early morning hours and small in later morning hours. In equino~~x~~ctial months (March, April, September and October) the diurnal variation is double oscillation and maxima appear after midnight and in later afternoon hours and minima in the morning and in the evening hours.

The diurnal variation in winter corresponds to the universal change of potential gradient (9h L. M. T. = 0h U. T.). In summer months the top of the exchange layer exceeds the summit of Mt. Fuji, and the potential gradient is higher in afternoon hours and smaller in night hours. And in equino~~x~~ctial months characteristic of both summer and winter appears.

2. Atmospheric electric elements near the ground.

Kondo (1959) discussed the secular change of atmospheric electric elements using the observational data at the Kakioka Magnetic Observatory for the period 1930-1957. He found that the potential gradient is decreasing and the electrical conductivity is increasing since 1953. He thought the cause of this decrease in the potential gradient and increase in the electrical conductivity was the artificial radioactivity of fallouts due to the test explosions of nuclear bombs.

Secular variations of the potential gradient at Kakioka (36°14'N, 140°11'E) and Memambetsu (43°55'N, 144°12'E) are shown in Fig. 7. The curve of Kakioka is the deviation from the mean value 130 V/m for 1936-49, and that of ~~for~~ Memambetsu is that from the mean value 124 V/m for 1950-53. In the fall of 1958 the test explosions were stopped and the potential gradient gradually recovered its normal value, but in the summer of 1961 the test explosions were again started and the potential gradient is decreasing speedily.

Hatakeyama and Kawano (1953) reported the diurnal change of the potential gradient at several places in Japan. In Tokyo we have observations of that in rather old time 1897-1903, which is shown in Fig. 8. We are making the observation of potential gradient in Tokyo since January, 1962. The mean diurnal variation January-August, 1962, is shown also in Fig. 8. This type of diurnal variation is usually seen in large cities.

In the upper part of Fig. 8, the mean diurnal variation at Kakioka for the period 1936-55 is shown. The distance between Tokyo and Kakioka is about 70 km and the type of the diurnal variation at Kakioka has never changed up to the present. Sixty years ago, the air at Tokyo was very clear and the type of the diurnal variation was rural.

Misaki (1950, 1961) devised a method for measuring the ion spectrum and discussed the relation between the ion spectrum and the electrical conductivity. According to his method the inner cylinder of aspiration apparatus is divided into two parts. The value $\left(\frac{i_1}{C_1} - \frac{i_2}{C_2}\right)$ is observed and the characteristic curve is formed taking $\left(\frac{i_1}{C_1} - \frac{i_2}{C_2}\right)$ as ordinate and potential applied to the outer cylinder as abscissa (i_1, C_1, i_2, C_2 are current and capacity of each part respectively). Ion spectrum is obtained by deriving the first derivative of this characteristic curve and the second derivative is not needed.

He made experiments for obtaining the mobility spectrum of atmospheric ions in the mobility region between 3.0 and 0.2 cm^2/V.sec. in 1960 in the polluted air at Tokyo and in the clear air at Karuizawa. Results of the diurnal series of observations made at both sites indicate some effects of pollution on the relation between the electrical conductivity and the mobility spectrum. In the polluted air, scores of per cent of the conductivity is attributed to the large or the intermediate ions while the conductivity in the clear air is practically attributed to the small ions only, as is generally believed.

The spectrum of the small ions does not shift on the mobility axis, maximum concentration lying in the interval 1.0-0.7 cm^2/V.sec., regardless of the variations in the conductivity. On the contrary, the equivalent mobility, i. e. the ratio of the polar conductivity to the small ion concentration, changes with the variations of the conductivity in the intensely polluted air. An example of the results of observations are shown in Fig. 9.

The ionizations by α-, β-, γ- rays and β-, γ- rays and the natural radioactive dust concentration in the atmosphere near the ground have been observed continuously with two ionization chambers and an electrostatic precipitator at Tanashi near Tokyo since April, 1958, by M. Kawano and S. Nakatani (1958, 1959). They discussed the results of observations.

On fine days the diurnal variation of the ionization by α-, β-, γ- rays is similar to that of the ionization by β-, γ- rays. As is shown in Fig. 10, the maximum value occurs in early morning (4-6 h), and the minimum in the daytime (11-13 h). On cloudy and rainy days the time variations are very irregular and the values are considerably larger than those on fine days. On fine days the values of $(\beta,\gamma)/(\alpha,\beta,\gamma)$ are about 2-5 per cent, being large in the daytime and small at night, but the values on cloudy and rainy days are considerably smaller than those on fine days.

The natural radioactive dust concentration is large at night and small in the daytime, and the diurnal variation being similar to that of ionization. But the amplitude of the diurnal variation curve of the dust concentration collected with the electrostatic precipitator is remarkably larger than that of the ionization by β-, γ- rays measured with an ionization chamber.

The results of simultaneous observations mentioned above seem to be important for the researches on the natural radioactivity and on the frequency distribution of the particle size of the radioactive dusts in the atmosphere.

M. Kawano and S. Nakatani (1961) studied the size distribution of dust particles suspended in the atmosphere near the ground which carry the naturally occurring radioactive substances by the cascade impactor and autoradiography. The cascade impactor was used for classifying the dust particles into four groups by their particle sizes, and the autoradiography was used for counting the number of α-tracks of each class at 0 hrs and 18 hrs after collection by the impactor.

Table. Size distribution of dust particles which hold the α-activity.

Class	I	II	III	IV
Particle size (μ)	5.2-1.3	2.5-0.9	0.9-0.5	0.5-0.3
Number of α-tracks at 0 hrs after collection (per unit area)	1	10	13	200
Number of α-tracks at 18 hrs after collection (per unit area)	0	0	4	17

According to the results of measurements, as shown in the Table, a large part of naturally occurring radioactive dust was concentrated in the size range below 0.5μ, and the radioactivity was radiated almost solely from radon and thoron daughter products of short half lives.

M. Kawane (1957) pointed out the abnormal increase of the ionization by α-, β-, γ- rays was found during the solar eclipse on April 19, 1958. As is shown in Fig. 11, the maximum value occurred at the time of maximum obscuration and was more than twice that on the other days.

3. Atmospheric electric elements during disturbed weather.

Ch. Magono and K. Orikasa (1960, 1961) and K. Orikasa (1962) made simultaneous observations of the surface electric fields, the charge on raindrops and snow particles, the form of snow particles and the intensity of rainfall and snowfall from 1956 to 1960 at Sapporo. And the latter author made similar observations simultaneously at two stations 1.2 km apart each other.

Analysing the data of these records, the following conclusions were obtained. When the rainfall was light or steady, positive field relatively smaller than those of fine weather or negative field was observed, and when there was light or steady snowfall, positive field was observed. During continuous heavy rain or snowfall and during heavy rain shower or snow shower, wave patterns of the electric field were often observed.

In almost all the cases of positive or negative electric field and of the wave patterns of field, mirror image relations ~~held~~ continued generally between the sign of electric field and the sign of electric charge on rain or snow particles. But in the beginning of rain or snowfall and when the rapid increase in the intensity of rain or snowfall occurred, the sign of the electric field and the sign of electric charge on particles beca~~us~~me the same. An example of the observation is shown in Fig. 12.

To explain the mirror image relation mentioned above, the author considered that the rain or snow particles were mainly electrified in the cloud and carried electric charges down to the ground, consequently the cloud may be electrified to the sign opposite to the net charge which was carried down to the ground by the particles. The case of the same sign of both the electric field and the electric charge on rain or snow particles was explained hypothetically by considering the space charge due to charged rain or snow particles.

Kikuchi and Magono (1961, 1961a) measured charges on natural snow crystals before and after their artificial melting during snowfall. It was found that the snow crystals obtained considerable positive charge when they were melted. This observation appears to explain the above mentioned general observational fact that in steady rainfall negative surface electric field is predominant and raindrops carry positive charge in most cases, while in steady snowfall positive surface electric field is predominant and most of the snow crystals are charged negatively.

T. Ogawa (1960) and T. Ogawa and S. Saga (1961) made the continuous observations of the electric current carried by rain drops, the rate of rainfall and the surface potential gradient. Providing the Wilson's theory of ion capture by water drops, they explained, the raindrop starts a cloud with a small charge in the same sign as the electric field and reverses its sign at a point between the cloud base and the ground. A quantitative representation between the rain current, the rate of rainfall and the potential gradient was assumed and a relation between the surface potential gradient and the potential gradient in the charging region of raindrops below the clouds was deduced. An example of the effect of splashing of raindrops at the ground was shown, in which the intensity of rainfall was 10 mm/hr or more the effect reduced the surface potential gradient in the value of about 2 V/cm toward negative.

Department of physics in the University of Singapore has plans to expand itself and a new Atmospherics Physics Laboratory will soon be built. Last year and up to August of this year, under the supervision of Hon Yung Sen, J. Pakiam investigated the electrical conductivity of the atmosphere near the ground during the disturbed weather and some interesting results were obtained but they are not yet published.

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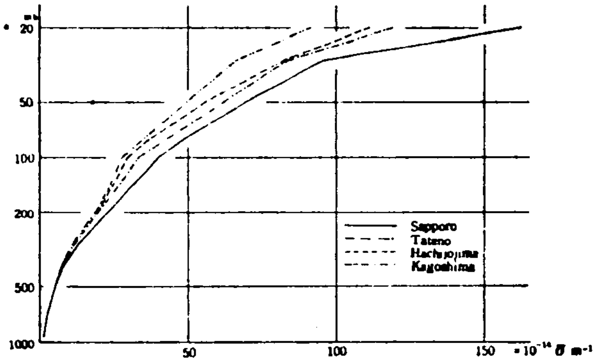

Fig. 1. Mean values of the negative polar conductivity.

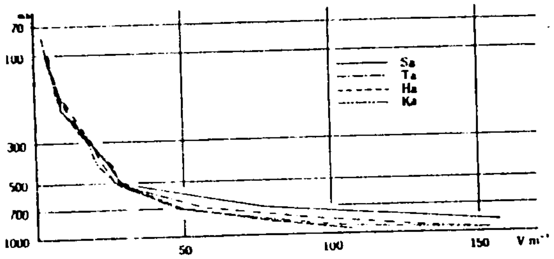

Fig. 2. Mean values of the potential gradient. Sa: Sapporo, Ta: Tateno, Ha: Hachijojima Ka: Kagoshima

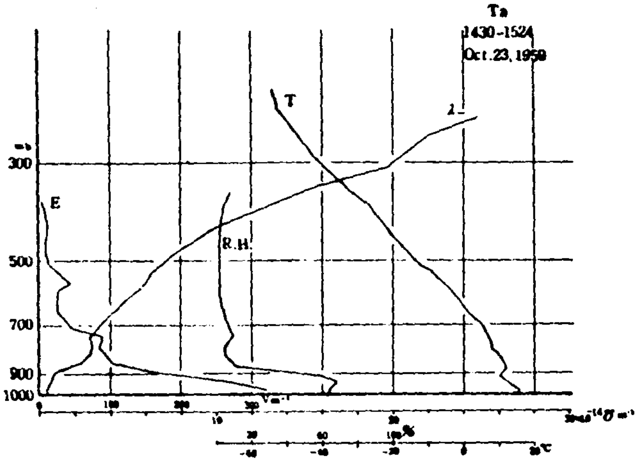

Fig. 3. Ascent curves of the negative polar conductivity ( ), The potential gradient (E), the temperature (T) and the relative humidity (R,H,) observed at Tateno.

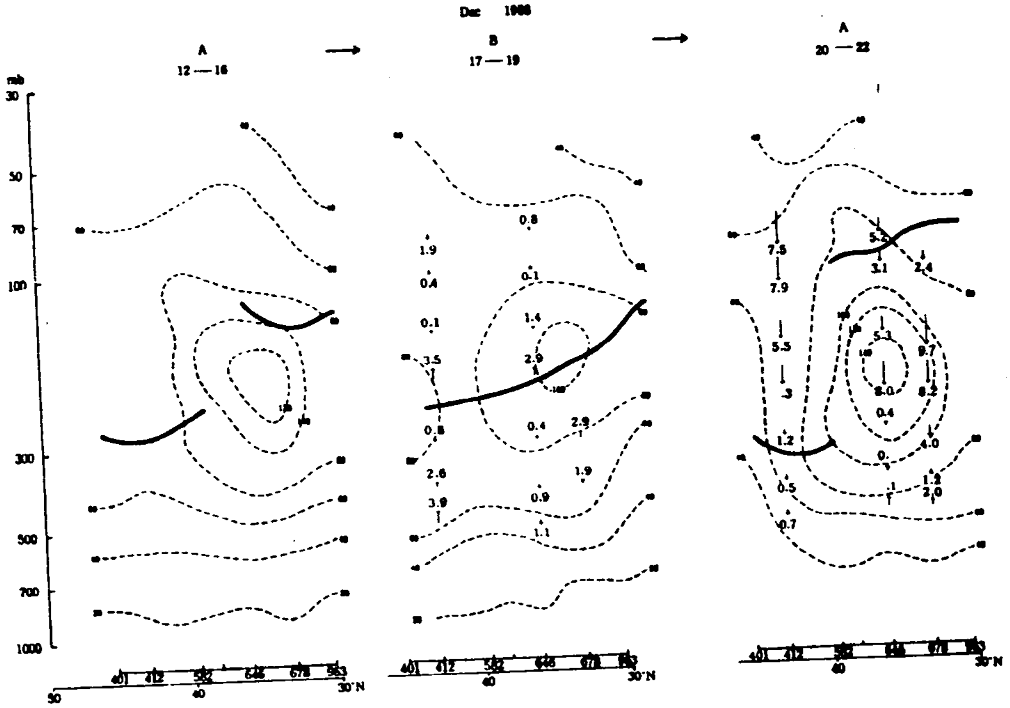

Fig. 4. Vertical air currents computed from the time and space variation of the concentration of small ions. Arrow: The direction of vertical motion (unit: cm/sec.). Broken line: Isotach (knots). Thick Line: tropopause.

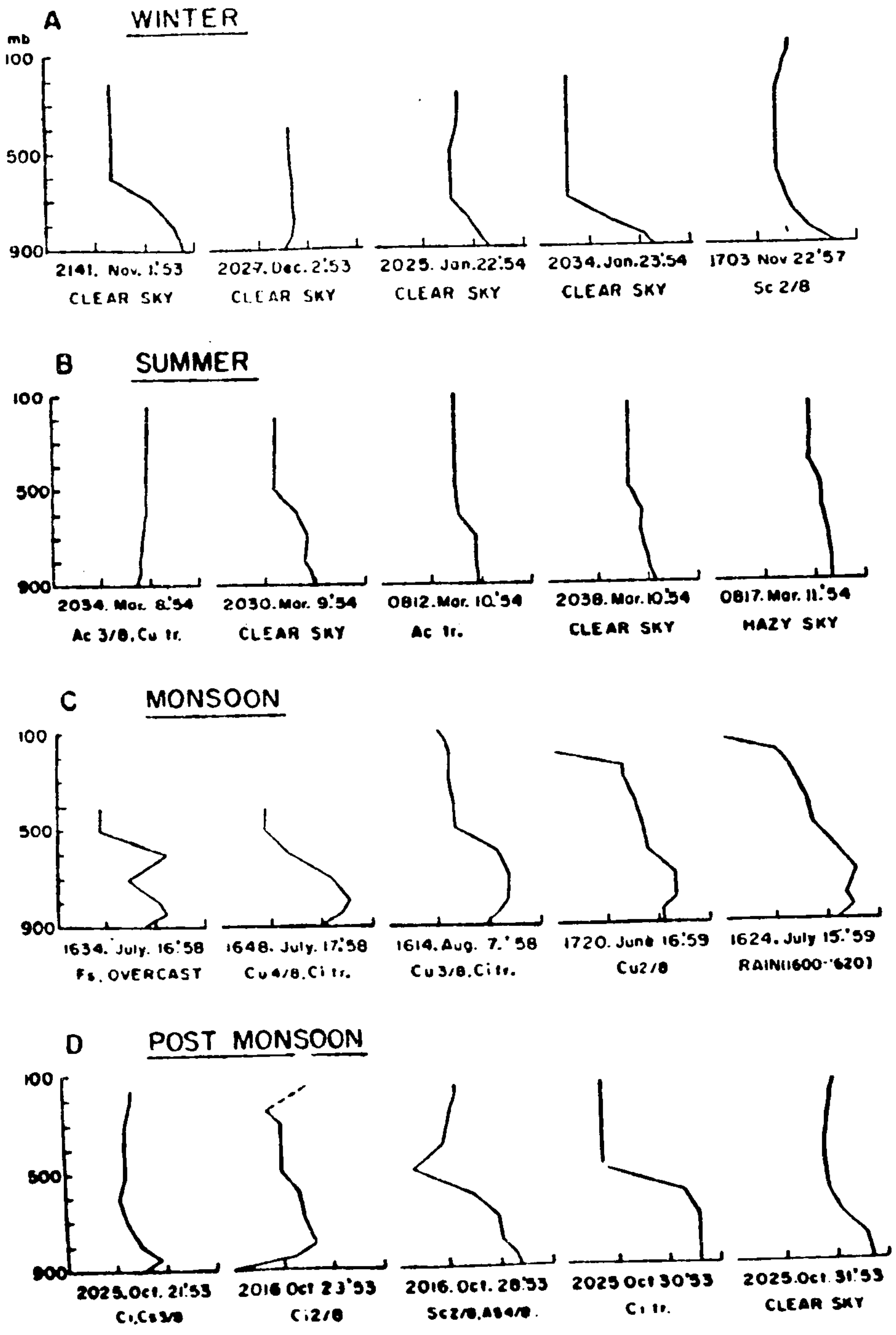

Fig.5. Seasonal variation of potential gradient with height at Poona. The horizontal scale of each graph is logarithmic, with potential gradient by radiosonde from 1 to 1,000 V/M.

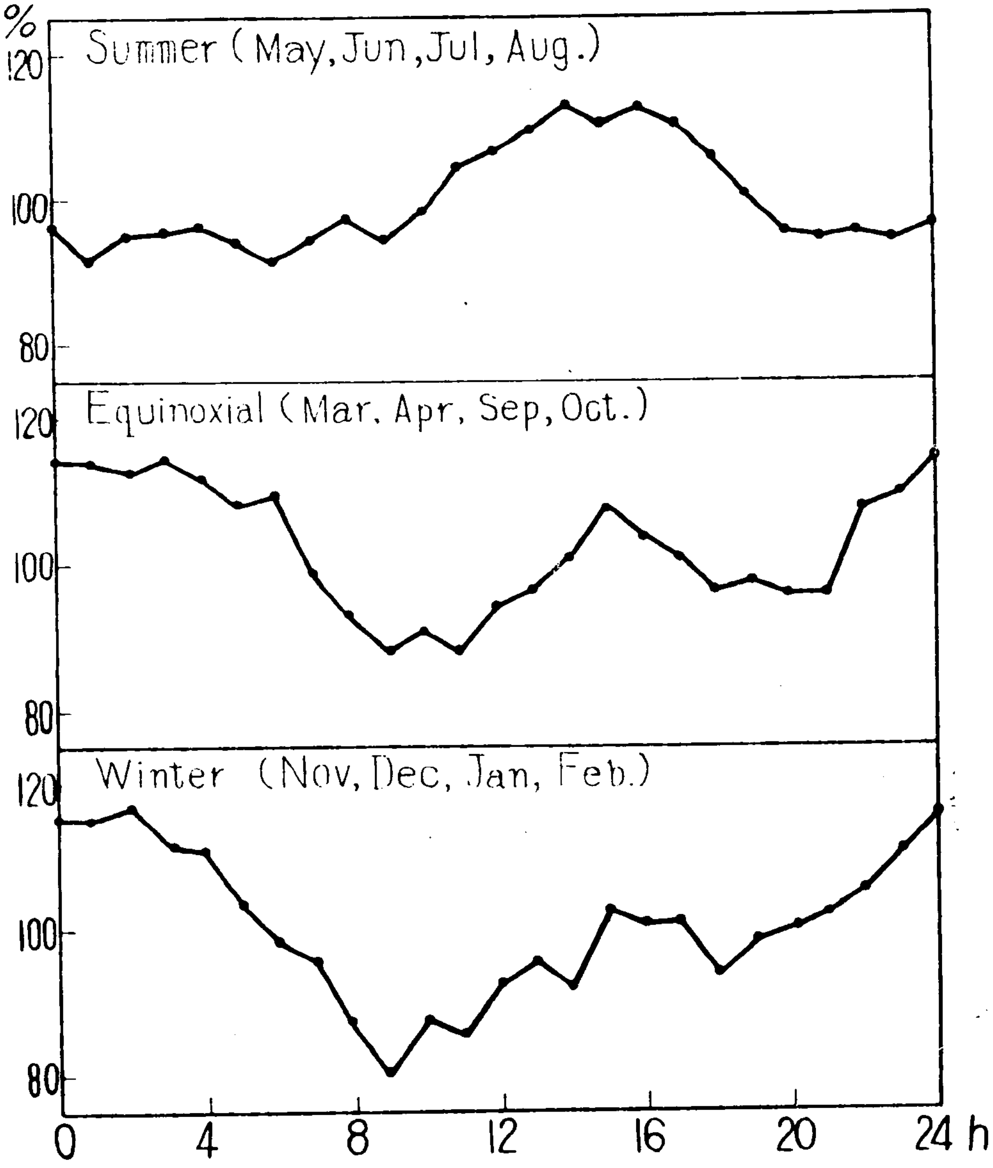

Fig. 6. Diurnal variation of the potential gradient at the summit of Mt. Fuji.

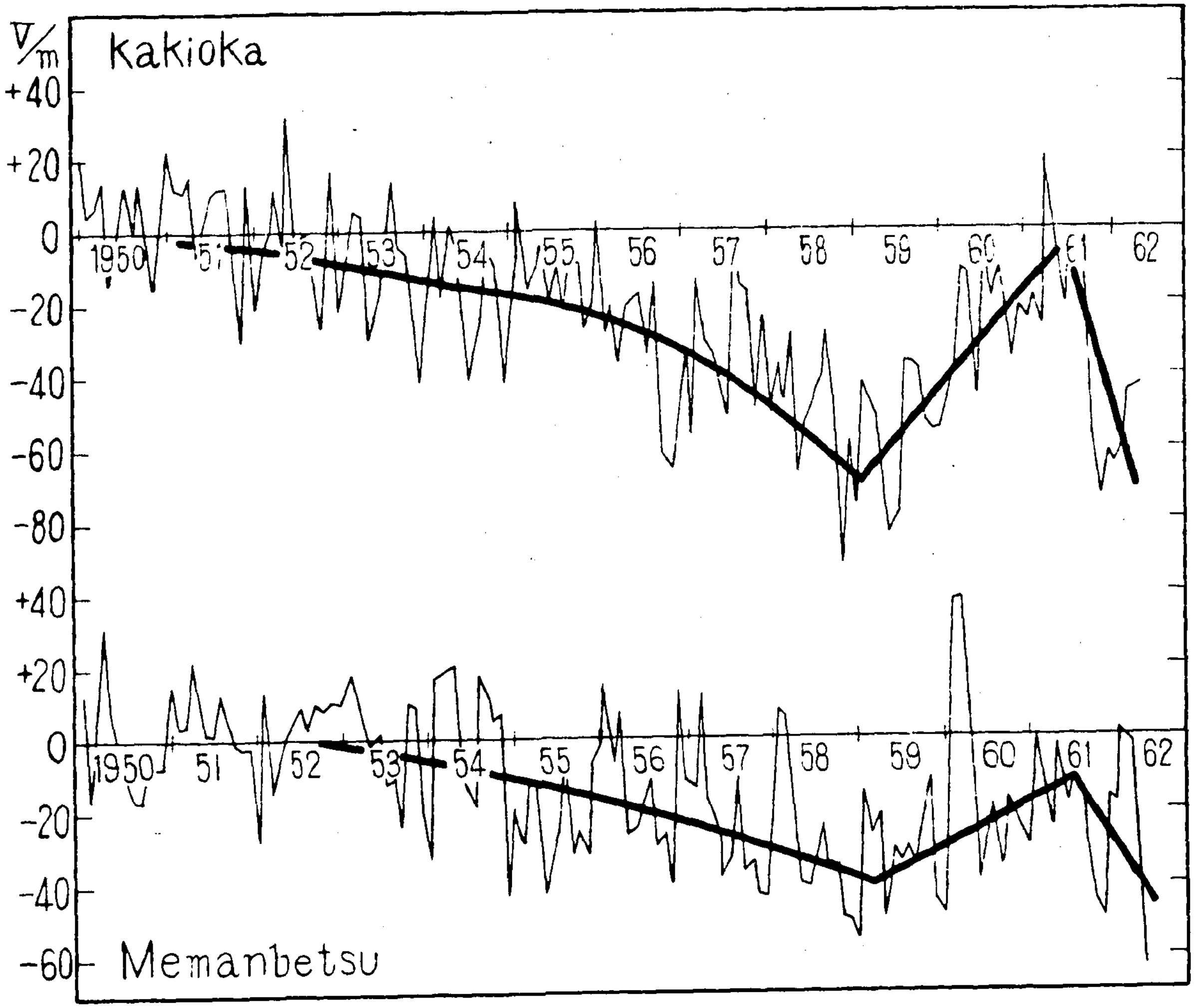

Fig. 7. Secular variation of the potential gradient at Kakioka and Memanbetsu.

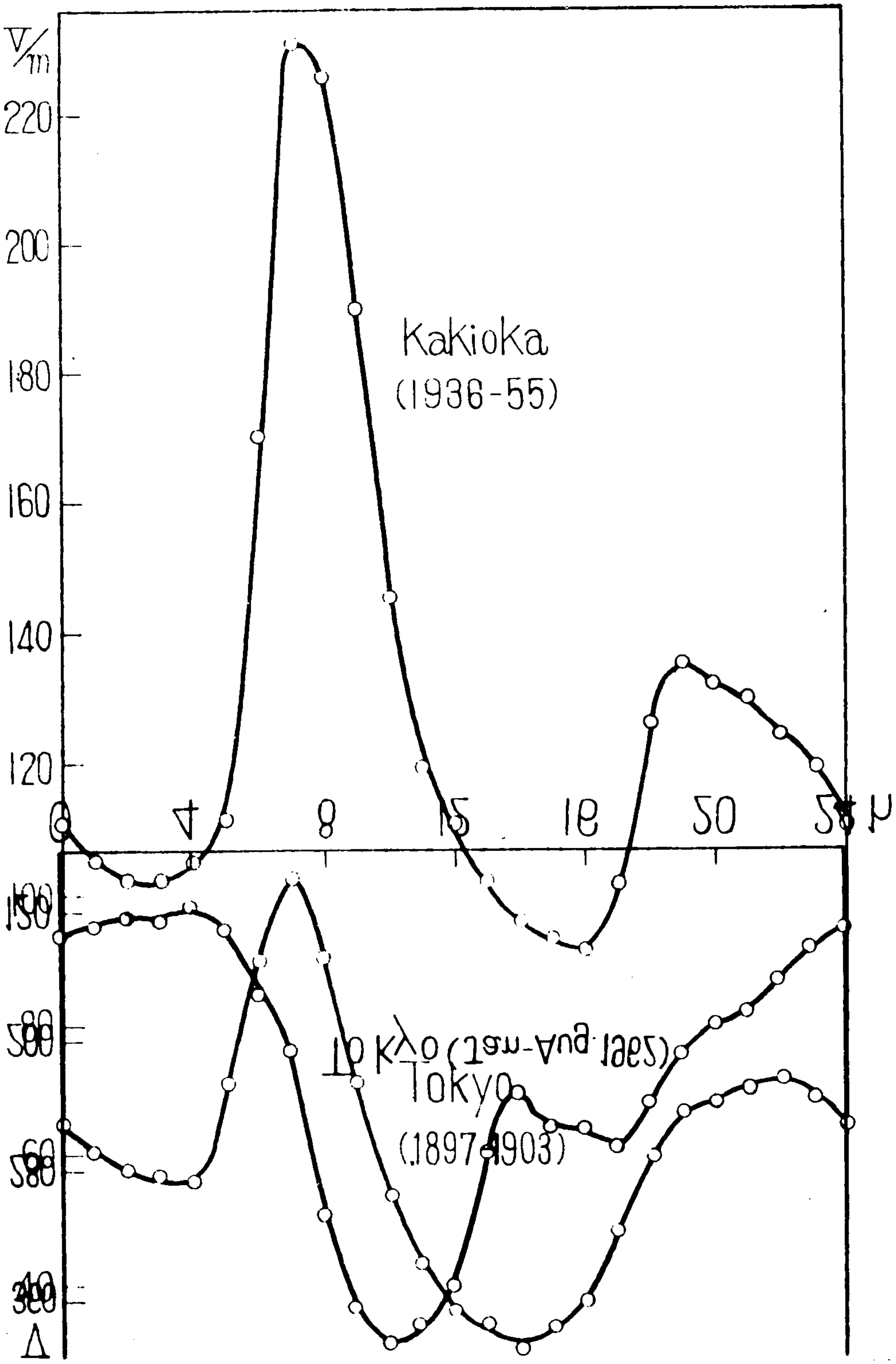

Fig. 8. Diurnal variation of the potential gradient at Kakioka and Tokyo.

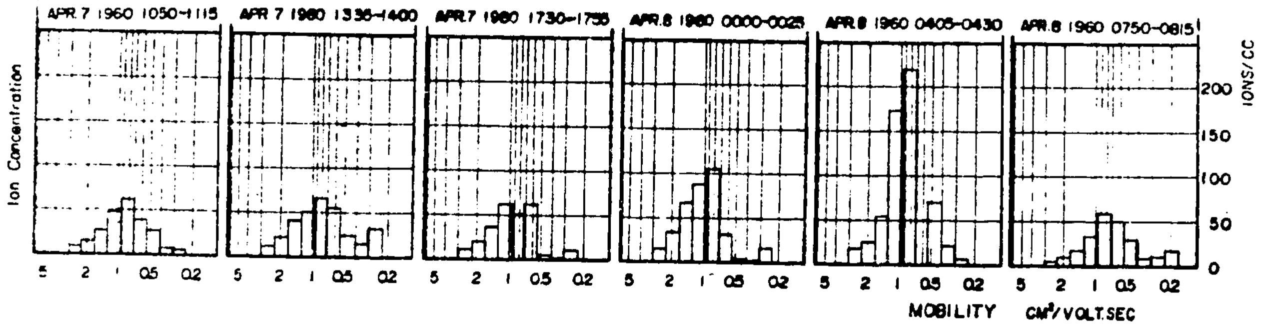

Fig. 9. Diurnal series of the Positive ion Spectra (Tokyo)

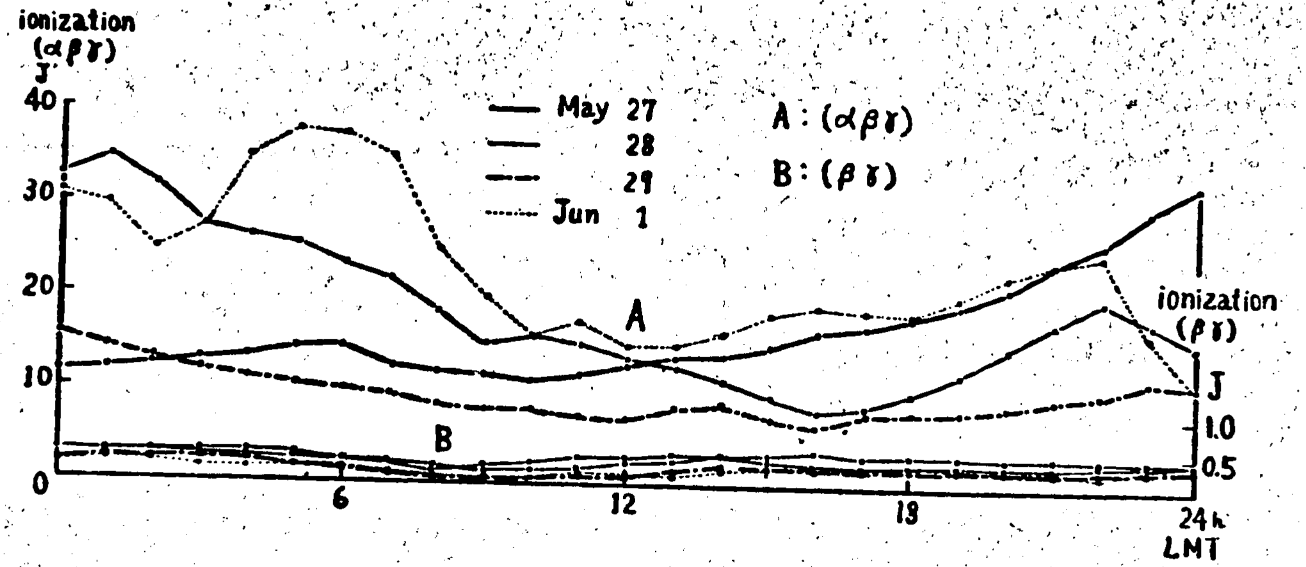

Fig. 10. The Diurnal Variation Curves of Ionization in the Atmosphere on Several fine Days.

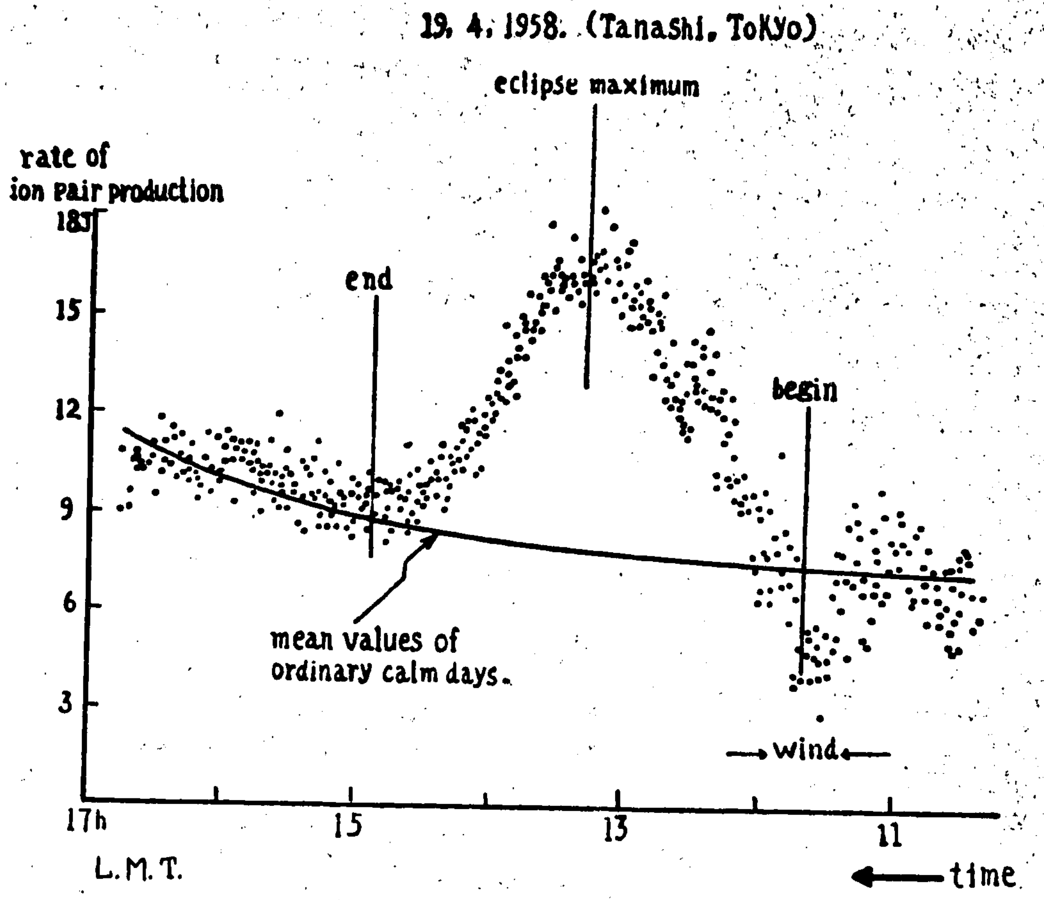

Fig. 11. The Record of the Ion Pair Production During the Solar Eclipse, April 19, 1958.

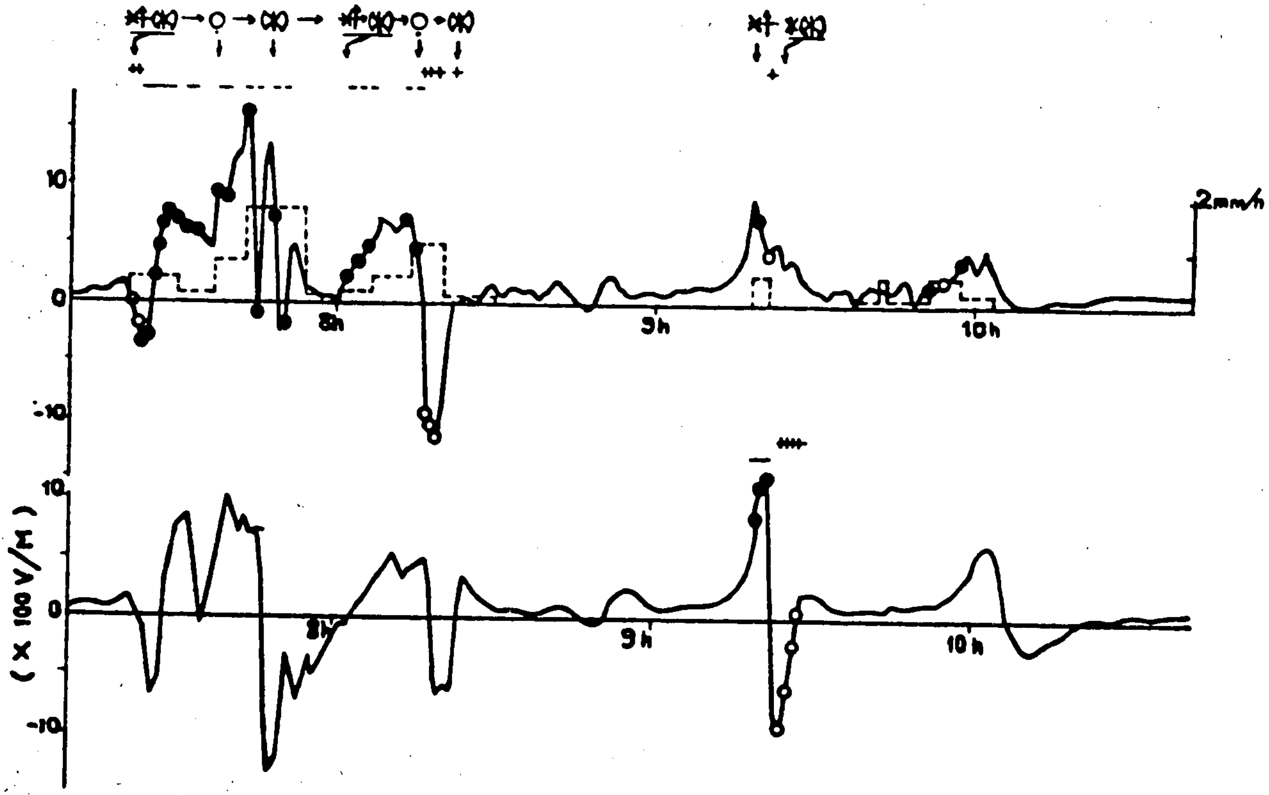

Fig. 12. An Example of the Simultaneous Observation of the Surface Electric Field, the Charge on Snow Particles The Form ofSnow Particles and the Intensity of Snowfall During Snow Showers at Two Stations 1.2 kin apart of each other.

Received December 17, 1962

SESSION 1.3

Report on Atmospheric Electricity in Central Europe 1959-62

by R. Mühleisen

Preface: The following summary is based on publications, dispatched reports from "Atmospheric Electriciens" in Central Europe. The author would regret it deeply, if any publication would have been disregarded, because it was not known to him. On the other side the dispatched reports and publications have been so numerous, that not every one has been mentioned. The gravity has been put on the new knowledges.

Disposition: The report is divided into various subjects:

1) General matters of atmospheric electricity, phenomena in fine weather.
2) Atmospheric electric aerology, atmospheric electric circuit and potential of the ionosphere.
3) Conductivity, ions, radioactivity.
4) Precipitation electricity.
5) Thunderstorms, lightnings, sferics, whistlers.
6) Electrical phenomena in space.
7) Biological action of atmospheric electricity.

1) General matters of atmospheric electricity, phenomena in fine weather.

In the International Geophysical Year registrations of the atmospheric electricity have been made at numerous stations such as: Arosa, Payerne (Switzerland), Swidrze (Poland), Murchischon-Bay (Spitzbergen), Hohenpeissenberg, Garmisch, Zugspitze, Black Forest, Eifel, Potsdam (Germany) and others. The results of these measurements are manyfold. The difficulties in separating the global and local influence have been explained. Therefore it must be concluded that atmospheric electrical registrations on the ground can give informations especially about the local events of atmospheric electricity in some cases, but only at excellent places and very seldom about the global events, such as the voltage between ionosphere and earth and therewith the world thunderstorm activity or about a spacious quality of the airmasses, such as the columnar resistance. The local and the global part are about equally large. There are always some informations not allowing an exact separation. This holds good for the single case, but also very often for the temporal mean value.

Also the registration of atmospheric electricity by Saxer L. and Sigrist W. 1) in Arosa (1800 - 2650 m above NN) proves that. Although Arosa is a place with great air-cleanness, the local influence can be found. Only the station in 2650 m NN shows equalised courses of the day in a few cases. Of some interest seems to be the discovered course in parallel of field at the ground and content of Ozon in the layer 0 - 20 km above the ground. The explanation of the relation between the O_3 and the columnar-resistance is the following: The percentage of O_3 increases as well as the electric field in sink processes because the columnar-resistance is getting less and the vertical-current-density is getting more.

Israel H. 2) brings the spacious atmospheric electric phenomena in connection with geophysical effects, as radioactivity of the atmosphere and the exchange. The atmospheric electric fluctuation means a quality to him which can be exploited on the synoptical way and can be used as an indication of the type of exchange.

Mühleisen R. 3) has continued the investigations about the atmospheric electric fluctuation at the coast of the German sea. The strong and short periodical variations of field, vertical-current and electric space-charge density have already to arise on the open sea and will be caused by strong exchanges as it could be proved by registration of temperature, water-vapour and the speed of the wind and by observations of the low Sc-clouds at the same time. The exchange has to follow in big packages whereby the air near the water must to be exchanged by fresh air from a height of 100 - 300 m in a period of several minutes. The air near the water probably gets a positive space-charge by the electrode-effect, which the air from above does not possess, and so the steep changes of the atmospheric electric quality will arise at the fixed station.

The electrode-effect 4) has also been discovered over the lake of Constance. The electric field E has been measured in various altitudes from 0 - 100 m at fixed stations and with captive-balloons. The value in an altitude of 10 m or more are just half of the value above the water surface. The measured and the calculated space-charge-density is in agreement. If these results will be transfered to the circumstances at the coast of the German sea, it can be found that the peaks of the fieldstrength and the space-charge-density are in accordance with the very constant values of the lake of Constance.

Ninet C. 5) calculates a formula under consideration of the "eddy diffusion", which describes the correlation of the electric parameter of the atmosphere: space-charge, field-strength and conductivity. By the assumption of Whipple about the convection current this formula can be used in order to win the eddy diffusion coefficient by the values of the electrical quantities measured near the ground. The author has made these measurements and has got the eddy diffusion coefficient as function of the temperature-gradient, the speed of the wind and the Richardson number.
Ninet believes that the values received by this method have come into accordance with the experiences, although he made some confined suppositions. This work is an valuable contribution to the problem "electrode-effect".

Reiter R. 6) gives a summary about his registrations at the Zugspitz-massif in the last 6 years. Besides others he tries to explain some interesting observations. He found out a relation between the ratio of the small ions concentration n+/n_ and the increasing speed of the wind. The herewith connected positive space-charge shall have the action of an exchange generator. In the evening decrease of the wind velocity the positive space-charge also disappears and herewith the atmospheric electric potential gradient sinks. That is Reiter's explanation for the sunset effect.

Kilinski E. 7) disposed a difficulty with atmospheric electric measurements. The impairing of the isolation by spiders' webs can be prevented by rotation of the antenna such as a round vertical current plate.

2) Atmospheric electric aerology, atmospheric electric circuit, and potential of the ionosphere.

First there should be mentioned some of the general publications about the subject on atmospheric electric aerology. Israel H. 8) describes measuring methods and measuring results in the free atmosphere in details. He puts them in connection with the conditions near the ground. and the meteorological conditions such as exchange, inversions etc.

A chapter by Georgii W. 9) is devoted to the special atmospheric electric measuring opportunity in a glider. In his institute Reinhardt M. has instrumentated a doubleseat glider for meteorological and atmospheric electric measurements. He is able to measure the vertical component of the atmospheric electricity field with a field mill and two radioactive collectors on the wing and under the wing. Besides this the horizontal component of the potential gradient and the positive and negative conductivity of the air can be measured continuously during the flight. It can be reported about the already existing results after a concentrated exploitation.

Mühleisen R. and Fischer H.J. 10) report on the difficulties in exact measuring the atmospheric electrical field in the free atmosphere and its remedy, based on their numerous investigations with balloons and captive balloons. A special starting method has been developed in order to avoid a positive charging of the balloon team with triboelectrical effects at the suspending wire. A negative charging of the wire, what happened always during flights through the ice satisfied areas, has been cleared up by captive-balloon investigations as charge formations at rime.

The captive-balloon measurements by Lugeon J. 11) give further explanations about the relation of the field and the conductivity in the lower atmosphere. The electrical quantities make possible an exact determination of the limits of atmospheric mist layers; they can be determined up to about 10 m by the conductivity. This is more exact than it is possible to derive from the course of temperature and humidity. It has been noticed that the meteorological quantities show these mist layers scarcely or even not at all.

An exploitation of the atmospheric electric work made by Lugeon J., Junod A., Wasserfallen P. and Rieker J. 12) in the IGY gives some new and precise material about the course of the field and conductivity in the free atmosphere. These mean values given in the following table have been worked out from 28 atmospheric electric and 33 conductivity measurements above the Murchison-Bay and from 95 atmospheric electric and 81 conductivity sondages above Payerne (see table 1).

A comparison with former values also from other authors demonstrates that the field values in the stratosphere are eminently lower than it had been assumpted in earlier times. These facts have also been worked out by Mühleisen R. and Fischer H.J. 13) Their mean values became less as well shown in table 1.

Table 1

h_{NN}(km)	dV/dz (V/m) 1)		$\lambda_+(10^{-14}\Omega^{-1}m^{-1})$ 1)		dV/dz(V/m) 2)
	Murch.B.	Payerne	Murch.B.	Payerne	Weissenau
0,007	89,0	-	1,70	-	-
0,49	-	107,3	-	2,55	-
1,0	53,1	98,3	3,27	3,07	104
3	24,5	50,7	5,13	5,32	26,2
5	13,8	18,4	8,44	8,32	12,4
10	5,3	5,2	27,1	25,3	4,4
15	3,0	3,3	68,9	66,6	1,95
20	3,5	2,3	118	143	1,40
25	0,4	1,1	180	-	0,70
32					0,35

Mean values of the potential gradient dV/dz and of the conductivity λ_+ in the free atmosphere published by Lugeon et al. (1) and Mühleisen und Fischer (2)

To the global events there is a contribution by Fischer H.J.14) The atmospheric electrical potential gradient between earth surface and about 15 km above has been measured continuously by more than 50 balloon ascents. The ionosphere potential has been found out by integration of the altitude. The mean value was 282 kV in agreement with other authors. The precision of the measurements has been ± 8 %. The diurnal and annual courses of potential mean values agree very well with the mean values of the Carnegie measurements. But the single values fluctuate up to ± 30 % of the mean-values. The same fluctuation can be found in the Carnegie mean values of single days. Therefore it seems not to be correct to compare single diurnal courses of stations on the continent with the mean diurnal courses on the oceans like it is sometimes done.

Fischer has found a seasonal maximum in the course of the ionosphere potential during the northern winter. He explains this in agreement with Whipple (1929) by a much larger electrical efficiency of the tropical thunderstorms. Considering all thunderstorms on the earth with the same importance, they would have their maximum of activity during the northern summer and no accordance with the mean results would be. If one gives however the tropical thunderstorms a greater weight than the other thunderstorms on the earth, a special explanation of the newest isobronten demonstration of the WMO material distributed to different degrees of latitude proves that the maximum of the thunderstorm activity is during the northern winter, indeed.

3) Conductivity, ions, radioactivity.

A great numer of publications has been submitted on the subject of conductivity.

Bricard J. 15) improves his former theories about the combination of small ions at aerosol particles. In calculation of the coefficient in the formula for the ionization equilibrium he takes in consideration, that the diffusion is not taking the normal course, if the particle radii have the same dimension as the mean free path. For the radii more than 10^{-5} cm the deviation can be neglected. It gets new values for the combination coefficient in the radii range 0,6 x 10^{-6} to 4 x 10^{-6} cm, which have a stronger deviation as the former ones, but they agree well with the results of Keefe, Nolan, and Rich.

Ninet's work (see 5 in chapter 1) concernsalso the conditions in the ionconcentration near the ground.

Besides others Reiter R. 16) has registrated the conductivity and the concentration of small ions at some places of his atmospheric electricity stations at the Zugspitze. Remarkable but not quite clear is the fact that the ratio $n+/n\_$ shall increase with the speed of the wind: For $v_W = 0$ he finds $n+/n\_ = 1,0$; for $v_W = 5$m/s he finds $n+/n\_ = 2,0$.

Occasionaly he finds a strong increase of the negative conductivity of the air at the sun radiated mist and fog layers. He supposes that it is caused by a photoemmission by the solar UV. It does not seem to be correct, because there is no light of sufficient short wave length in the altitude of 3000 m.

There also appeared some new publications in the subject of measuring technique. Hock A. and Schmeer H. 17) describe a new small-ion counter, where they have disposed the counterfield effect by grounding the aspiration-condensator coat and by putting back the electrodes intothe cylinder, where they have used double-electrometer valves in the entrance of the direct-current amplifier.

An interesting new method about the direct registration of the atmospheric small-ion spectrum has been published by Junod A., Sänger R., and Thams J. 18) The authors used a measuring condenser with a linear, quickly increasing voltage, where the currents become compensated by a bridge circuit. Not only the current voltage characterism will be won, but also a mobility-spectrum by a thoughtful use of electronics. It is a great advantage, that all signals exist as alternating voltages and therefore the direct-current amplifier can be avoided.

Hasenclever D. and Siegmann H. 19) published a new method of dust measurement using small ion dissipation. In a ionization chamber, working in the range of satisfaction, small ions will be produced with a radioactive probe. The measured ionization current changes when dusty air enters the chamber. The small ions become partly combined with the dust particles. These charged dust particles will not be measured for their lessened mobility; the decreased current is a measure for the concentration of dust. The authors show that not the dust concentration, but the product of dust concentration and medium particle radius has been measured. because of the dependence of the dissipation coefficient on the radius of the particles.

Siksna R. 20) developed an aerosol measuring instrument at the same time, which works with the same system. Here the small ions will be produced in a separate tritium-ion generator and mixed with air in a special chamber. The content of small ions in the air will be measured with an aspiration condenser. The pecularity is that the production of small ions, the mixing of the air, and the measuring of small ions is separated. The time of mixing is also independent of the speed of the wind and given by the speed of the air flow through the measuring condenser. Both arrangements can be calibrated only limited. The increase of small ions depends on the dissipation coefficient and this depends on the aerosol spectrum. The aerosol spectrum has a further influence on the result because the time up to the equilibrium is dependent also on the dissipation coefficient.

The mixing time at disposial has to be more than the time constant. Comparing measurements with the same aerosol spectrum can be made with this method, where it will also be the advantage of a continuous measuring. In spite of all it is not satisfying, because there will be kept only a single information.

Siksna R. and Lindsay R. 21) developed a small-ion generator with a tritium source in a titan foil for the above mentioned instrument. Herewith they have been able to place in a small room a large activity and to produce a small ion concentration up to 5 x 10^6 per cm^3 of air. Of great advantage is the half-value time of the tritium of about 12 years and the assurance that no unwanted changes will happen with the aerosol.

There are also some works of interest on the subject of atmospheric radioactivity. They have only been mentioned if they are in connection with atmospheric electrical problems, such as the air conductivity near the ground, the electrode effect or the atmospheric exchange.

Budde E. and Israel H. 22) discussed the diffusion coefficient of the radon in the air in soil. H. Israel compared the exhalation and the radon concentration in the lower atmosphere calculated with the various values of the diffusion coefficient with the measured values of these quantities. He receives the result that a value of D = about 0,05 cm^2/sec approaches best to the actual condition. This value depending on the sort of soil is about 50 to 500 times as high as the one of Budde.

Lugeon J., Junod A., Wasserfallen P., Rieker J. 23) registrated the radioactive content of the air near the ground besides the different qualities of atmospheric electricity in Payerne as well as at the Murchison-Bay (Spitzbergen).

Reiter R. 24) displayed his results of some of his investigations of the natural and the artificial radioactivity measured in his two stations Wank and Farchant. Because these two stations have a difference in level of 1,1 km at a relative little difference of base, the author can make some declarations about the dependence of the components on the altitude. Out of it he derives the influences of the meteorological parameters on the natural and artificial radioactivity. He determines the exchange coefficient by the calculated half-value altitude and he compares it with the temperature gradient. These relations cannot be taken as the general, because they are based on the conditions in a tight valley of the mountains.

Ernst F., Preining O., and Sedlacek M.[25] investigated the size distribution of the radioactive particles in the atmosphere of Vienna by using a Goetz-aerosol-spectrometer. The filter has been tested by the autoradiographic method, later the filter cut in single pieces has been investigated by a counter. They make the conclusion that the greatest activity of particles can be found in the area of less than $0{,}7\,\mu$ Stokes' radius.

Bricard H., Pradel J., Renaux A.[26] employ their dissipation coefficient to work out the frequency of the dissipation of radioactive small ions on the aerosol particles of different radii. For that the size distribution by Junge has been used. It has been supposed that the RaA atoms caused by decay of radon, form small ions which combine later with the aerosol. Using the formula the distribution of the activity on the aerosol particles of different sizes can be worked out. The results have been compared with the values also measured by the authors.

4) Precipitation electricity and electrification.

Reiter R.[27] investigated the frequency of the signs of the potential gradient in his stations in the mountains of Wetterstein. By a statistic exploitation of the spacious measuring material he found out the following proportions of signs during precipitation:

Table 2

Type of precipitation:	rain	rain shower	snow shower	snow fall
pos. signs of the PG:	10%	30-40 %	40-50 %	80 %
neg. " " " "	90%	60-70 %	50-60 %	20 %
change per hour:	0,8	2,5-3	2-2,5	0,9

He analysed the number of the changes of signs per hour in the various forms of precipitation in a similar way and he finds out the results in table 2.

It seems to be very interesting that the changes of signs are much more numerous in the valley than in higher altitudes. In the same work the dependence of the sign of the potential gradient on the altitude during steady precipitation in the two phases has been discussed. Above the melting zone the potential gradient is about 3 - 4 times greater than the value of fine weather, while it is negative and about 2/3 of the value of fine weather beneath the melting zone.

5) Numerous and valuable work has been made about thunderstorm and thunderstorm theories, lightning phenomena and their electromagnetic signals sferics and whistlers.

Wolf F. (28) discusses the present ideas of the cause of thunderstorms and the lightning-formation. Toepler's ideas about the formation of discharges have been put in the forefront again.

Pühringer A. (29) put up for discussion a new thunderstorm theorY , based on the electro-magnetic induction. In the author's opinion an electrical field will be induced by the motion of a cloud in the magnetic field of the earth. This produces an electrical dipol moment which shall build up a strong electrical field in the outer room. The efficiency, necessary for a thunderstorm, shall be withdrawn from the cinetic energy of the wind.

Michnowski St. 30) indicates the important part of the point discharge in the preservation of the charge exchange between the earth, thunder-clouds and ionosphere. Measurements of the sum of the point discharge for a longer period in Swidrze gave a result of the mean ratio of a charge run out of a point $\frac{Q+}{Q-} = 1,5$.

Müller-Hillebrand D. 31) describes some interesting thunderstorm observations at Monte San Salvatore. The value of the electric field has formerly been estimated from about 20 kV/m to 330 kV/m. The author noticed only a field-strength of about 3-5 kV/m near lightning-strokes in the ground. He tries to explain whereby the strong fields have been screened by a larger space-charge area; registrations of the electric field, point discharge, precipitation current and precipitation strength of the same time support this assumption. An exact temporal analysis of the formation and discharge of a flash had been possible by the measuring of the lightning current at the place of stroke and the electrical and magnetic field-strength in a distance of 2,8 km at the same time. It had been shown that the steps of a leader stroke are extremly short. The single impulses can have a temporal interval down to 0,2 μ sec.

In another publication the author tries to extend the protective radius of lightning conductors by radioactive point discharges. At the approaching of a thundercloud, all points emit some corona currents, which will be led away by the wind as space charge. It had been asserted radioactive points could increase the point discharge current so much that the space charge cloud would

a
lead to catch discharge. In a laboratory experiment there was no difference noticed concerning the corona current of a radioactive point and a normal point after arising the corona discharge.

With another experiment it was however shown that a strong point discharge of 8 mA has a strong influence on the electrical field strength in the surrounding.

Outdoors the point discharge current of the radioactive points was always less than a current of non radioactive points. Obviously the ion cloud around the radioactive point delays the beginning of the corona discharge.

Müller-Hillebrand D. 32) has won an interesting material about lightning frequency since 1958. With a rather narrow net of stations (115 stations) in Sweden he was able to registrate more than 100.000 earth flashes in 1958. These made 65 % of all registered discharges.

Malkowski G. 33) determines the mean value of the diameter of a convective precipitation cell d = 4 km by a collective of 1000radar observations during showers and thunderstorms. He gives a curve for the frequency distribution of these values. At the observations of echos with the weather radar instrument it is of some interest whether a precipitation cell visible on the radar screen can be considered as a thunderstorm or a shower without lightnings. This had been undertaken by a sferic direction finding instrument by finding the position of thunderstorm centers at the same time.

Norinder H., Knudson E. 34) made spacious investigations about the discharge mechanism of lightnings in a free field station near Uppsala (Sweden). The collected data had been exploited. The length of the lightning path between cloud base and earth gave values of 0,6 - 2,4 km with a mean value of 1,4 km. Observating 1135 flashes, there were 79 % between clouds and earth and 21 % within the clouds. Analysing the multiple discharges it had been displayed a decrease of the magnetic field-strength with the number of strokes. The intervals between the lightnings had been noticed from 16 thunderstorms. It was found, that the most intervals are 20 - 70 sec. At a single thunderstorm of extreme strength 80 % of the intervals had been shorter than 1 minute.

Berger K. 35) made lightning obersations with an oszillograph on the Monte San Salvatore in 1958-61. The registrations had been exploited concerning the front duration, the maximum current, the average and maximum current increase slope. On the base of this measurements there had been 4 different types of lightning discharges, which differ in front duration, maximum current, steepness of increase and current curve:

a) flashes with leader strokes in upward direction; in general they only come from high and well grounded conductors. The form of current shows a slowly increasing with a current maximum of 20 to some 100 A;

b) flashes with stepped leader from a negative cloud; the main discharge has a maximum current of 15 - 45 kA and a front duration of 4 - 12 μ sec;

c) following strokes from a negative cloud. The maximum current strength is smaller. The front duration is shorter and less than 1 μ sec. in general;

d) discharges from positive clouds to the earth with a slow current increase and a high discharge strength. A discharge exchange of more than 100 C is of no rarity.

Norinder H., Knudson E., 36)
made experimental investigations about the multiple-lightning strokes in the same lightning channel in 1956-57. Multiple lightning strokes have been regarded in the laboratory if a high ohm-resistance has been inserted in the discharge circuit. Because multiple lightning strokes can give some indications on the discharge mechanism in the thundercloud, oszillographic registrations of the strokes series and the discharge currents of natural multiple strokes. In order to registrate the front time and the discharge current three oszillographs with different time bases have been used. The electromagnetic field had been received from a frame areal and led to the oszillograph by an aperiodical amplifier. Herewith the changes of the magnetic-field strength had been registrated and an estimate of the current changes in the lightning channel has been possible. The measuring results had statisticly been exploited concerning the amplitude dispersion, front time and temporal intervals. Later on the method had been completed by day-light photography. The increase of voltage in the aeral triggered a connection circuit, which released the camera. This combined method made it possible to declare something about the discharge process in the cloud.

Papet Lèpine J. 37) has been occupied with a theoretical work about the mechanism of the lightning discharge and the herewith existing change of the magnetic field. The author shows a method to calculate the temporal course of current in the lightning channel from the magnetic field changes measured near lightning discharges.

Fritsch V. 38) has been occupied with the problem of geological and geoelectrical influences on the place of lightning-strikes. He can confirm the opinion, that there are lightning nests. A special result was, that the danger by lightnings grows with increasing geological age of the terrain.

Michnowski St. [39] describes an interesting observation in northern Viet-Nam, where electrical discharges had been in a cumulus cloud without any signs of existing ice crystalls in the cloud. The altitude of the upper cloud limit was supposed to be 2500 m, while the 0° isothermefor this season should have been about 4000 m.

Dessens H. and his coworkers[40] made investigations with an installation of 100 burners which are arranged on a quadrat of a sidelength of 100 m. They tried to produce artificial cumulus clouds. During the first few experiments there have been developed sometimes tornade pipes with wind speeds of some hundreds of km/h. It had been noticed that lightning discharges ensue always along natural tornade pipes. Dessens hopes that an installed ventilator will stimulate the formation of a whirl of a tornado pipe. Dessens expects that the so called Meteotron gives him the possibility for direct lightning investigations and for experiments in plasma-physics.

An earlier theoretical publication by W.O. Schumann refers to a resonnance frequency of the condenser ionosphere earth. This frequency shall be about 9 c/sec. **König** H. [41] investigated there upon atmospherics of this extremly low frequency. His receiver connected with a long-wire antenna enclosed the range from 0,5 - 13.c /sec. In fact he got signals with frequencies 8 - 9 c/sec. He believes that one part of these signals is caused by lightnings, which have excited the resonnance circuit ionosphere earth to oscillations. Another part of signals arises at sun rise. König supposes, these signals would be caused by abrupt changes of the altitudes of the lower boundary of the ionosphere. Other types of signals with lower frequencies will be brought into correlation with local weather-phenomena. König has examined his interesting results by a simultaneous registration on a second station in a distance of 50 km resp.450 km on one hand,on the other hand during the eclipse of the sun on 15.2.1961 (E.Haine).

Malkowski G. 42) determines the entrance-range of a sferics receiver by a decrease of the sferics frequency during a antizyclonic situation. At a field strength limit of 0,4 V/m he comes to a range of 850 km.

Israel H. 43) compares the sunrise effect of sferics at 27 kc/sec registrated at 3 different stations, Aachen 50,8° N, Tokyo 36° N, San Salvador 13,5° N. The beginning of the decrease of the sferics intensity varies from station to station during the annual course. The nearer the station is to the equator the earlier and more unregularly the effect begins.

Mattern G. 44) delt with the reception of sferics from great distances. He had built up his station on a solitary island without foreign electric installations. He is able to receive all lightning signals from the whole earth. This however leads to overlapping signals so that a lower limit of sensibility (about 50 μV) must be fixed.

Norinder H. and Knudsen E. 45) investigated whistlers 1957 - 59 in order to explain the connection of thunderstorm activity and whistlers. It has been proved that only one part of flashes produces whistlers. They mostly appear in groups for a time of 1/2 to 2 1/2 hours. The longest time of observation had been 6 hours. These times favourable for whistlers have been interrupted by long periods of silence. Registrations of sferics at the same time showed that only sferics with the highest field-strength have been followed by whistlers. The exploitation of the field course of the sferics with a harmonious analysator gave as a result that the energy maximum of the radiation is on about 5 kc/sec. A comparison between the temporal series of the multiple whistlers and the oszillographic registrated multiple-lightning strokes showed accordance concerning the time intervals.
Different whistler shapes had been regarded by the analysis with a "Sonagraph". One third of all registrated whistlers during the

thunderstorm season 1959 could not have been put into relation of thunderstorm centers by a sferic-direction finder. All these whistlers appeared only during a short period and must have been produced in the neighbourhood of the conjugate geomagnetic point.

In another publication Norinder H. 46) supposes that the propagation of whistlers will be influenced by ionospheric irregularities. He follows the ideas of Budden, K.G. in a theoretical publication.

6. Space phenomena of atmospheric electricity

In this chapter only some investigations can be reported which are due to cosmic rays. The results come from balloon ascents made in one institute.

Waibel E. 47) determined the ionization spectrum of the cosmic rays. He was able to separate the protons from He- and Li-nuclei in the primary radiation. If one extrapolates to the limit of the atmosphere, the α-intensity is about one seventh of the proton intensity.

Erbe H. 48) finds a clear relation between the intensity in definite altitude measured by a Geiger-counter telescope and the intensity on the ground.

Ehmert A., Erbe H., Pfotzer G., Keppler E. 49) discussed the pecularity of cosmic rays in a solar eruption in autumn 1960. During the summer season 23 balloon ascents had been made in Kiruna (Sweden). Some X-rays eruptions and injections of solar protons have been observed.

Ehmert A. 50) indicates that the experimental "rigidity spectres" of the primar cosmic protons and α- particles can be described by a variation of the electric potential of the earth against far space. Its variation is correlated with the solar activity. The decelerating potential has a variation of 1 Gigavolt at sunspot minimum and 2,7 Gigavolt during a magnetic storm. The field is supposed to be beyond the radiation belt, as one can conclude from the intensity observations of moon rockets.

7. Biological action of atmospheric electricity.

Knoll M., Rheinstein J., Leonard G.F., and Highberg P.W. 51) investigated the influence of artificial atmospheric small ions on the reaction time and the visual moment. An increase as well as a decrease of 7 % of the reaction time has been found for densities of about 10^3 to 10^6 ions/cm^3, if the subject is breathing through the mouth. There is no influence when the subject is breathing through the nose. The polarity of ions does no matter at all. An influence for the optical moment - i.e. the shortest time between two flashes, which can be recorded separately - has not been found. The influence of ions resembles the effect of many drugs on the human system.

König H. 52) has registrated the atmospheric impulse radiation since four years. The receivers are able to record all sferics in three entrance ranges: 100, 300 and 1000 km. Until now there was not found any clear relation with aspects of illness on human beings.

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SESSION 1.4.

Atmospheric Electricity Research
in
Great Britain, Ireland, Africa and New Zealand.

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1. Introduction

The purpose of this paper is to present a survey of research in Atmospheric Electricity performed in the countries concerned and reported since the Second Conference on Atmospheric Electricity in 1958. The survey is not intended as an index to all the relevant literature, nor is the space allotted to any item to be regarded as a measure of its importance. I have arbitrarily left out work on atmospherics and electromagnetic wave propagation. To make the picture more complete it is well to refer to the present quite considerable and wide-spread interest in the subject of Atmospheric Electricity in these countries.

I will mention five centres in England. At Leatherhead the Electrical Research Association with over 1000 voluntary observers has since 1950 collected data on thunderstorms in Britain. At Imperial College, London, the experimental and theoretical studies of the electrical properties of ice and water are proceeding in Professor Mason's Sub-Department, and the work of Dr. Browning and Dr. Ludlam (1962) on the airflow in convective storms may well lead to a new approach to the problem of thundercloud electrification. Dr. Wormell's group at Cambridge University are extending their investigations on ions and Aitken nuclei, and are also studying low frequency fluctuations in the earth's electric field and the field spectrum of near lightning flashes. Dr. Latham, now at the Manchester College of Science and Technology, is continuing his studies on the frictional electrification of ice. At Durham University Dr. Chalmers' group are investigating precipitation and air-earth currents with mobile as well as static apparatus, point discharge, space charge, and electrical effects associated with water and ice. In New Zealand, at Auckland University, Professor Kreielsheimer is concerned with potential gradient and point discharge effects at balloon altitudes. There are reports from three centres in Ireland. Professor Pollak and his group at the Dublin Institute for Advanced Studies are working on the electrical equilibrium of aerosols and ice-nucleus concentration determinations, and have constructed a small portable photoelectric nucleus counter. At University College, Dublin, under Professor Nolan, research is on charged and uncharged nuclei and the application of the Boltzmann Law to earlier observations. Dr. O'Connor and his group at

University College, Galway, are engaged in a study of natural sources of Aitken nuclei and space charge.

The African continent, with its fine opportunities for research in tropical and sub-tropical regions, now has several centres. In South Africa, at the Bernard Price Institute of Geophysical Research, Johannesburg, work under Dr. Malan includes the study of lightning flashes of various types, lightning photography, the study of upward discharges above clouds, and flash counting techniques. Also in South Africa, in the University of Natal, at Durban, Professor Clarence's Department is containuing research on whistlers and lightning. Observations are now being made at the University College of Sierra Leone, at Fourah Bay, of point discharge and precipitation currents. At University College, Ibadan, point discharge currents are being studied, and an interesting investigation of lightning by sound-ranging on the thunder has also begun. Other centres in Africa where there have been projects for Atmospheric Electricity research are at Salisbury, Southern Rhodesia, Makarere University College, Uganda, and University of Nigeria, Nsukka.

2. Ionization in the Atmosphere

The time required for a cloud of uncharged nuclei to reach equilibrium has been further investigated by Rich(1), Pollak(2) and Metnieks(2) (1962). Their calculations involve integrating the equations for the rate of change of concentration of small ions and charged nuclei respectively:

$$\frac{dn}{dt} = q - \alpha n^2 - \eta_o \, n \, N_o - \eta \, n \, N, \text{ and}$$

$$\frac{dN}{dt} = \eta_o \, n \, N_o - \eta \, n \, N.$$

Here n, N are the concentrations respectively of small ions and charged nuclei, assuming equal numbers for either sign, and N_o the concentration of uncharged nuclei. The number of small ion pairs produced per cm^3 per sec is q, and η, η_o are the appropriate combination coefficients. It is assumed that

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(1) General Electric Company, Schenectady, U.S.A.

(2) Dublin Institute for Advanced Studies, Ireland.

multiple charging or recombination of nuclei may be neglected. The authors started with initial values $N_o = 10^4$ cm^{-3} and $\bar{n} = 950$ cm^{-3} and $q = 1.6$ cm^{-3} sec^{-1} and considered three different values for the fraction of nuclei charged at equilibrium, corresponding to three different values of nucleus radius. The results of the calculation show how much more slowly the charged nuclei approach their equilibrium concentration compared with the small ions, except for very small nuclei. With their arbitrary initial conditions the authors found that for nuclei of radius 3.6 x 10^{-6} cm n is at its equilibrium value after 7 minutes whereas N takes nearly an hour to reach 90% of its equilibrium value. These results together with the recent history of an air mass may be used to estimate whether the nuclei in it are in charge equilibrium. In one observation, however, upwind of a town, and where charge equilibrium might have been expected, the concentration of charged nuclei was only 0.6 to 0.8 of its equilibrium value, perhaps of undetected sources of nuclei.

Pollak and Metnieks(3) (1962) measured the rate at which a stored aerosol approaches charge equilibrium. Nuclei of various sizes were produced by heating a nichrome resistance-wire inside a 4.2 m^3 balloon. At intervals during the decay of the resulting aerosol they took a sample and measured the fraction of the nuclei charged. Simultaneously another sample was brought to charge equilibrium, using a weak α-ray source, and the fraction of charged nuclei measured. A state of charge equilibrium was recognized when the fractions for the two samples were equal. For stored nuclei of equivalent radius 3 x 10^{-6} cm and concentration 22,000 cm^{-3} equilibrium was reached within 15 min. As the size and concentration increased so did the time taken. Nuclei of radius 10^{-5} cm and in concentration falling with time from 234 x 10^3 to 59 x 10^3 cm^{-3} required several hours. The largest had not reached it even after several days. These results confirm the experimental predictions described above.

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(3) Dublin Institute for Advanced Studies, Ireland.

The use of an α-source in bringing an aerosol to charge equilibrium has been investigated theoretically and experimentally with a stored aerosol by Flanagan and O'Connor(4) (1961). They conclude that it provides the best method at present available to test for charge equilibrium.

Following work briefly reported by Nolan(5) (1955) at the First Conference on Atmospheric Electricity the problem of the equilibrium concentrations of charged and uncharged nuclei in air has been further examined by Keefe(6), Nolan(6) and Rich(7) (1959) by applying the Boltzmann Distribution Law, assuming that because of their frequent collisions with small ions the particles should be in charge as well as in thermal equilibrium. A charged particle carrying x electronic charges ϵ is treated as a spherical conductor of radius r so that it has electrical energy $\frac{1}{2} x^2\epsilon^2/r$ in addition to the energy E_o of an uncharged particle. The particle energy is thus given by

$$E = E_o + \tfrac{1}{2} x^2\epsilon^2/r$$

By Boltzmann's Law the number in unit volume N(E) having energy E is given by

$$N(E) = Ag(E)e^{-E/kT}$$

where A is a constant and g(E) is the statistical weight of the energy state E. Since a particle has the same energy whether its charge is positive or negative the statistical weight of the energy state $x > 0$ is $g_x = 2$. Hence the number per unit volume with x elementary charges regardless of sign is

$$N_x = 2\ N_o \exp\left(-\tfrac{1}{2}\ x^2\epsilon^2/rkT\right)$$

where N_o is the concentration of uncharged particles and $|x| > 0$. If the numbers of positive and negative particles are equal, the number per unit volume carrying x elementary charges of one sign is $\frac{1}{2}N_x$. Writing $y = \frac{1}{2}\ \epsilon^2/rkT$ the total number of charged particles of <u>one</u> sign in unit volume is given by

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(4) University College, Galway, Ireland
(5) University College, Dublin, Ireland
(6) University College, Dublin, Ireland
(7) General Electric Company, Schenectady, U.S.A.

$$N/N_o = e^{-y} + e^{-4y} + e^{-9y} + \ldots.$$
$$= -\tfrac{1}{2} + \sqrt{\frac{\pi}{y}}\left(\tfrac{1}{2} + e^{-\pi^2/y} + e^{-4\pi^2/y} + e^{-9\pi^2/y} + \ldots\right)$$

The latter form is more convenient for the larger particles, say $r > 2 \times 10^{-6}$ cm, when all the exponential terms are negligible compared with ½, so that

$$N/N_o = -\tfrac{1}{2} + \tfrac{1}{2}\sqrt{(\pi/y)}$$

When $r > 2 \times 10^{-6}$ cm, and if the total concentration $Z = N_o + 2N$, then

$$Z/N_o = \sqrt{(\pi/y)}$$
$$= \sqrt{(2\pi rkT/\epsilon^2)}$$
$$= K\sqrt{r} \quad \text{where K is constant.}$$

The values of Z/N_o so deduced are in good agreement with the observations of Nolan and Kenman (1949) on the equilibrium charge distribution of nuclei, derived from hot platinum, in the size range $0.7 \times 10^{-6} < r < 14 \times 10^{-6}$ cm.

It is further shown that for the larger radii the Boltzmann Law treatment predicts an average charge per particle of $\sqrt{(2rkT/\pi)}$. For cloud droplets of radius 5×10^{-4} cm this would give a specific charge of 6.8 e.s.u. gm^{-1}. The average electrical energy per particle is shown to be ½kT, the value to be expected from the classical law of equipartition of energy if the charge on a particle is regarded as a coordinate for one degree of freedom, the energy being proportional to the square of the charge.

Keefe, Nolan and Rich then apply the Boltzmann Law to an aerosol in charge equilibrium to deduce the ratios of the various combination coefficients for ions and nuclei. When $r > 10^{-5}$ cm, but not for the smaller particles, the values of these ratios agree well with those deduced from earlier formulae based on diffusion of ions and ionic mobility - the "diffusion-mobility formulae".

An experimental investigation of ionization equilibrium in maritime air has been made by O'Connor and Sharkey(8) (1960) on the west coast of Ireland. Upwind of the site there was no source of man-made nuclei within 15 km and no major source within 1500 km. Assuming that the Boltzmann Law applies,

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(8) University College, Galway, Ireland

particles of a given size should have a definite fraction of their number charged. O'Connor and Sharkey determined the radii r of nuclei in the sea air from the diffusion coefficient found using a diffusion box and photoelectric nucleus counters. They also measured the total nucleus concentration Z and that of uncharged nuclei N_o. A graph of Z/N_o plotted against r showed general but by no means complete agreement with the theoretical curve based on the Boltzmann law. The authors note particularly the frequent large and erratic fluctuations in Z when its average value was high, and claim that on these occasions equilibrium studies were impracticable except by enclosing a large sample in a gasometer. They discuss the possible lack of equilibrium due to the intrusion of small uncharged nuclei from natural sources on the sea shore.

Keefe and Nolan(9) (1961, 1962) have suggested a model for the capture of small ions by uncharged nuclei. When $r \leqslant 10^{-7}$ cm the combination is assumed to be due mainly to simple kinetic theory collision effects with the effective target cross-sectional area increased by a factor due to electrical image forces. For large nuclei, when $r \geqslant 10^{-5}$ cm, diffusion effects are predominant. In the intermediate range with r about 10^{-6} cm, as in the air at sea level, capture is thought to be due jointly to both mechanisms. The authors calculated the combination coefficient for ions and uncharged nuclei and found moderately good agreement with values observed, but they emphasize the lack of good experimental data.

A study of nucleus and ion concentrations has also been made at Cambridge. The work, by Adkins and by Law(10), is referred to later.

5. Potential Gradient and Space Charges

The fact that local concentrations of space charge often seriously modify the electric field near the ground in all weather conditions, but particularly in disturbed weather, has been emphasized by Adkins(11) (1959). He made continuous records of potential gradient with a field mill, of space charge concentration using a steel wool filter connected to a vibrating reed

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(9) University College, Dublin, Ireland
(10) Cambridge University, England
(11) Cambridge University, England

electrometer, and of small ion concentration with an Ebert ion counter. In fine weather he found large fluctuations in space charge concentration which made its mean value difficult to estimate, though it would probably be about +2 pC m^{-3}. On several occasions in undisturbed weather he noted a close correspondence between the records of space charge and potential gradient. Sometimes this was associated with exhaust smoke from passing traffic; sometimes the records followed a similar course for an hour or more, usually in quiet, stable conditions, when the observed space charge concentration changes would need to reach up some tens of metres to account for the observed field variations. From his measurements in disturbed weather Adkins finds evidence for four processes. These are

(a) the electrode effect (which he discusses in detail),

(b) the modification of the potential gradient within some tens of metres of the ground by large-ion space charges resulting from point discharge, the small ion density remaining almost unaffected,

(c) in heavy rain, modification of the potential gradient by space charges of small ions produced by splashing (Adkins reproduced this effect in a laboratory study and showed that the charge is proportional to the existing field), and

(d) the control of the potential gradient near the ground by regions of high space charge associated with a column of rain.

Adkins discusses the effective current due to splashing both in steady rain and in heavy rain.

Law(12) (1961a,b) has developed an automatic condensation nucleus counter operating a pen recorder to study the vertical distribution of nuclei within 3 m of the ground in connexion with studies of space charge concentration. His unpublished work shows that convection plays an important part in the vertical transfer of electric charge.

The space charge concentration near the ground has been deduced by Smiddy and Chalmers(13) (1959) from measurements at two heights using Smiddy double field mills to minimize field distortion. In fair weather a

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(12) Cambridge University, England

(13) Durham University, England

small negative space charge observed is explained in terms of radioactivity of the ground, and, in heavy rain, concentrations of negative charge up to 1000 pC m^{-3} are reported. The authors suggest that the lack of agreement with their simultaneous measurements using Obolensky filtration apparatus is due to the presence of small ions.

Following the construction by Stein(14) (1958) of a field mill to be carried by a radiosonde balloon, an ingenious double field mill for radiosonde working has been designed and made by Currie and Kreielsheimer(15) (1960). The stator and rotor members each comprise the opposite quadrants of a circular plate. With the two stators connected together the output is proportional to the mill self-charge if the two rotors move in phase but proportional to the external potential gradient if the rotors maintain a relative displacement of 90°. Errors in field measurement due to the charge on the instrument are thus automatically eliminated. The device has now been prepared for carriage in a glider of the Imperial College Gliding Club for thunderstorm investigations in England.

Adamson(16) (1960) has designed a field mill with overall negative feedback giving a very closely linear relation between output and field to be used in conjunction with an unshielded air-earth or rain current continuously recording system. The mill output is fed via a differentiating circuit into the current amplifier in such a way as to give compensation for the displacement current which is proportional to the rate of change of field. The apparatus has a time constant of 20 second excepting thunderstorms it is suitable for all weathers.

Wildman(17) (1962) has devised a field mill suitable for use when the signal due to the conduction current is no longer small compared with the induction signal. His machine rotor has two concentric rings of holes covering and uncovering two sets of insulated studs, giving two separate signals with different dependence on field and conduction current, allowing the effects of these two to be distinguished.

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(14) Auckland University, New Zealand
(15) Auckland University, New Zealand
(16) Durham University, England
(17) Durham University, England

4. Point Discharge and Precipitation Currents

A new method of measuring point discharge current down a tree has been introduced by Maund and Chalmers(18) (1960). The ions leaving a discharging point cause a reduction in the potential gradient downwind. With one field mill upwind and another downwind the measured change in potential gradient can be used to find the point current. Although the method is indirect, no modification of the discharging object is necessary. The authors found evidence that a tree in full leaf gives much less point discharge current than had previously been assumed, a matter of importance in discussing the total charge brought to earth.

Milner and Chalmers(19) (1961) report measurements of potential gradient and discharge current from a point fixed 2 m above a horse-chestnut tree 13 m high. For a given value of upwind speed their results show a linear relation between point current and potential gradient. These authors also describe a new method of measuring point discharge current down a tree. They drilled two holes through the bark of a lime tree, one 3 m above the other, and inserted tubes containing mercury to make electrical contact with the sapwood, connecting the leads to a galvanometer. This effectively short-circuited that section of the tree and the current measured was almost all the point discharge current. Here too they found a linear relationship with potential gradient, and some indication that a tree gives less point current when in leaf. Further observations with the same apparatus, by Chalmers (1962), underline the need to exercise caution when interpreting point discharge records. He reports that the tree current is not only always less than that through an artificial point, but that during the rapid field changes accompanying lightning the tree current has a quite different course from that of the artificial point, which follows the agrimeter record in the usual way. An approximate relationship embracing the linear law for current to an earthed point has been deduced theoretically by Chalmers(20) (1961); the current $i = 2\pi\epsilon VW$ where ϵ is the electric permittivity of air, V the potential gradient and W the wind speed.

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(18) Durham University, England

(19) Durham University, England

(20) Durham University, England

Using Adamson's field-change compensated exposed collector system (1960) Ramsay and Chalmers(21) (1960) have measured the current brought to earth during continuous non-stormy precipitation. The comparatively short time constant of 20 sec enabled them to examine in greater detail than before the connexion between current density and potential gradient. This was reasonably linear for observations in the winter 1957-8 and of the well-known form $I = a(F + C)$ where F is the potential gradient and a and C are constants. Correlation was poor in the summer of 1958. The connexion is most nearly linear during sleet and "wet snow", and supports the earlier conclusions of Chalmers (1956, 1959) that in nimbostratus clouds the precipitation, when in the form of snow, receives a negative charge, leaving positive behind in the cloud: but when it melts it acquires a positive charge, leaving negative behind.

5. Thunderstorm Electricity

A new theory of thunderstorm electrification has been advanced by Latham and Mason(22) (1961b). It is based on the results of their detailed laboratory experiments which are in excellent agreement with their theory of electric charge transfer associated with temperature gradients in ice by a kind of thermoelectric effect (1961a). To quote one of the authors, Mason (1961): "The positive hydrogen ions (protons) and the negative hydroxyl ions (OH-), formed by the thermal dissociation of a small fraction of the ice molecules, become separated under the influence of a temperature gradient. If we imagine a steady temperature difference maintained across a piece of ice, the warmer end will initially possess higher concentrations of both positive and negative ions. Ions of both types will diffuse down this concentration gradient towards the colder end, but because the mobility of the positive ions is at least ten times that of the negative ions, they will move ahead and produce an excess of positive charge in the colder part of the ice."

This charge transfer process is considered to operate, in a storm when supercooled water droplets captured by falling soft hail pellets, freeze on

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(21) Durham University, England.
(22) Imperial College, London.

contact, throw out small positively charged splinters, and so leave a negative charge on the hailstone. This charged splinter production was verified in the laboratory by the authors, working with a simulated hail pellet growing by accretion of supercooled water droplets. They confirmed the earlier experimental findings of Mason and Maybank(23) (1960) who observed the splintering and usually negative charging, on freezing, of a supercooled water droplet suspended on an insulated fibre. While a droplet is freezing it will have a liquid centre at 0°C and a solid outside part at a lower temperature, giving a radial temperature gradient in the ice shell. According to the charge transfer process there will be an excess of positive space charge in the outer layers of ice, and, when the droplet bursts, the outer layer will tend to carry off positive charge, leaving the residue negatively charged. Such negatively charged hailstones in falling away from the positive splinters would produce a positive dipole in agreement with that in a thundercloud.

Latham and Mason (1961b) proceed to calculate the rate of charge production in a thundercloud. For soft hail pellets of average radius $\bar{R}$ and fall velocity v the volume swept out per sec is $\pi\bar{R}^2 v$ and so each pellet makes $E\pi\bar{R}^2 n_d v$ collisions with supercooled droplets in concentration n_d if E is the collision efficiency. If there are n_h hailpellets per unit volume there are thus $E\pi\bar{R}^2 n_d n_h v$ collisions per unit volume per second. The soft hail has an equivalent precipitation intensity p, i.e. the mass of water falling per unit area per second given by $\frac{4}{3}\pi\bar{R}^3\bar{\rho}n_h v$ where $\bar{\rho}$ is the mean density of the hail. In terms of p the number of collisions becomes $\frac{3}{4} E \frac{p}{\bar{R}\,\bar{\rho}} n_d$. If the charge produced per droplet is q_d, the rate of charge production per unit volume is given by

$$\frac{dQ}{dt} = \frac{3}{4} E \frac{p}{\bar{R}\,\bar{\rho}} n_d q_d$$

Using the values $E = 1$, $p = 5$ cm h^{-1} or $5/3600$ cm s^{-1}, $\bar{R} = 0.2$ cm, $\bar{\rho} = 0.5$ g cm^{-3}, $n_d = 1$ cm^{-3} and the authors' laboratory value $q_d = 4 \times 10^{-6}$ e.s.u., we have

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(23) Imperial College, London

$$\frac{dQ}{dt} = 4 \times 10^{-8} \text{ e.s.u. cm}^{-3}\text{s}^{-1}$$

$$= 1 \text{ C km}^{-3}\text{min}^{-1}$$

The authors consider this rate adequate to provide enough charge to give the first lightning flash within about 20 minutes of the detection of precipitation particles by radar, and they suggest that their theory gives the principal mechanism of thunderstorm electrification.

Latham and Mason (1961a,b) have also investigated the charge produced by the momentary contact of two pieces of ice at different temperatures. From the temperature gradient charge transfer theory they predict a maximum charge transfer of 3×10^{-3} ΔT e.s.u. cm^{-2}, where ΔT is the temperature difference, for a contact time of 0.01 seconds. For longer times the samples rapidly come to the same temperature and the charge will tend to zero. These results were confirmed experimentally by the authors. Calculations of the rate of charge production in a storm by this process, with hailstones falling through a cloud if ice crystals, give only 10^{-4} C km^{-3} min^{-1}, and the authors conclude that although the sign of the charge on the hailstone will be negative, as required, the contribution to storm electrification will be only slight.

The theory of the charging of hail pellets by these two processes has been extended by Latham and Mason (1962) to the case of collisions occurring in polarizing electric fields of up to about 1000 V cm^{-1} as found in thunderstorms. They also examined this question by laboratory experiment. They conclude that such fields have little effect on the rate of charging predicted by the main theory outlined above.

There is a serious discrepancy between the observed charge for ice-ice contacts reported by Latham and Mason and that by Reynolds, Brook and Gourley (1957), the latter being some five orders of magnitude larger. There seem to be no other measured values, but Hutchinson(24) (1960) reported that for momentary contact between two ice crystals grown from the vapour and having temperature differences up to 14 deg C any charges due to the contact

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(24) Durham University, England

were below the apparatus sensitivity of 6×10^{-6} e.s.u. The area in contact lay between 0.2 and 2 mm^2 and the contact time between 0.2 and 0.5 sec. A similar conclusion was reached by Evans (25) (1962). Charges as large as those reported by Reynolds, Brook and Gourley should have been detected easily. The discrepancy has already led to some discussion by Reynolds and Brook (1962) and Mason and Latham (1962).

Evans (1962) also has measured the charge remaining when a supercooled drop on a fibre freezes, bursts, andejects fragments. Although his results refer to only 50 drops there is an indication that the charge produced is often larger than the Latham-Mason theory can easily explain.

The production of ice splinters on exposing a frost deposit to an airstream at different temperatures has been examined by Latham(26) (1962). The particles were found to carry a charge, its sign and magnitude depending on the difference in temperature between deposit and airstream, and explained by the Latham-Mason temperature-gradient charge transfer theory.

At the Electrical Research Association Laboratories at Leatherhead, England, an inexpensive and reliable lightning flash counter has been developed (Golde, 1962). It operates on positive potential gradient changes caused by negative strokes to earth up to a distance of 40 km. The recovery time is of the order of 1 second so that if multiple strokes occur only one will be recorded. Since the instrument is also triggered by the appropriate cloud to cloud discharges it is necessary to know the ratios of negative to positive earth and cloud strokes respectively.

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(25) Durham University, England

(26) Manchester College of Science and Technology, England.

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SESSION 7.3

ELECTROMAGNETIC ENERGY RADIATED FROM LIGHTNING

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Abstract— This paper is to survey the study recently developed on the electromagnetic energy radiated from lightning, i.e. atmospherics, not including propagation. Characteristics of the electrostatic, induction and radiation fields of lightning are fully described, including the frequency spectrum in the neighbourhood of the source. Consequently this paper will supply a foundation to the study of propagation of atmospherics, slow tail, ELF and VLF propagations, whistlers, mechanism of lightning discharge, etc.

I. Introduction

This paper is to survey the general feature of the developments of observation and theory which have been made recently in the field of electromagnetic radiation from lightning and at the same time to suggest the items of collaborated study for the future.

In order to study the characteristics of lightning discharge many kinds of measurement have been made and developed, i.e. optical, photoelectric, electrostatic and electromagnetic methods have prevailed all over the world. Here in this paper, specifically, the characteristics of electromagnetic energy, i.e. atmospherics in a broad sense, radiated from lightning, not including propagation, are described.

The atmospherics propagate through the space between the ionosphere and the earth in the wave guide transimission mode or in the ray mode reflecting between them. Some of the energy penetrate the ionosphere into exosphere along the geomagnetic line of force, and go to the other hemisphere where they are reflected back and return to the source again along the same geomagnetic line of force. As the exosphere is the medium of plasma with magnetic field, it is dispersive and during the journey atmospheric pulses become whistlers from which the density of electron in the exosphere is evaluated and the existence of proton in it is proved.

Frequency spectrum of atmospherics at the various distances from the source will show the propagation characteristics of LF and VLF waves. Since the long waves are not disturbed by geomagnetic storms and propagate with low attenuation, they are very useful to the international comparison of the frequency standards as well as to the radio method of navigation. It is because the radio engineers and geophysicists make much of the study atmospherics and whistlers.

Consequently the investigation of characteristics of electric fields in the neighbourhood of lightning discharge, are very useful to the study of the mechanism of lightning discharge, the propagation of longer radio waves and the interference of atmospherics to radio communications.

For this purpose workrs have made so far the waveform measurement with wide band receivers, in which the band width is less than 1 kc/s to avoid interference in fairly clouded higher frequency region. ELF band, 1 c/s-3000 c/s, which attracts recently attentions of engineers and scientists, is measured with receivers of pass band 1 c/s-50 c/s for a lower frequency region and with waveform recorders for a higher frequency region, "slow tail". For HF, VHF and UHF regions observations are made with single frequency receivers of very narrow band width to avoid the interference of radio communications.

Lightning discharges are divided into 2 classes, i. e. the cloud-earth discharge and the intra-cloud discharge. The cloud-earth discharge consists of the pre-preliminary discharge, the preliminary discharge (Ig, Ignition stage or B, breakdown stage, I, intermediate stage and a, L, leader stage.), b, R, the return streamer stage, c, J, the junction streamer stage, s, F, the final discharge stage, etc. Corresponding to each of these optically observed stages, a characteristics change of electric field is observed with fairy good response. (1)(2)(3)(4)(5)(6)

The intra-cloud discharge displays also characteristic field changes somewhat different from those of cloud-earth discharges. Therefore the investigation of electrostatic, induction and radiation field of these stages and the comparison among them are very useful to investigate the details of characteristics of lightning phenomena. It is because the electronical methods, developed remarkably in the last decade, are recommended to reveal quantitatively the details of the phenomena better than the optical methods.

II. Electrostatic Field

In accordance with the observation at distances 25-250 km, Pierce(3) found with capillary electrometers the relation between the positive and negative slow mean field changes with distance. The field obeys inverse cube relation and corresponds to a change of electric moment of 110 coul-km, i. e. to a field-change of 1 v/m at 100 km. It is well known that near a storm most field-discharges are positive, while as the distance of the activity increases negative field-changes become more frequent.

For any particular year and for magnitudes less than about 100 v/m, the ratio N+/N-, where N+ and N- are the number of all positive and negative field changes, is constant. This constant value may differ from year to year, but there is no significant change with magnitude between 100 and 0.1 v/m. Above 100 v/m positive field-changes become increasingly predominant as the magnitude of the field-change rises.

A field-change of 100 v/m correscorsponds to a distance of about 20 km; the constancy of N+/N- belowe 100 v/m therefore implies that discharges, producing a reversal in the sign of the associated field-change beyond 20 km, do not occur. The changes from year to year in N+/N-, for field changes < 100 v/m, are therefore not to be regarded as characteristic of the year but rather as representing differences between particular storms.

Slow negative field-changes are due to air or cloud discharges which either lower positive change or, more probably, raise negative charge. Slow positive field-changes are produced by flashes which do not reach the earth, and which probably involve the downward movement of negative charge. Slow positive field-changes with fast elements are produced by flashes conveying negative electricity to ground: Usually, a gradual L rise in field is succeeded by one or more rapid R elements separated either by quiet intervals or by slow J changes, and there is often a final S or F section.

Takagi(5) observed that in ground discharges the slow electrostatic change is negative for near flash (within 5 km), positive to negative at distances 5-15 km, positive at 15-20 km or more, and the large ground stroke pulse has almost always a positive and very steep front.

The difference between the slow field change of a ground discharge and that of cloud discharge is that the polarity of the dipole contributing to the slow change of a ground discharge is negative and has a reversed relation to that of a cloud discharge, because the net field change is negative in a near distance and becomes positive in a long distance. Hillebrand(4a) obtained a rather unexpected result during his observation of lightning discharge. With lightning strokes at a distance of 3-8 km from his laboratory at Uppsala, it turned out quite often that the cathode ray was disappearing for a period of 5-10 μs. The magnetic field was considerably greater than the field calculated for the return stroke with a velocity of about one-fifth to one-quarter of taht of light. His interpretation would be postponed to future study and he wonders why was this fact not found in earlier observations.

1. Pre-preliminary discharges. Takeuti(7) observed that about 50 % of the ground discharges are preceded by a pre-preliminary discharge, duration 50-800 ms with median of 177 ms, which occurs within 500 ms before the first ground stroke,. and so this discharge precedes the "preliminary discharge". In some thunderclouds the greater part of the first ground stroke is preceded by the pre-preliminary discharge, while in others the strokes are preceded only by the preliminary discharge. On the average the ground discharges preceded by the pre-preliminary discharge have fewer ground strokes than those preceded only by the preliminary discharge; the pre-preliminary discharge probably neutralizes the negative charge in the ground stroke. The relation between the pre-preliminary discharge and the preliminary discharge is not yet known at present, but its characteristics

are almost similar to cloud discharges and it seems very likely to excite preliminary discharges.

2. B or Ig field change.(2)(6) The B field change, duration 2-10 ms, is negative at distances upto 2 km, positive at distances in excess of 5 km and positive or negative between 2 and 5 km. (Malan); negative upto 6 km, positive in excess of 10 km and positive and negative or indeterminate between 6 and 10 km (Ishikawa). Taking into account that the maximum change of electric field occurrs at a distance $D=\sqrt{2}H$, where H is the height of charge centre, B field change is attributed either to positive charge moving upwards from a minimum height of 1.4 km, or to negative charge moving downwards from a maximum height of 3.6 km.(2) The fact that the calculated heights of 1.4 and 3.6 km are in close agreement with the respective heights of the base of the cloud (1.5 to 2 km) and the lower region of the negative-charge centre N (3 to 4 km), strongly suggests that the B field change is due to a discharge between N and the positive charge centre p situated near the base of the cloud to make the discharge channel between p and N conductive.

3. I field change.(2)(6) The I field change, duration 0-400 ms, is the part to connect the B and L field changes and the rate of change of field is either fairly uniform or variable.

4. L field change.(1)(2)(6) The L field change, duration 4-30 ms, corresponds roughly to the photographed stepped leader process, but whenever a direct correlation is obtained

the L field change lasts from 1. 14 to 4.5 times as long, the difference increasing with the order of the stroke in the series. This indicates that successive strokes come from progressively higher regions. The L field changes are negative and hook-shaped when near, and positive and approximately parabolic when far. The change in sign with distance shows that the leader lowers negative charge from the cloud and distributes this charge along its channel.

Two types of L variation preceding the first rapid R element are distinguished upon the field records.(3) In the first, the increase in field is uninterrupted up to the R portion, while in the second the initial slow field-change is succeeded by a quiet part usually lasting until the rapid section, although there is sometimes a fairly short slow rise in field immediately preceding the R element. Somewhat similar effects have been noted by Schonland and given the titles α and β ; this nomenclature is retainded here, the two kinds of initial field-change being denoted by L (α) and L (β). The average duration for the L (α) change is 50 ms, while the corresponding figure for the L (β) variety is 175 ms. The proportion of the total change of field, due to the whole discharge, occurring during the L section, is found to be significantly higher for L (β) than for L (α) variations; the appropriate percentages are 55 % and 40 % in Europe(3) and 75 % and 9 % in Japan.(6)

5. <u>R or Main discharge field change.(1)</u> The R field change is made up of 2 parts. The rapid portion Rb has a duration of 50 to 250 µs (most frequent value 165 µs),

and evidently corresponds to the rapid upwards movement of the return streamer, its duration is between 1.5 and 2.0 times as great as the time taken for the return streamer to reach the cloud base. Rb is followed by slower field-change Rc which lasts from 70 to 900 µs, corresponding roughly to the duration of continuing luminosity in the return streamer channel. Both Rb and Rc are of positive sign at all distances as would be expected if they were due to the removal to earth of negative charge from the leader channel and the cloud. But at the distance of more than 15 km Rb indicates a superposed pulse which deflects at first on the positive side and then negative.(1)(5)(6) Rc from a near flash to ground frequently shows small hook-shaped field changes which occur for a period up to 6 ms after Rb. Its duration is between 200 and 600 µs and its amplitude is 0.2 to 0.01 times of Rb. It seems that these hook-shaped change can be directly related to the M components of luminosity in the return streamer channel. At a distance they show minor radiation pulses only.

6. <u>J field change.</u> This field change(8) in the interval between separate strokes of the multiple discharge to ground is found to be negative for near flash (within 5 km), negative to positive at a distance 5-12 km, positive at 12-20 km. At distances between 20 and 150 km, Malan(8) found 23 % positive, 37 % zero and 40 % negative, while Worwell and Pierce(9) found 25 % pasitive and 75 % zero. It is believed that during this process there occurs a discharge between the positive charge brought to the top of discharge channel by

the return streamer and the negative charge in the cloud. This discharge makes conductive the part of a column in the cloud, which has abundant negative charges, to excite the next dart leader. Taking into account the change of sign of J field change with distance, Malan(8) considered that the discharge proceeds upward in the cloud and at the same time the effect of positive charge, which is high above the cloud and discharges upwards, does not come out at a short distance due to the masking effect of the J field change and appears progressively with increasing distances. According to the observation at Soccoro Mountain (alt. 7,200 ft or 2,200 m) by Brook(10) the J process, in which a streamer moves slowly upward in the intervals between the return strokes was clearly visible as it penetrated the remote regions of the cloud. The upper most region from which the return stroke originated was observed to move (in steps reminiscent of darts) upward and outward, illuminating new regions of cloud, before a new section was added to the channel of the previous return stroke and a new stroke occurred. Some discharges to ground appeared to originate from a vertical column, but far the greater number were seen to progress horizontally or inclined at about 30° to the horizontal. The horizontally progressing junction streamer occurred about 3 times as often as the vertical streamer. These observations are consistent with the field measurement of Worwell and Pierce.(9)

Hewitt(11) employed a radar equipment at a frequency of 600 Mc/s for the study of streamer movement within thunderslouds in the intervals between strokes to ground. The observations show that ascending echoes occur at increasing ranges and angles of elevation in the interstroke intervals, the heights increasing with the order of the intervals in the series. This is in accord with what would be expected if the echoes came from J streamers and the observed vertical velocity agrees with that found for the J streamer. A futher observation show that echoes at lower heights less than 4 km persist throughout the series of ascending streamers and often show considerable horizontal movement.

7. F field change. Malan(12) found that the F field change is a large final slow positive field change most frequently occurs after flashes having fewer than 4 strokes in the multiple stroke process. It is shown that this field change is due to, a continuous discharge to ground of part of the negatively charged column higher than that reached by the last stroke. The mechanism of progress of upward discharge in the column is similar to the J process. The discharge to ground changes from intermittent to continuous when the charge density becomes too low. It is believed that during this process there occurs a more active discharge between the positive charge at the top of the cloud and the negative charge above it, and the effect of this discharge is not clear at short distances due to masking effect of F process in the negatively charged column, but it appears remarkably with increasing distances.

8. **Intra-cloud discharge field change.** Cloud discharges show large slow continuous electrostatic field changes which are positive when the discharge is near and become negative when the distance increases.(5)(13) Small rapid step-like or pulse form changes which are responsible for sudden bursts of bright luminosity are usually superimposed in sporadic fashion on the slow field change.

Takagi(5) found that in cloud discharges the slow electrostatic change is positive for near flash (within 5-10 km), negative at 10-20 km or more. It suggests that the cloud discharge generally dissipate a positive dipole in a cloud. The observed and estimated field intensities of the electrostatic field changes due to cloud discharges are shown in Table 1, where the estimated value is obtained by assuming that the charges +25 abd -25 coul, are located at the height of 8 and 4 km respectively on a vertical line. The similar values are estimated on the ground discharge.

Table 1. The observed and the estimated field intensities of the electrostatic field changes due to cloud discharges.

Distance (km)	Observed Rapid process (v/m)	Observed Slow process (kv/m)	Estimated absolute value* (kv/m)
0- 5	50-300	1 -30	2.6 -21
5-10	10-100	.1 - 5	0 - 2.6
10-15	2- 20	.1 - 1	.25- .31
15-25	..5- 10	.05- .5	.09- .25

* It is assumed that 25 and -25 coul of electricity are located at the altitudes 8 and 4 km respectively on a vertical line.

III. Induction field.

1. B or Ig pulsations. According to Ishikawa,(6) Clarence and Malan,(2) at a distance more than 15 km the B or Ig field change starts with a train of large and predominantly positive pulses of varying and gradually decreasing amplitude. The interval between the pulses is irregular and varies from 80 to 230 μs. The most frequent duration of the pulse train is between 2 and 4 ms, the longest train observed lasting for 12 ms, the durations corresponding with those of the electrostatic B field changes. Small amplitude pulsations of which time separations are between 5 and 10 μs are often superimposed on the large low-frequency B pulses. They usually continue with varying amplitude up to the incidence of the return stroke.

2. I pulsations.(2)(6) The pulsations in the interval between the B and L stages are high frequency pulsations of very small amplitude. Periodic spurts of isolated pulses, of amplitudes comparable with those of the B pulses, often occur during the I phase. These pulses are positive when the rate of change of electrostatic field increases and negative when the rate of change of field decreases. When the return stroke follows the large B pulse train in less than 30 or 40 ms, the whole intermediate interval is occupied by the characteristic high frequency L pulsations described in the next paragraph, which suggests that in these cases the I stage is short or absent.

3. L pulsations.(2) The field changes immediately preceding the return stroke consist of a train of steep and

predominantly positive pulses following each other at 5 to 10 µs intervals. Some of the pulses are of larger amplitude than those intervening. The larger pulses follow each other at intervals between 30 and 60 µs, which is the same as the pause time between the bright steps of stepped leaders. The observation, however, that strokes subsequent to the first are often preceded by similar pulse trains indicates that they cannot wholly be due to the stepped process in the downward leader. Since the effects in the intervals between the strokes of a flash must be due to J streamers, it is reasonable to conclude that the similar field changes immediately preceding the first stroke are also mainly caused by streamer discharges inside the cloud, which supply charge to the advancing leader. The pulses during the L part of the discharge are smaller in amplitude than the B pulses. The amplitude ratio of B to L pulses varies from 3:1 to 20:1, the higher the rate of change of the electrostatic field during the B stage, the larger this ratio.

IV. The Radiation Field.(2)(13)(14)

1. *Preliminary discharge process.* The radiation field of a preliminary discharge process in the ground discharge is remarkable in every frequency. It is observed even when the static field change is not clearly approved. The B, I and L stages show always some indication of high frequency radiation. Usually the amplitude of L is largest, and then that of B and I the smallest; the radiation field of B and I stages are negligibly small in the frequency

range between 200 c/s and 20 kc/s. The radiation field of subsequent dart leaders is not essentially distinguished from that of J process filling up in interstroke period especially at higher frequencies.

The records obtained during the daytime illustrate three common types of radiation L fields. (i) The α type (duration 2-25 ms) having a small almost uniform train of pulsations whose amplitudes are often less than 1/100 of that of the return stroke. (ii) The slow β type (duration 3-19 ms) whose initial pulsations are slightly larger than the later pulsations, which resemble those of the α type. (iii) The large amplitude fast β type (duration 1-7 ms) whose initial pulsations may have amplitudes up to half as large as the first return stroke pulsation. Intermediate types are also obtained. The time intervals between the L pulsations vary from 30 to 100 μs which indicates that they originate from stepped leaders. Night time atmospherics show the same three types of leader, but the apparent time interval between the steps is smaller owing to successive ionospheric reflections.

2. <u>The return streamer process.</u> The salient points regarding the radiation field of ground discharge is as follows. At 3 kc/s the radiation is confined to the return strokes. This remaines true up to about 20 kc/s except that preliminary and interstroke pulses occasionally appear with amplitudes 1 % to 2 % of those of the return strokes. With increasing frequency up to about 1-2 Mc/s return strokes

still have the largest amplitude, but radiation from other parts of the discharge become progressively large. At 4-12 Mc/s, especially at higher than 10 Mc, the latter surpass the return strokes in amplitude. An interesting phenomenon is observed at these higher frequencies. The radiation is intense and continuous during the course of the first few strokes of a flash, except for pauses varying from 2 to 20 ms immediately following a return stroke.(5)(13) After the initial burst of activity the pulses become more and more spaced in time. With increasing frequencies, the intermittent impulsive radiations change gradually into continuous radiations, but at frequencies higher than 100 Mc/s they occur very often associated with electrostatic pulses.

3. The cloud discharge precess. In the intra-cloud discharges small rapid step like field changes responsible for sudden burst of bright luminosity are usually superimposed in sporadic fashion on the slow field change. At frequencies from 3 to 10 kc/s there are usually only one to three very small radiation pulses which are associated with rapid but not necessarily the largest K field changes. As the frequency increases to 2 Mc/s more and more radiation pulses appear, those associated with K field changes remaining the largest. At 4-12 Mc/s the radiation becomes practically continuous and the K pulses can no longer be distinguished from the rest of the radiation. The cloud discharge has somewhat similar high frequency characteristics to the J process in the ground discharge and it is generally composed of slow J-like streamers and many rapid local streamers. At higher

frequencies than 100 Mc continuous and intermittent radiations independent of any process like stepped leaders are observed. Lightning flashes within 5 km show very often a continuous radiation, which has a duration larger than 100 ms, accompanied by an electric field of complicated variation.

The following figures give the ratios of the amplitudes of the return stroke radiation of ground discharges to the amplitudes of the most intense radiation components of cloud discharges at different frequencies:

Frequency	Amplitude ratios
3 kc/s	20/1-40/1
6 "	10/1-20/1
10 "	10/1
20 "	5/1
30 "	2/1-3/1
50-100 "	1/1-1.5/1
1.5-12 Mc/s	1/1

The above figures agree with the suggestion of Aiya that cloud discharges contribute little to the radio noise level below 1 Mc/s.

V. Frequency Spectrum.

The frequency spectrum of atmospherics is very impotant to the study of wave propagation, propagation of atmospherics, mechanism of lightning discharge, but it is also very difficult to obtain a frequency spectrum at various distances from the source, at various stages of lightning discharges, at various geographical features, at various meteorological and seasonal conditions. Although the data avalable at present are very few, the followings are the main results of observation from ELF to UHF all over the world.

Tayor and Jeans(15) recorded the intensity of atmosperics at 1-40 kc/s emitted from the ground discharge at distances between 150 and 600 km. Watt and Maxewll(16) made similar observations at 1-100 kc/s at distances between 30 and 50 km. Horner(17) measured at 11 Mc/s and 6 kc/s at distances between 1.5 and 6.5 km. Takagi(14) measured at 100 kc/s-500 Mc/s at 15-20 km. Schafer(17) measured at 150 Mc/s at 1-32 km. Summarizing these data and normalizing at a distance of 10 km for the receiver bandwidth of 1 kc/s, we obtain a frequency spectrum as shown in Fig.1. As the method of measurements and characteristics of the apparata are different from each other, the curve in the figure is not fully reliable; it is only to show the general tendency. The waveform of atmospherics in the neighbourhood of lightning discharge depends on the geographical feature (sea, mountain, plain, city, town, tower, etc.), geographical position and the kind of discharge (ground discharge, cloud discharge, etc.) and changes from time to time during the discharge process.

Two widely quoted expressions have been given for the current surge during the return-stroke of the lightning flash to earth. Both(18) have the same double exponential from $i_t = i_o(e^{-\alpha t} - e^{-\beta t})$, where t is the time in sec. and i_t the current at time t , the origin of time being taken at the start of the return-stroke. Bruce and Golde(19) gave the following figures for the parameters, namely, $i_o = 28,000$ A, $\alpha = 4.4 \times 10^4$ $\beta = 4.6 \times 10^5$, while Norinder(20) suggested the values $i_o = 20,000$ A, $\alpha = 7 \times 10^3$, $\beta = 4 \times 10^4$.

It is well known,(18) for instance, that individual lightning flashes differ considerably in their spectral characteristics, the excitation of which may be anticipated to be related to conditions, and therefore currents, in the return-stroke channel. Perhaps the most striking evidence, however, for the existence of at least two main types of current surge is that derived from the study of atmospherics. The frequency spectra of the electromagnetic fields radiated respectively by return-strokes carrying the Norinder and Bruce-Golde forms of current surge, with the current assumed to be uniform along the channel, can easily be calculated.

Hill(21) calculated the radiation energy of lightning in the VLF range, considering only the return stroke, and found that the spectral energy distribution is centred at about 11 kc, with a total width at half-maximum of 12 kc.

In 1952 it was suggested by Shumann(22) that the earth and ionosphere may together act as a cavity resonator for electromagnetic wave and that the first resonance should occur at 10.6 c/s. Refinement of the thery indicated that losses due to absorption by the ionosphere or radiation through the ionosphere should reduce the resonant frequency by at least 1.5 c/s. Experimental evidence for the existence of the first resonant mode was reported first by Schumann and König(23) and, in considerably more detail by König.

The theory of ELF resonances was more recently discussed by Wait, and experimental evidence for the existence of the first and higher resonant modes, based upon measurements of electric fields, was presented by Balser and Wagner.(24) Their results were also applied by Kaemer to the calculation of an ionospheric loss parameter which is a function of the height and the conductivity of the sharply bounded ionosphere assumed in the first order thery. Additional experimental results were published recently by König, by Maple, by Lokken, Shand and Wright, by Polk and Fitchen, and by Sao, Jindo and Kumagai; König(25) reported that almost the same type of ELF were observed at Bonn and Munich which was classified into 5 types correlating with weather phenomena and on the occasion of solar eclipse the similar change were observed with the sunrise and sunset phenomena; Polk(26) confirmed the existence of comparatively strong natural oscillations in the 7 to 10 c/s frequency range, but the resonant frequency exhibits short-time variations and at night they are considerably weaker than during daylight hours and stronger than usual during periods of geomagnetic activity; Sao(27) suggested that only 25 % of lightning discharge emit ELF and 81 % of ELF come from sources, which radiate VLF, around the observatory and not from sources all over the world.

VI. The Study Programme for the Future.

1. According to the observation for a long time it seems that the characteristics of atmospherics, which define its frequency spectrum, depend on the configuration and development of thundercloud. They show variations in accordance with the seasonal and meteorological conditions as well as geographical features such as plateau, plain, mountain, sea, lake, town, city, tall tower, etc. Therefore it is recommended that the

frequency sepectrum from ELF to UHF is to be measured at various distances from the source, at every meteorological and seasonal conditions as well as at every geographical feature. It will contribute to the study of wave propagation, mechanism of lightning discharge, properties of whistlers, etc. Really some authors showed that the occurrence of whistlers depend on the frequency spectrum of mother atmospherics and on the propagation conditions, and those atmospherics which have a peak near 5 kc, in place of ordinary 10 kc, excite whistlers very often.

2. At present many scientists observe the production, development and destruction of thunderclouds at many points on the ground with electronical instruments, and evaluate the electrical configuration of thundercloud. But this is afterall the indirect method and it is complicated, requires a large area, many man-power, etc. Therefore it is recommended to determine the specification of a radio-sonde and a Radar with PPI and RHI scopes suitable to observe horizontal and vertical configurations of thundercloud.

3. Although we could not succeeded disturbed by a typhoon, we made a measurement of characteristics of a ground discharge with a large paper baloon, connected with a grounded conducter, at 200 m high upon the plateau of Mt. Haruna (1446 m), around which many equipments for measurements were arranged. It is therefore recommended that the most useful method of this kind would be discussed and determined so that a similar but more elaborate method may come out.

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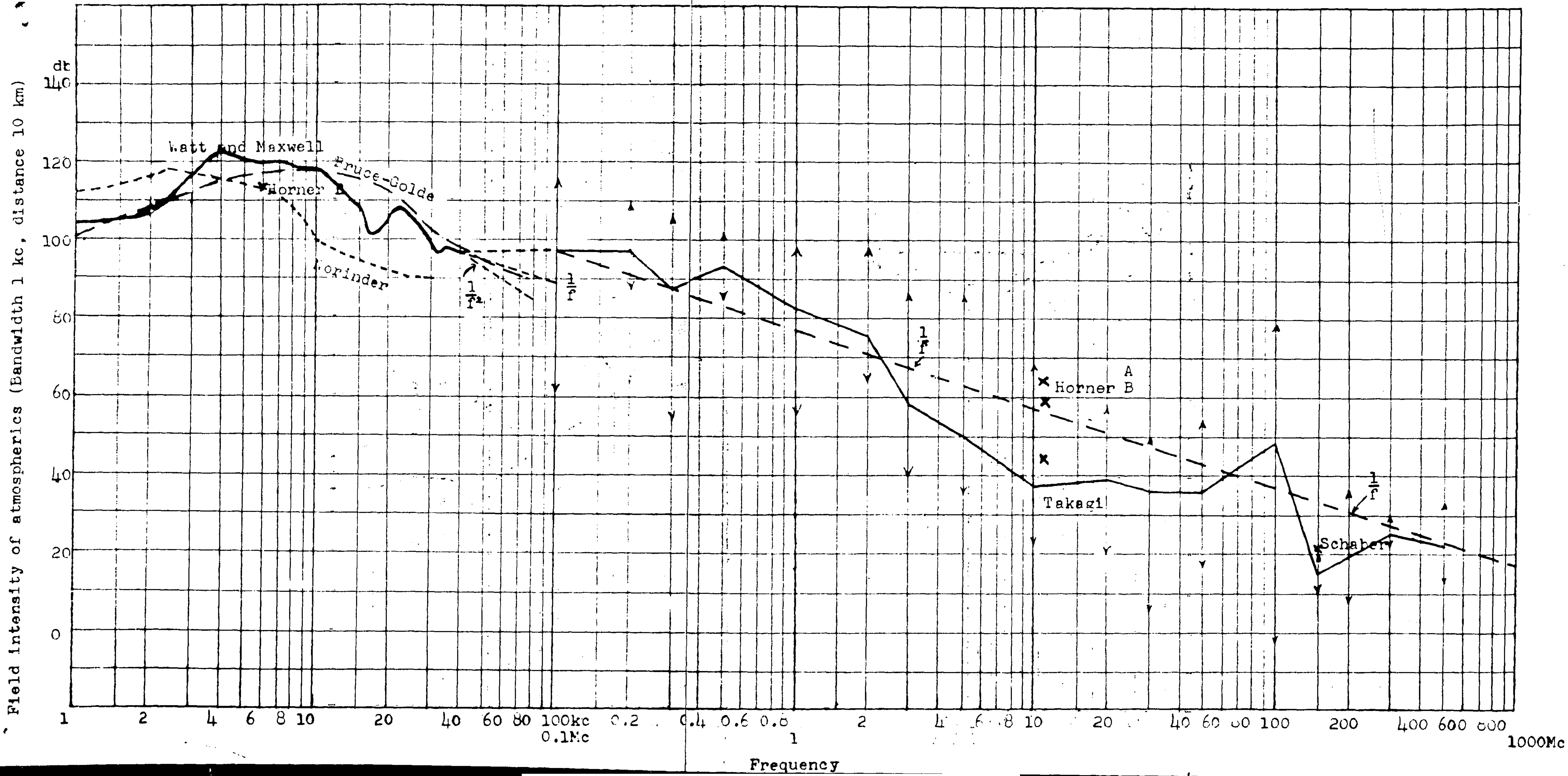
db
140
120
100
80
60
40
20
0
Field intensity of atmospherics (Bandwidth 1 kc, distance 10 km)
Watt and Maxwell
Bruce-Golde
Horner B
Lorinder
1/f²
1/f
1/f
Horner A
Horner B
Takagi
Schaber
1/f
1
2
4
6
8
10
20
40
60
80
100kc
0.1Mc
0.2
0.4
0.6
0.8
1
2
4
6
8
10
20
40
60
80
100
200
400
600
800
1000Mc
Frequency

SESSION 9.5

To be presented at the Third
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The Concepts of Atmospheric Electricity as Applied to the Ionosphere

by

K. Maeda

(Kyoto University, Japan)

Abstract

1.1) Electric charges in the ionosphere are carried by free electrons and ions which are maintained by a balance of solar ionizing radiation and decay processes. The electron density can be measured by vertical radio sounding from the ground surface and the N(h) profile is calculated from the data of this sounding. However, such N(h) profile is not complete, but the whole profile can be obtained with the aid of sounding rocket bearing suitable sensors. As for the outer ionosphere extending to the magnetosphere, the N(h) profile is estimated by topside sounding, satellite signal reception (Faraday rotation and Doppler shift experiments) and whistler observation. The N(h) profile is a knowledge of basic importance not only for radio propagation study but also for understanding the interrelationship between the geomagnetic variation and the ionospheric behaviour. For the latter problem the ion density profile is also essential, which could be revealed by sounding rocket so far, though incomplete.

1.2) The dynamic behaviour of electrons and ions will be described in terms of velocity distribution, drift velocity, collision, electrical conductivity and current, some of which are mutually connected.

Among others the velocity distribution and drift velocity of electrons are the most basic quantities. The classical magneto-ionic theory should be revised by taking into account the velocity distribution and some fruitful outcome from such revised concept can be expected in understanding the wave absorption, Doppler broadening and so forth. It is well known from laboratory experiments that a certain non-linearity exists in the electron drift velocity. However, when the problem should be treated under the influence of magnetic field, as in the case of ionosphere, a great difficulty arises in mathematics. Such is also the case of velocity distribution. Monte Carlo method will be one of the effective tools to attack these problems and some laboratory experiments will be designed to solve them. Also some possible methods of measuring directly those quantities by sounding rocket will be devised.

1.3) The Pedersen, Hall and Cowling conductivities ($\sigma_1, \sigma_2, \sigma_3$) based on the above dynamic behaviour of charge carriers play an important role in the dynamo-theoretical study on electric field and current, which is responsible for the geomagnetic variation. The result of such study tells us that the effective total conductivivy has a peculiar characteristics, which can account for the abnormal intensification of dynamo current under the disturbed state of the ionosphere and that a large shear in the current flow can take place near the boundary of two zones having different conductivities. It is also noted that the wind system in the ionosphere is not yet established in spite of its great importance.

2.1) The measurement of radio noise over the ground has been made widely over the world and the world maps of radio noise intensity are available. This sort of noise is thought to originate in lightning discharge and other climatic phenomena. When we once go up into the ionosphere and still higher level, the situation will change. Radio noise originated near the ground can invade there by extraordinary wave mode(whistler mode) and such penetrated energy is expected to be fairly large especially during night. A spacial distribution of radio noise from such origin will be studied.

2.2) On considering the radio noise in the ionosphere and exosphere, one can imagine the possible existence of noise from extra-terrestrial source. If this is really the case, the noise distribution is subject ~~of~~ to wave propagation law which involves the frequency of the wave and geomagnetic field as important factors.

2.3) Moreover one might imagine the generation of radio noise by some certain electric phenomena occurring in the ionosphere and exosphere. Liberation of free charges by impinging meteors might be an example, and synchrotron radiation of high energy electrons in the radiation belts may be another source of noise.

2.4) Besides the above, we have to notice that there is an evidence to believe the existence of a certain amplifying action for radio waves in the exosphere. The phenomenon known as VLF emissions, such as dawn chorus, hooks etc. is the evidence. The problems of possible sources and amplifying mechanism should be studied, and one may suppose that such amplifying action, if it really exists, can contribute to raising the energy of radio noise.

2.5) All the above points will be finally consolidated to the problem on the nature and structure of radio noise in the ionosphere and its outer space. In connection to this problem one more important point must be added. That is the study of how the radio waves penetrate the ionosphere. The problem is to know the rates of penetration and reflection of radio wave energy when the waves go up and come down through the ionosphere. The problem will be attacked analytically. The rocket experiments and satellite observations (such as LOFTI) will be very useful for the study of the problem as a whole.

STAATLICH AUTORISIERTE
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Wien, am Jänner 1963
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Volker FRITSCH, Wien 1.)

Geoelektrische Probleme der Blitzforschung

Die Frage, ob und wie der untere Teil der Blitzbahn durch die elektrische Beschaffenheit des Untergrundes beeinflußt wird, wird in der Fachliteratur schon lange diskutiert. Aber erst die moderne geoelektrische Meßtechnik konnte jene genauen Aufschlüsse über die elektrische Struktur des Untergrundes geben, die notwendig sind, um dieses Problem auf eine exakte Grundlage zu stellen.

Der Elektrotechniker ist im allgemeinen gewohnt mit recht homogenen Leitern zu rechnen. Der Untergrund ist aber, elektrisch betrachtet, ein Leitergebilde von meist sehr komplizierter Natur. Widerstandsschwankungen um mehrere Zehnerpotenzen über wenige Meter Entfernung sind keine Seltenheit. Daher sind auch scharf ausgeprägte elektrische Diskontinuitätsflächen vorhanden. Man versucht diese Frage durch statistische Erhebungen in Verbindung mit geoelektrischen Bodenuntersuchungen und durch Modellversuche zu klären.

Um das Problem statistisch eindeutig zu klären, wäre es zunächst nötig, für jeden Punkt der untersuchten Fläche einen Bruch anzuschreiben, der die durch Blitzentladung abgeleitete Elektrizitätsmenge pro Flächeneinheit angibt. Diese Angabe wäre dann zeitlich auf eine Gewitterperiode, also auf ein Jahr, zu beziehen.

Nehmen wir an, wir hätten diese Ziffern für eine große Fläche und für einen genügend langen Zeitraum, dann wäre unsere Frage, ob ein Zusammenhang zwischen der Entladungsdichte und geoelek-

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Dr.Volker FRITSCH, Leiter der staatlich autor.Versuchsanstalt für Geoelektrik und Blitzschutz und Professor der H.f.E.

trischen Faktoren besteht, aber noch nicht ohneweiteres zu beantworten. Wir wissen, daß die geoelektrische Struktur des Untergrundes möglicherweise eine Komponente ist. Ganz sicher aber existieren neben ihr noch mindestens zwei weitere: eine meteorologische und eine topographische. Wir müssen daher die geoelektrische Komponente isolieren. Darüber wollen wir noch später einiges sagen. Zunächst wollen wir aber untersuchen, mit welcher Genauigkeit wir die Entladungsdichte überhaupt schätzen können.

Leider stehen heute, wenn man von einigen Ländern absieht, nur sehr wenige und lückenhafte Statistiken zur Verfügung.

Auf den letzten internationalen Blitzschutzkonferenzen wurde die Frage der Blitzzähler diskutiert. Meßtechnisch bestehen da sicher keine Hindernisse, aber gewisse Probleme, wie zum Beisp. die Trennung der Erd-und Wolkenblitze, sind noch nicht geklärt. Auch hat jeder Blitz gewissermaßen eine "Meßreichweite", die von der eigenen Stromstärke, dem Verlauf der Blitzbahn und weiteren Faktoren ebenso abhängig ist, wie von der Meßempfindlichkeit des Anzeigegerätes. Während auf der einen Seite Doppelzählungen kaum zu vermeiden sein werden, dürften andere schwächere Einschläge wieder überhaupt nicht registriert werden. Unter diesen Voraussetzungen wird man erst nach vielleicht zehnjährigen Meßperioden einigermaßen repräsentative Vergleichswerte erhalten. Während so langer Zeiträume ändern sich aber oft die meteorologischen Voraussetzungen regional nicht unbedeutend. Ich habe zahlreiche Leitungsstatistiken untersucht. Man erkennt da sehr deutlich, daß die sogenannten Gewitterstraßen sich innerhalb oft recht weiter Grenzen verschieben. Jedes Jahr sind andere Abschnitte der von den Straßen senkrecht gequerten Leitungen besonders oft betroffen und daher kann man oft erst nach 30 Jahren wieder brauchbare Mittel erhalten, aus denen man Schlüsse ziehen kann.

Die topographische Komponente ist konstanter, obwohl, besonders im Gebirge, der Einfluß dieser Komponente durch die meteorologische mitbestimmt wird.

Es ist also sowohl die Ermittlung der Zahl der Blitzschläge und deren Einschlagstelle, als auch die Trennung der drei wichtigsten Komponenten in einfacher Weise nicht möglich. Wir müssen zu Untersuchungsmethoden greifen, die viel komplizierter und obendrein weniger zuverlässig sind.

Betrachten wir einmal die rein physikalischen Voraussetzungen. Wenn sich die Vorentladung des Blitzes der Erdoberfläche nähert, so wächst ihr bekanntlich aus dieser eine "Gegenentladung" entgegen, die auch "Fangentladung" genannt wird. Vereinigen sich diese beiden, dann ist der ionisierte Kanal geschlossen, in dem die Hauptentladung zustandekommt. Für jenen Punkt der Erdoberfläche, von dem die Hauptentladung daher ausgeht, ist somit sicher,im hohen Maße die Entwicklung der Gegenentladung bestimmend. Es ist nun aber klar, daß diese Gegenentladung in erster Linie von einer Zone ausgehen wird, in der unter dem Einfluß der vordringenden Vorentladung ein hoher Potentialgradient entstehen wird. Dadurch wird das Problem physikalisch etwas durchsichtiger, denn man erhält Hinweise auf den Einfluß der geoelektrischen Struktur und auf die Höhe, in der diese noch wirksam sein kann.

Die Äquipotentialflächen des normalen luftelektrischen Feldes werden durch die geoelektrische Beschaffenheit selbst eines inhomogenen Untergrundes, sicher nicht beeinflußt. Erst, wenn stärkere Entladungsströme fließen, gewinnen sie Bedeutung. Nun sind die Widerstandsunterschiede im Untergrunde aber oft recht bedeutend. Im Hochgebirge zum Beispiel, sind solche von mehreren Zehnerpotenzen über Entfernungen von nur wenigen Metern keine Seltenheit. Es ist dann physikalisch verständlich und auch durch Modellversuche erwiesen, daß die Gegenentladungen besonders aus schmalen gutleitenden Einschlüssen hervorquellen. Die geoelektrischen Diskontinuitätszonen unterscheiden sich daher wesentlich von homogenen Gebieten. Natürlich wird durch die Gegenentladung nur der unterste Teil der Blitzentladung beeinflußt, meist wohl nur die zwei bis drei letzten Stufen der Vorentladung, die zusammen eine Länge von ungefähr 80 bis 150 m im Mittel haben dürften. Über diesen Höhen ist dann der geoelektrische Einfluß des Untergrundes ohne Bedeutung für die Ausbildung der Blitzbahn. Diese Überlegung scheint übrigens auch vertretbar, wenn man verschiedene Blitzphotos näher analysiert.

Betrachten wir zuerst die Möglichkeit, das Problem auf statistischer Basis zu behandeln: Voraussenden möchte ich, daß nur Statistiken einen Wert haben, die sich über lange Zeiträume erstrekken.
Die Statistik, die in einigen Ländern gepflegt wird, ist natürlich mehr nach wirtschaftlichen als nach wissenschaftlichen Gesichtspunkten ausgerichtet. In erster Linie steht die meteorologische und die Schadenstatistik zur Verfügung. Kritische Vergleiche in Österreich haben gezeigt, daß als einzig sichere Bezugsbasis die Zahl der jährlichen Gewittertage angesehen werden kann. Die Angaben über Zahl der Gewitter, oder gar über deren Intensität, sind zu ungenau.

Die Schadenstatistik ist in den einzelnen Ländern verschieden organisiert. In manchen Ländern werden die Daten nicht veröffentlicht, oder sie sind unvollständig. In Österreich gibt es heute eine 15-jährige, für das Bundesgebiet einheitlich organisierte Statistik, bei der auch darauf geachtet wurde, daß sie Aussagen macht, die auch den Wissenschaftler interessieren. Da in Österreich das Versicherungswesen durchwegs in öffentlicher Hand ist, so besteht für die einzelnen Institute, die meist den Ländern gehören, kein Grund, Angaben geheim zu halten. In jedem der neun Bundesländer gibt es eine "Landesstelle für Brandverhütung", die auch die Blitzstatistik führt. Da praktisch alle wichtigen Objekte beobachtet werden und überdies auch alle Blitzschläge berücksichtigt werden, die irgendwie zur Kenntnis der Landesstellen gelangen, so ist diese Statistik ziemlich umfassend.

Gestatten Sie mir, daß ich nur einige Zahlen anführe: Österreich hat eine Fläche von nur 84.000 km^2. Trotzdem also Österreich ein sehr kleines Land ist, kann uns eine österreichische Statistik etwas sagen, denn dieses Land ist topographisch und siedlungsmäßig sehr verschiedenartig. Österreich umfaßt zunächst alle Landschaften, vom Hochgebirge, das fast bis 4000 m ansteigt, bis zur Tiefebene. Es hat ein stark differenziertes Klima. Siedlungsmäßig umfaßt es alle Einheiten, von der Millionenstadt bis zu den kleinsten Alpengehöften und schließlich sind Industrie und Landwirtschaft über bestimmte Zonen verteilt. So wird manches, das man in Österreich beobachtet hat, vielleicht auch für größere Länder interessant sein.

In Österreich werden jährlich ungefähr 1000 Blitzschläge statistisch erfaßt, also ein Blitzschlag auf ungefähr 80-100 km^2 . Diese Ziffer liegt natürlich tief unter der tatsächlichen. Einen Anhaltspunkt erhält man, wenn man die Verhältnisse am Rande von Wien betrachtet. In der Stadt Wien wurden pro Flächeneinheit ungefähr achtmal, wenn man das dicht verbaute Gebiet betrachtet, ungefähr zehnmal so viel Blitzschläge beobachtet als in den unmittelbar angrenzenden Gebieten. In der Umgebung von Rom hat G. Bruckmann, allerdings auf Grund viel weniger zuverlässiger Unterlagen, ein Verhältnis 5:1 berechnet. Beide Städte sind ungefähr gleich groß. Diese Differenz ist nur darauf zurückzuführen, daß in der Stadt die Beobachtungsdichte viel größer ist als in den landwirtschaftlich besiedelten Gebieten der Umgebung. Man wird daher annehmen dürfen, daß ungefähr 95% aller Blitzschläge gar nicht beobachtet worden sind. Unter diesen Umständen darf man fragen, ob eine solche Statistik überhaupt eine Aussagekraft hat. Ich glaube, daß man diese Frage dennoch positiv beantworten darf, wenn man bedenkt, daß die Beobachtungsstellen zwar auf die jeweils dicht verbauten Gebiete zusammengedrängt sind, die vielleicht nur 5-10% der Gesamtfläche Österreichs ausmachen, daß diese aber wieder recht gleichmäßig über das ganze Staatsgebiet verteilt sind. Wenn man von Wien und vier weiteren Städten mit ungefähr 100.000 bis 250.000 Einwohnern absieht, verteilen sich die Beobachtungsstellen auf ungefähr 17.000 Siedlungseinheiten, die in 79 Bezirken zusammengefaßt sind. Wir haben nun diese Bezirke zur Grundlage der Blitzstatistik gewählt. Sie sind im Durchschnitt etwas über 1000 km^2 groß, also relativ klein, andererseits aber doch so groß, daß durchschnittlich auf einen im Jahr 12 beobachtete Blitzschläge fallen, und da die Statistik heute über 15 Jahre läuft, so erhält man für den Bezirk im Durchschnitt über 150 beobachtete Blitzschläge. Die örtliche Verteilung einer solchen Zahl kann doch schon einiges sagen.

Wir wollen daher unsere Statistik nicht auf die Flächeneinheit, sondern auf die Zahl der beobachteten Objekte beziehen, da nur diese exakt erfaßbar ist. Es ist, um die Zuverlässigkeit dieser Reduktion beurteilen zu können, wieder notwendig, die Verteilung dieser Objekte über die einzelnen Staatsgebiete zu untersuchen. Nur dann, wenn diese einigermaßen homogen ist, wird eine auf die Zahl der Objekte bezogene Statistik in den einzelnen Staatsgebieten vergleichbare Angaben liefern können.

Im ganzen Staatsgebiet entfallen, wenn man die Wald-, Wasser- und Ödlandflächen abzieht, in denen kein Beobachtungsdienst besteht, durchschnittlich 22 Objekte auf den Quadratkilometer. Diese Verteilung ist in ungefähr 65% des Staatsgebietes fast die gleiche, in 10% der Gebietsfläche ist sie um 27% und in 25% der Gebietsfläche um 45% geringer. Es handelt sich bei den letzten beiden um die Hochgebirgsgebiete in Salzburg und Tirol. Man kann also von einer ziemlich homogenen Verteilung der Objekte über das ganze Staatsgebiet sprechen. Daher wird eine auf die Zahl der Objekte bezogene Statistik ausreichend repräsentativ sein. Selbst die erwähnten schwächer besiedelten Gebirgszonen werden ausreichend statistisch erfaßt, denn die Siedlungen sind in diesen Gebieten zwar auf die schmalen Täler beschränkt, diese aber sind wieder ziemlich gleichmäßig über die ganze Alpengrenze verteilt und sie reichen bis in bedeutende Höhen, bis in die Nähe des Zentralkammes.

Wir bilden nun für die einzelnen Bezirke Quotienten, in deren Zähler die jährlich beobachteten Blitzschläge und in deren Nenner die Zahl der beobachteten Objekte steht. Da dieser Bruch sehr klein ist, so wird er mit 10.000 multipliziert. Er gibt also die Zahl der Blitzschläge pro 10.000 Objekte an. Nun soll aber noch die topographische und meteorologische Komponente ausgeschieden werden. Der Einfluß der Höhenlage wurde genau untersucht;er ist kaum nachweisbar und überdies nicht systematischer Natur. Die meteorologische Komponente wurde in der Weise berücksichtigt, daß auf die Zahl der jährlichen Gewittertage, die in dem betreffenden Bezirk beobachtet wurden, bezogen wurde. Es bleibt also nur die durch die geophysikalische Bodenbeschaffenheit bedingte Komponente übrig.

Gestatten Sie mir nun, daß ich das Ergebnis dieser langjährigen Statistik vom Standpunkt der Geoelektrik aus kurz bespreche:

Sie sehen im Bilde eine Tabelle, in der für das ganze Staatsgebiet die besprochene, auf 10.000 Objekte bezogene Ziffer,

Bild 1. Angabe von Z_H für die geologischen Zonen

wir wollen sie Gefährdungsziffer nennen, angegeben ist. Das Staatsgebiet wurde zu diesem Zweck in Teilgebiete zergliedert, die geologisch einheitlich beschrieben werden können. Man sieht, daß die Gefährdungsziffer für die alten geologischen Formationen, besonders für die archäische "Böhmische Masse" weit höher ist als für die jungen Formationen. Man kann eine ziemlich gleichmäßige Zunahme der Gefährdungsziffer mit dem geologischen Alter feststellen. Diese Verteilung wurde von mir vor ungefähr 20 Jahren auch beobachtet, als ich für das Land Sachsen die Blitzstatistik von Lehmann und Schneider ausgewertet habe. Auch damals waren die alten Formationen durch eine besonders hohe Blitzgefährdung ausgezeichnet.

Diese Tatsache ist nun keineswegs leicht zu erklären. Eine Arbeitshypothese, die jetzt untersucht wird, werden wir noch besprechen.

Die Statistik zeigt aber auch, daß es eng begrenzte Zonen, deren Blitzgefährdung weit über jener der Umgebung liegt, gibt. Ich habe bereits 1934 auf eine kleine Gemeinde Absroth in Nordböhmen hingewiesen, in der die auf Grund der Angaben von J.Schwirtlich berechnete Blitzgefährdung ungefähr 140 Mal so groß ist wie jene der nächsten Bezirke in Sachsen. Die statistische Auswertung der österreichischen Statistik durch Bruckmann hat nun zwei weitere Gemeinden in Kärnten eindeutig als Blitznester erkannt. In einer Ortschaft von 150 Häusern hat der Blitz in 6 Jahren zehnmal eingeschlagen, in der anderen, die 258 Häuser hat, zwölfmal. Die Blitzgefährdungsziffer ist ungefähr zwölfmal so hoch wie jene der Umgebung. Unter Annahme einer Poissonverteilung hat Bruckmann die Wahrscheinlichkeit für diese beiden Ereignisse mit 0,00009 und 0,0005, sowie die Wahrscheinlichkeit dafür, daß zwei Orte mit so hoher Blitzgefährdung im gleichen Bezirk existieren, mit 0,0019 berechnet. Man kann also von Blitznestern sprechen.

Ein weiteres Blitznest habe ich auf Grund der Angaben des Forstpersonales in der Steiermark konstatiert. Sie sehen es im nächsten Bilde. Auf diesem Plan sind die Einschlagstellen eingetragen, die

2. Bild. Blitznest bei Bad Aussee

in den letzten Jahren beobachtet wurden. Vergleicht man diese Beobachtungen mit der Statistik, so erkennt man folgendes: Im Bereiche des Blitznestes entfallen ungefähr 21 Blitzschläge im Jahr auf den Quadratkilometer, für das Bezirksgebiet kann man mit 0,3 bis 0,5 Einschlägen pro Quadratkilometer rechnen. Die Gefährdung des Blitznestes ist also 40 bis 50 Mal so hoch wie jene der Umgebung.

Ich habe dieses Gebiet auch geoelektrisch untersuchen lassen und zeige Ihnen das Ergebnis im nächsten Bild.

3. Bild. Geoelektrische Untersuchung Bad Aussee

Das geoelektrische Profil, das mit einer Auslegung von 2x20 m gemessen wurde, zeigt einen Verlauf, wie wir ihn über tektonischen Störungen oft erhalten. Im Bereiche des Blitznestes und

an seinen Grenzen sind Widerstandsminima ausgeprägt. Außerhalb dieser Zone steigt der spezifische Widerstand zu beiden Seiten auf Werte von ungefähr 250 Ohm m, die in dieser Gegend als normal zu bezeichnen sind.
Es handelt sich also um eine ausgeprägte geoelektrische Diskontinuität.

Neben statistischen Untersuchungen steht die Auswertung von Modellversuchen. Wenn ich deren Ergebnis bespreche, so darf ich eine Bemerkung vorausschicken: Es ist vollkommen klar, daß der Modellversuch niemals die natürlichen Verhältnisse rekonstruieren kann, er wird stets nur Hinweise geben können. Diese aber sind wertvoll, wenn man bedenkt, daß z.B. in Osterreich nach den Gesetzen der Wahrscheinlichkeitsrechnung innerhalb eines Zeitraumes von 20 Jahren erst jedes 79.000 Haus dreimal vom Blitz getroffen wird. Wollte man also diese Fragen nur aus Naturbeobachtungen heraus klären, so müßten Jahrzehnte vergehen, ehe man die ersten Hinweise für die Behandlung des Problems erhielte. Dagegen gestattet der Modellversuch eine beliebig große Zahl von Beobachtungen unter Bedingungen, die man ebenfalls beliebig wählen kann. Man wird daher auf den Modellversuch nicht verzichten, sondern seine Ergebnisse sinnvoll mit den Naturbeobachtungen verbinden.

Mit Schlagweiten von weniger als einem Meter haben u.a. H.Norinder Und O.Salka in Uppsala gearbeitet. Ein Meßergebnis zeigt das nächste Bild. Das vordringende Entladungshaupt wird dadurch eine Spitzenelektrode ersetzt, die in der Mitte über einer mit Sand bedeckten Metallscheibe hängt. In dieser erkennen wir links eine gutleitende Einlagerung. Wir sehen, daß die Entladung zum größten Teil nach diesen Einlagerungen hin abgelenkt wird. Nur wenige Teilentladungen gleiten nach den Punkten B und C hin ab. Gegen diese Versuche wurde eingewendet, daß in der Natur Einlagerungen von der Art, wie sie Norinder und Salka verwendet haben, nicht vorkommen. Ich habe daher diese Versuche im Hochspannungs-

4. Bild. Modellversuch von NORINDER u. SALKA

feld der Technischen Universität Dresden wiederholt und dabei natürliche geologische Leiter - Sand, Humus und stark angefeuchteten Lehm . verwendet. Außerdem habe ich mit Entladungen bis zu 2 m Länge gearbeitet. Ein Meßergebnis sehen Sie im nächsten Bild. Die Entladungselektrode wurde bei A...B...C...D...E angeordnet. Im oberen Bild sieht man die Verteilung der Einschläge über einen gewachsenen Boden, in dem gutleitender Lehm eingelagert ist. Die meisten Einschläge sind über der gutleitenden Zone konzentriert. Im unteren Teilbild ist der umgekehrte Fall dargestellt. Die schlechtleitende Zone ist aus ziemlich trockenem Sand gebildet. In ihr ist nur ein Einschlag zu verzeichnen. Dagegen sind diese an der Diskontinuitätsfläche konzentriert. Im nächsten Bild sind alle Ergebnisse miteinander verglichen.

5. Bild. Versuche in Dresden

6. Bild. Versuche in Dresden

Die Maxima und Minima sind besonders über der gutleitenden Einlagerung, bei positiver Spitze viel stärker ausgeprägt als bei negativer.

Das Ergebnis meiner Untersuchungen deckt sich also gut mit jenem der Versuche von Norinder und Salka. Auf der Hochschule für Elektrotechnik in Ilmenau hat K. Gopalan Modellmessungen gemacht, bei denen der Untergrund durch ein System Ohmscher Widerstände ersetzt wurde. Die Entladungslänge war leider nur gering, nämlich 44 cm.

Als Beispiel möchte ich die Analyse des Meßergebnisses zeigen, das Gopalan in Tafel 14 seiner Dissertation bringt. Man sieht, daß über der Diskontinuitätsstelle ein bedeutender Anstieg der Einschläge zu beobachten ist. Die Verteilungskurve zeigt über der rechten Diskontinuitätsstelle einen viermal so hohen Wert wie über der linken. Das Widerstandsverhältnis ist rechts: 1:20, links aber nur 1:4.

7. Bild. Versuche von GOPALAN

Im Zusammenhang damit sind auch Experimente interessant die K. Dummer auf der Hochschule für Elektrotechnik in Ilmenau gemacht hat. Von diesen will ich zwei Bilder zeigen. Dummer hat den Verlauf der Entladung in feuchtem Sand untersucht, also die sog. Blitzröhren. Im nächsten Bild ist der Verlauf einer Blitzröhre in einem homogenen Sandboden dargestellt. Sie verläuft von

8. Bild. Blitzröhre nach Dummer

der Einschlagstelle ziemlich geradlinig und ungefähr senkrecht zur Oberfläche in der Richtung zum Grundwasser. Im nächsten Bilde sehen wir den Verlauf in einem inhomogenen Untergrund. Der Sand hat wieder einen spezifischen Widerstand von ungefähr

9. Bild. Blitzröhre nach Dummer

150 Ohm m. Zu beiden Seiten sind aber gutleitende Einlagerungen mit spezifischen Widerständen von 4 und 12 Ohm m angeordnet. In diesem Falle teilt sich die Entladung nach beiden Richtungen hin und steuert die gutleitenden Zonen an. Diese Untersuchungen zeigen somit einen ähnlichen Verlauf der Entladungsbahn wie er in der Luft, nahe der Erdoberfläche, beobachtet worden ist.

Wir wollen nun damit die in der Natur beobachteten Ergebnisse vergleichen. Die Beobachtung von Blitzschlägen in Energieleitungen hat verschiedene Autoren zu verschiedenen Erkenntnissen geführt. G. Lehmann, der wohl über die älteste Statistik dieser Art verfügt - sie ist 30 Jahre alt - kommt zu dem Resultat, daß über geoelektrischen Diskontinuitätszonen mehr Einschläge zu verzeichnen sind als über geoelektrisen homogenen Zonen. Andere Autoren kommen zu entgegengesetzten Resultaten. Diese Verschiedenheit der Ergebnisse könnte aber physikalisch durchaus verstanden werden, wenn man bedenkt, daß die einzelnen Autoren ganz verschiedene Leitungen untersucht haben, nämlich solche über homogenen und inhomogenen Untergrund. Außerdem sollte man bei einem kritischen Vergleich nur solche Statistiken berücksichtigen, die sich über mindest 5 - 10 Jahre erstrecken. Bei kürzeren Meßreihen ist die Streuung zu groß und es können kaum brauchbare Durchschnitte ermittelt werden.

Ich habe nun auch die bereits besprochene österreichische Statistik in dieser Richtung analysiert. Das österreichische Bundesgebiet ist mit einem Netz von ungefähr 10000 geoelektrischen Sondierungen überzogen, so daß man die geoelektrischen Eigenschaften der einzelnen Gebiete einigermaßen beschreiben kann. Zunächst kann man zeigen, daß die geoelektrische Homogenität der jüngeren geologischen Formationen im allgemeinen größer ist als jene der alten. Die bereits gezeigte Tabelle würde dann lehren, daß die Blitzgefährdung mit zunehmender Homogenität abnimmt, was auch mit dem Ergebnis der besprochenen Modellversuche übereinstimmt. Ich habe nun weiter in Österreich zwei Gebiete von ungefähr 50.000 Objekten ausgewählt, von denen das eine geoelektrisch ziemlich homogen, das andere sehr inhomogen ist. Die Statistik zeigt nun, daß in der geoelektrisch inhomogenen Zone 85% der Bezirke mit extrem hoher Gefährdungsziffer (mehr als 12,6) liegen. Die stärkere Gefährdung des inhomogenen Gebietes ist also offensichtlich. Zur Erklärung wird jetzt eine Arbeitshypothese untersucht. Im homogenen Gebiet ist meist auch die Grundwasserverteilung eine homogene. Landwirtschaftliche Objekte sind daher nicht an bestimmte Zonen gebunden, an denen Wasser vorhanden ist. Im alten, geoelektrisch inhomogenem Gebirge aber ist Wasser nur aus einzelnen mächtigen wasserführenden Spalten zu gewinnen. Die landwirtschaftlichen Objekte werden daher meist in deren unmittelbaren Nähe angeordnet, da ja früher für den Standort einer Landwirtschaft die Möglichkeit, Wasser zu gewinnen, von größter Bedeutung war. Damit rücken aber alle diese Objekte auch in die Nähe von Zonen hoher Blitzgefährdung.

Wenn ich damit meine Ausführungen, die keineswegs vollständig sind, abschließe, so würde ich mich wirklich freuen, wenn mein Vortrag dazu beigetragen hätte, Sie zu Vergleichen anzuregen, die Sie vielleicht Ihren eigenen statistischen Untersuchungen entnehmen können. Gerade auf diesem Gebiete ist eine internationale Zusammenarbeit notwendig, denn die Probleme liegen nicht einfach. Es wäre vielleicht eine dankbare Aufgabe dieser Konferenz, eine einheitliche statistische Erfassung der Blitzschläge anzustreben.

Session 4

Charge Generation in Thunderstorms

by

J. Alan Chalmers

Durham University, England

1. Introduction

I think I must first apologize for intruding into this discussion when I have no theory of my own to put forward; if what I have to say is more critical of the theories that have been discussed, rather than constructive suggestions of alternative theories, my excuse may be that it is difficult to formulate a new theory before we know what is wrong with the old ones.

2. Requirements of Theory

Mason has given a number of facts which must be explained by a satisfactory theory of thunderstorm electrification. However there seems to be one case where his remarks can be improved upon, and other requirements which can be added to his list.

Mason gives the requirement of generating current at the rate of about 1 amp. But this is the requirement just to provide the lightning flashes of an average storm, and to this must be added the charges which are used in the point-discharge current below a cloud, and the charges used in dissipating currents within the cloud. It is probable that a total generating current of 3-5 amp is a better estimate, with about 1 amp external current outside the cloud, including lightning flashes to ground, and 2-4 amp average internal dissipating current, including lightning flashes within the cloud. Wormell's (1953) results show that, after a flash, the potential gradient due to the cloud returns towards its previous value approximately exponentially, and this indicates the building-up of a dissipating current.

Mason's figures refer to an average storm, but there are storms which are much more violent than the average, and if Mason's theory, or any other, is to be considered satisfactory, it must be able to account for the electrical phenomena in these. Vonnegut and Moore (1958) quote cases where there are 10-20 lightning flashes per second, as compared with Mason's figure of 1 in 20 seconds. Thus the lightning current must be 100 amp or more and the charge being separated of the order of 10^5 C. The question then is whether this remains within the bounds of possibility, or whether some theory is required in which the relative motion of charges of different signs is not limited to that provided by gravitiation.

In nimbo-stratus clouds, the total separation of charge is approximately measured by the precipitation current at the ground. This seldom reaches a value of more than 10^{-10} amp/m^2, so that for an area of 10 km^2, corresponding to that of a thundercloud, the current is only about 10^{-3} amp, i.e. less than that of the thunder cloud by a factor of over 10^3. An acceptable theory of thunderstorm electricity must be able to explain how it is that the process concerned gives so much smaller electrical effects in the nimbo-stratus than in the cumulo-nimbus clouds, although, for example, the amounts of precipitation show much less difference.

It has been pointed out several times by Vonnegut and others that the current carried down by precipitation in the thunder cloud is never more than a small fraction of the charge separation, though most theories consider precipitation to be the mechanism by which charge is separated. Even measurements within the cloud at the Zugspitze (Kuettner, 1950) show that precipitation does not carry much charge. It is therefore necessary for a theory involving precipitation to be able to explain how the charge leaves the precipitation and becomes attached to cloud droplets.

Information available at present suggests that the external current, above and below the cloud, is probably less than the current of charge separation within the cloud and this leads to the conclusion (see Chalmers, 1961) that the source of the charging current must be within the cloud and not, as in Vonnegut's theory, outside.

3. Discussion of Mason's Theory

While Mason's theory appears to give an adequate explanation of the charges in a normal thunderstorm, it has yet to be shown whether it is able to account for very violent storms and whether it can explain why the nimbostratus cloud gives so much less charge generation. And the question of the transfer of the charge to the cloud droplets from the precipitation has not been discussed in detail though there may be an answer in the splashing that occurs at temperatures close to 0°C.

The measurements of Latham and Mason (1961b) on the production of charge and of splinters showed good agreement with their theory considering the average charge per drop. But the measurements of Mason and Maybank (1960) and the more recent measurements of Evans and Hutchinson (1963) have shown that some individual drops on freezing give much greater charges than the average and, in fact, give charges which are quite considerably greater than could be provided by the mechanism suggested by Latham and Mason (1961b). This forms a serious difficulty for their theory.

It seems surprising that Latham and Mason concerned themselves with electrical effects of temperature differences in ice, corresponding to the Thomson effect in metals and did not consider electrical effects at the surface of melting, corresponding to the peltier effect in metals. This is the more surprising when it is remembered that Workman and Reynolds (1950) have found very large electrical effects on freezing, even though, as Brook points out, they themselves no longer consider this as the main agency of charge separation in clouds.

Latham and Mason found that their theory of electrical effects in ice at different temperatures was adequate to account for the ice-impact results, when there was no water present; they then applied the same theory to riming phenomena, neglecting the ice-water boundary, and found it would give enough charge for a thunderstorm. But surely the ice-water boundary cannot be neglected and there is very likely to be preferential movement of ions across this boundary. It may be added that the total "freezing potential" measured by Workman and Reynolds (1950) involves not only the ice-water interface but also the metal-water and metal-ice interfaces.

4. Discussion of Workman-Reynolds Theories

There is at present a very serious discrepancy between the experimental results for the amounts of charge separated on ice impact, the results in New Mexico (Reynolds, Brook and Gourley, 1957) giving values greater by a factor of 10^5 than those in England (Latham and Mason 1961a, Hutchinson, 1960; Evans and Hutchinson, 1963). It is to be hoped that each side will attempt to repeat the experiments carried out on the other side.

The remarks made in regard to Mason's theory in respect of violent storms, of nimbo-stratus clouds and of the transfer of the charge to the cloud droplets apply also to these theories.

5. Discussion of Vonnegut's Theory

Some of the main arguments put forward for Vonnegut's theory seem to be more arguments against the theories that involve precipitation and ice. While Vonnegut's theory could more easily satisfy some of the conditions stated, such as those of the very violent storms, of the nimbo-stratus clouds and of the absence of much charge on precipitation, there still seem to be very serious difficulties in the theory.

It is difficult to visualise how it is that when negative charge has reached the base of the cloud in the down-draught, and there attracts positive charge produced by point discharge, it is the positive, rather than the negative charge which gets into the up-draught. Similarly, how is it that, when positive charge gets to the top of the cloud, it is not this charge but negative from above which gets into the down-draught? No answer can be contemplated in terms of the attachment of the charges to cloud droplets or precipitation particles, since this would again lead to differential motion under gravitation and a return of the problems that the theory is trying to avoid.

Also Vonnegut's theory is in opposition to the results discussed above regarding internal and external currents.

6. Warm Thunderstorms

It seems that the question of warm thunderstorms is a very vital one. If it can be confirmed that these do exist and do give the same separation of charge as normal thunderstorms, then this does seem to give a serious blow to those theories that involve ice as a necessary agent in the generation of thunderstorm charge. If, however, it should turn out that the polarity of a warm thunderstorm is opposite to that of the normal thunderstorm, this might be explained as due to the same process as is normally concerned in the production of the lower positive charge, but acting with sufficient effect to produce lightning.

7. Conclusions

While there may be substance in some of the arguments against precipitation being the mechanism by which charge is separated in clouds, it does not seem that Vonnegut's theory is wholly satisfactory and up to the present there has been no other reasonable alternative, and we are left with a choice of theories, none of which appears quite satisfactory.

What appears to be required is a theory which might involve ice, but in which the separation in space is achieved not by gravitiation but by some other agency. As a tentative suggestion, could there be some sort of centrifugal action in the main up-draught, where the electrification process occurs, flinging the heavier, negatively charged particles out of the up-draught while retaining the smaller positively charges particles to move upwards, giving a speed of separation much greater than the differential speed under gravity, and hence requiring a smaller content of charge in the cloud. The postulation of the up-draught would explain the absence of effects of such magnitude in the nimbo-stratus cloud, and allow of larger currents with very intense up-draughts. The effect need not be thought of as centrifugal action on a large scale, but rather as the throwing off sideways of the heavier particles by the turbulence that occurs in the up-draught. It does not seem that enough is yet known about the motion in the up-draught to be able to make any calculations to put this suggestion to the test.

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RELATIONS BETWEEN LIGHTNING DISCHARGES AND DIFFERENT TYPES OF MUSICAL ATMOSPHERICS

by

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1. Introduction

When observing atmospherics at very low and audible frequencies by the use of a special amplifier, different types of musical (tonal) quality are heard. One type is classified as a usual whistler characterized by a steadily decreasing whistling tone from the upper limit of hearing and downwards with a frequency which falls first rapidly and then more slowly. Unusual musical atmospherics are characterized by irregular and shifting frequency variations.

The first to detect usual whistlers with an amplification set was Barkhausen (1) in 1918, and he alleged that the whistlers had connections with meteorological phenomena on warm summer days. In 1930 Barkhausen (2) indicated lightning discharges as a source of whistlers.

The first theoretical analysis of whistlers was made in 1925 by Eckersley (3). No information was presented of relations between lightning flashes and whistlers, and in 1928 he and Chapman (4) co-ordinated whistlers with powerful heard atmospherics. Later, Eckersley (5) cites relations observed between visible nocturnal individual lightning flashes and whistlers. Early investigations of whistlers were also carried out by Burton and Boardman (6). In Storey's (7) well as experimentally as theoretically comprehensive work a connection is assumed between atmospherics from lightning discharges and whistlers caused by them.

The theoretical investigations of whistlers stimulated extended experimental observations and have obviously influenced the comprehensive observation program of whistlers carried out in North America during the International Geophysical Year (1957-58). The main objective of this program was to record whistlers on a number of synoptically situated stations in North America. Magnetic tape recorders were used and the recording periods were not less than two minutes each hour round the clock.

2. Motivation for whistler investigations in Sweden

The IGY program did not include any particular investigations of lightning discharges which caused whistlers. Therefore it seemed to be of special value to start whistler investigations in Sweden. To some extent they could be considered as a complement to the mentioned IGY program. The aim of the new project was to analyse the relations between and the variation features of those individual lightning discharges which caused whistlers.

With its northern latitudes Sweden seemed to be well situated for whistler investigations. A special circumstance facilitated such a project. For the past few years a number of field stations outside Uppsala had been used and operated for simultaneous analysis of electromagnetic field variations of lightning discharges. Some of the results are given in the following publications (8-11).

A number of recording cathode-ray oscillographs and direction finders were at hand. Therefore the new investigation project only necessitated the construction of special whistler recorders.

Results obtained in the project will in brief be presented here; details are given in a number of publications (12-18).

3. Observation station, equipment, method of observation and supervision

In order to avoid man-made noise the whistler station was placed *17 km east of Uppsala. The geomagnetic coordinates are* $\Phi\ 58^{\circ}4$, $\Lambda\ 107^{\circ}0$.

The following instruments were used:

(a) Whistler recording equipment,
(b) CRO recorder for lightning discharges and sferics wave-forms,
(c) CRO recorder of multiple lightning strokes,
(d) Direction finders of CRO type,
(e) Sonagraph frequency analyser,
(f) Harmonic frequency analyser.

The observation of whistler activities was done continuously at the station during the summer months June-August. There was a special reason for the concentration of the work during these months. It is well-known that the general occurrence of whistler activity is lower in summer, but on the other hand, it is only during this season that it is really possible in Sweden to observe thunderstorm activities at such distances as are necessary for a correlation with whistler phenomena.

During two seasons, 1958 and 1960, the observation and supervision program was carried out during the day, in 1959 both night and day, and

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During two seasons, 1958 and 1960, the observation and supervision program was carried out during the day, in 1959 both night and day, and in 1961 only at night.

The supervision was carried out in such a way that the thunderstorm activities were observed for 10 minutes every half hour. Simultaneously the occurrence of whistler activity was checked and detailed notes of the situations were made. Such notes formed the basis for the comprehension of the development of whistler situations.

When a whistler activity was ascertained, the observer either extended the continual observation or, if the whistler intensity seemed high enough, started a full recording procedure. This meant that all the mentioned apparatus were set into continual operation until the activity disappeared. In this way the following data were obtained: (1) the geographical position of the occasional lightning discharges, (2) the waveforms of the produced atmospherics, (3) multiple lightning strokes, their intervals and time sequences, and (4) tape recordings of whistlers. These data will obviously make possible a rather detailed analysis.

4. Observations of local lightning paths producing whistlers

At the very beginning of the whistler investigations in 1956, an attempt was made to determine what direction of lightning paths was followed by whistlers, e.g. if they were only linked to vertical lightning paths or to those in other directions. This was singly possible by simultaneous local observations of lightning paths and whistlers. Earlier direct observations from other localities which might have answered this problem were not at hand.

Comprehensive measurements of lightning discharges combined with daylight photographs of lightning paths during the thunderstorm season of 1956, when three field stations were simultaneously operating in the vicinity of the whistler station, did not result in any simultaneous observations. On the other hand, in 1957, operations of the three stations resulted in the most comprehensive number of local thunderstorm and lightning flashes ever obtained. More than 100 daylight photographs and 600 cathode-ray oscillographic records were obtained. In spite of the great number of lightning discharges within the area in the numerous thunderstorms during the season, we succeeded only during a single day in confirming that certain lightning discharges were accompanied by whistlers. This constitutes a glaring and permanent proof of how rare and hazardous the conditions must be for whistlers to develop within a thunderstorm area. There must, consequently, be special pre-requisite conditions in the thunder atmosphere and in the layers existing outside in space for a lightning discharge to give rise to whistlers.

The mentioned occasion during the 1957 thunderstorm season when two local thunderstorms were accompanied by whistlers occurred on August 6, with the first thunderstorm between 15.07 and 15.57. In one case it was possible to obtain a daylight picture (see Fig. 1) of a vertical lightning flash which according to simultaneous observations at the whistler station gave rise to a whistler. The distance from the station to the flash was 18 kilometres. The small distance of the stroke from one of the oscillographic recording stations allowed a calculation of the current in the path which reached a peak value of 7 kiloamperes. A second thunderstorm arrived at 19.15 on the same day. For half an hour the author was able to observe a number of typically vertical lightning paths which were all followed by whistlers. Observations based on the author's forty years' experience of studying lightning discharges characterized the thunderstorm observed as having an extraordinary and copious occurrence of vertical lightning strokes. Through the investigations of these two thunderstorms, it has accordingly been established that local vertical lightning paths generate whistlers. Oscillograms from the lightning stroke of Fig. 1 show to full evidence that negative charge was transported in the channel to the ground. The results obtained of the dominant role of vertical lightning strokes is quite in agreement with the current-jet hypothesis of whistler generation by Hoffman (19).

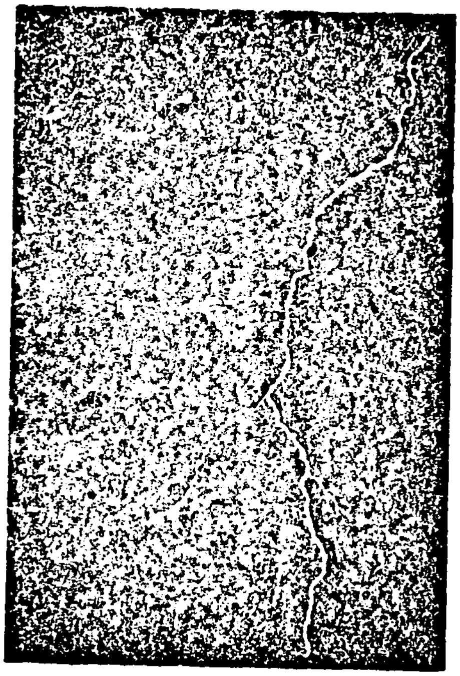

Fig. 1
Daylight photograph of vertical whistler-producing lightning flash.

5. Occurrence of whistlers

It has been found that whistlers occur in groups during periods of time lasting up to several hours. Between these periods, whistlers are entirely absent. On going through the routine observations carried out every half hour no occasion occurred when the observer only heard isolated whistlers. During these periods are observed either cases in which no whistlers at all occur, or else cases in which groups of whistlers occur. Such situations as are characterized by activity as regards whistlers have therefore been designated throughout as "whistler situations". A typical survey of a whistler situation during an observation period of 46 days is exemplified in Fig. 2.

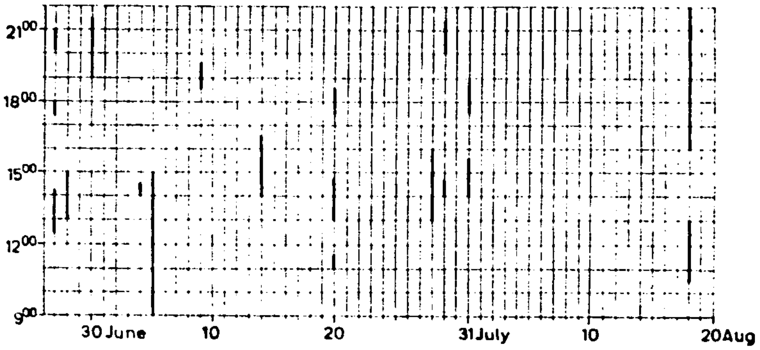

Fig. 2. General survey of whistler situations.

The following general conclusions can be drawn:

(1) Whistlers occur in great numbers during shorter periods of time between which there is a total cessation - this may extend over hours, days, and, in isolated cases, even weeks.

(2) Several whistler situations often occur on the same day or on consecutive days.

(3) A cessation of whistler activity cannot be connected with a general cessation of thunder activity.

Through the investigation of whistlers and their occurrence carried out as described above, it is confirmed that, in addition to lightning discharges, there are certain other required, locally manifested, geophysical conditions which are necessary if whistlers are to be generated at all.

6. Synoptic direction-finder observations related to whistlers

By the use of a direction finder in combination with records of whistlers, it is obviously possible to obtain and follow synoptical situations of whistler activities. It has been found that a thunderstorm region located in one direction can be accompanied by whistlers while another simultaneous thunderstorm located at the same or at other distances and in other directions may or may not produce whistlers simultaneously. It is possible to illustrate such varying situations by the use of a graphic reproduction in which suitable circles provided with time and distance indications are used. Thunderstorms are marked in the sectors in such a way that no blackening represents no whistlers, half blackening an average number of whistlers, and full blackening a high number. The graphical method is e.g. illustrated according to direction finder observations of an interesting thunderstorm situation on 28/7/58 reproduced in Fig. 3. Two marked thunderstorm centres exist partly over north-east Sweden and partly over the Gulf of Finland. The development of whistlers in these two thunderstorms during the course of the day is apparent from the graphic survey of Fig. 4. In this, very weak whistlers may be noted from both the thunderstorms during the observation period of 13.00. At 13.30 weak whistlers started at the centre in Sweden, and stronger whistlers which were very marked for both centres during 14.00-14.40 started at the centre in Finland. The whistlers' intensities decreased for both centres at 15.00 and ceased after 15.30.

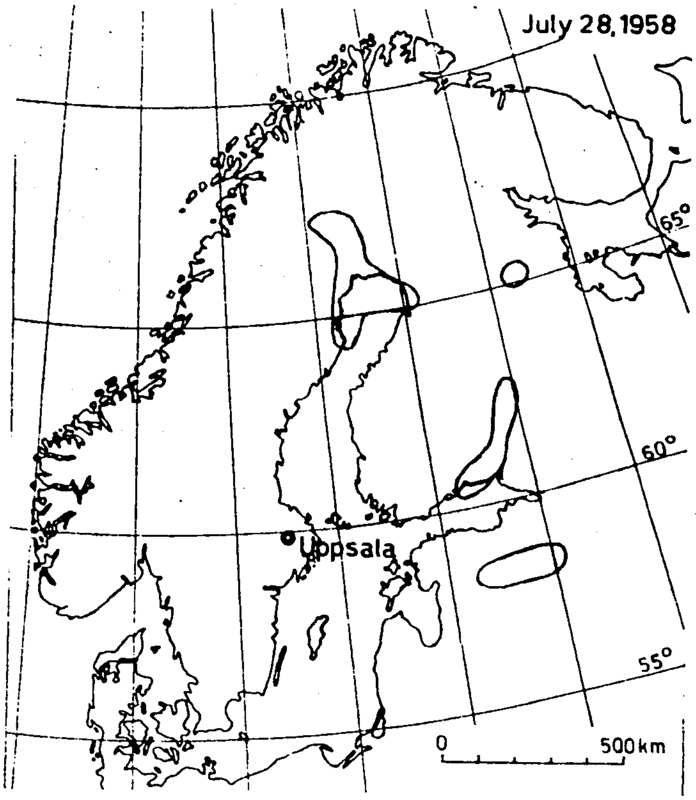

Fig. 3. Map with thunderstorm regions related to whistlers.

According to direction-finder observations three thunderstorm areas appeared on 7/9/59 (see Fig. 5), one situated in southern Sweden, one in

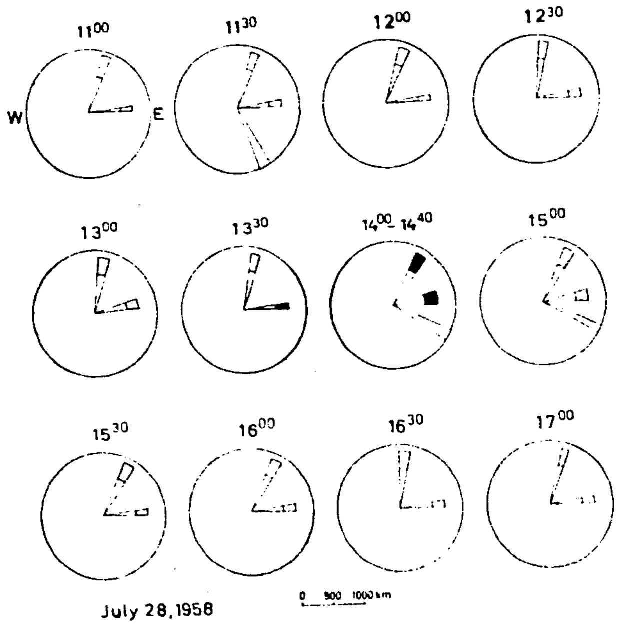

Fig. 4. Thunderstorm regions productive or non-productive of whistlers.

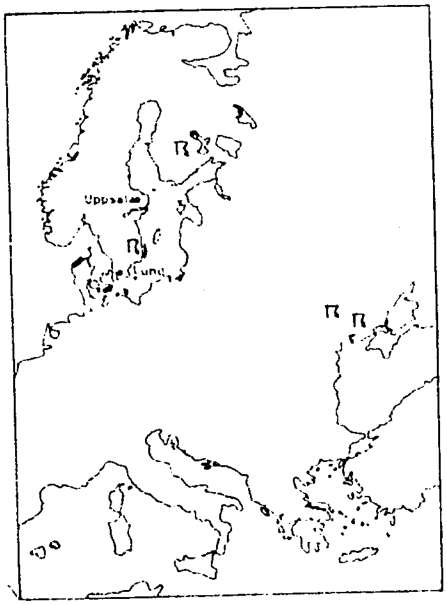

Fig. 5.

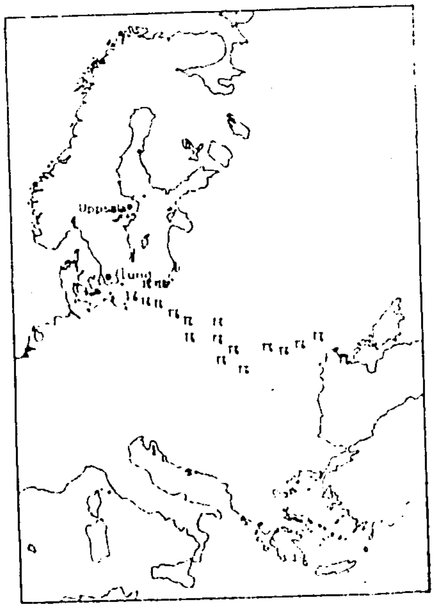

Fig. 6.

Fig. 5. Three simultaneous thunderstorms of which only one, located in Finland, was followed by whistlers.

Fig. 6. An extensive thunderstorm front in which whistlers were produced and located only in the regions of the Ukraine.

central Finland and one in the Ukraine. The thunderstorm area in southern Sweden was very intense but in spite of that it yielded no whistlers. Only the area in Finland gave whistlers, whilst they failed to appear at all from the area in the Ukraine.

A particularly interesting case occurred in the night of 19-20/7/59. As shown on the map in Fig. 6, there appeared a very extensive thunderstorm front which stretched from nothern Germany through Poland and the Ukraine down to the Crimea. The deflection of the direction finder alternated between 15°0 and up to 190°. The closest flashes which were accompanied by the greatest amplitudes, were located in northern Germany at a distance of 600 km. These lightning discharges were not followed by any whistlers. On the other hand, lightning discharges located in areas in the Ukraine at ca. 1300-1700 km and with small field deflections at the Uppsala station, yielded clear whistlers.

Investigations carried out hitherto with the aid of direction finders cannot result in an accurate determination of the local positions within a thunderstorm area where lightning discharges accompanied by whistlers occur. This task is by no means easy but a solution is possible through the improvement of instrumental equipment. As follows from the foregoing, it is almost hopeless to draw conclusions by means of oscillographic analysis of local lightning discharges. This depends in the first place on the hazardous occurrence of whistlers. Through the development of a special direction finder system for locating whistlers this problem will obviously be nearer a solution.

7. Atmospherics producing whistlers

As has already been pointed out, the activity of whistlers will be associated with a limited region in the thunderstorm. It is evident in this respect that not all lightning discharges indicated by atmospherics give rise to whistlers. In this respect a manifest difference is found within different whistler situations. One day, for example, the number of observed atmospherics with subsequent whistlers amounted to 85 % of the total recorded atmospherics during an interval of 5 minutes. On other days the corresponding number may only amount to 10 % in spite of the fact that the lightning discharges emanated from the same area.

It is of special interest to illustrate how the relation between atmospherics, with or without subsequent whistlers, changes if an intensive whistler situation appears. Such a typical situation developed on 28/6/58 and lasted for two hours. On account of the high intensity level of whistlers that day continuous recording was started and allowed a percentage distribution of atmospherics with or without subsequent whistlers during every 5-minute interval. The result is given in Fig. 7, where filled piles represent atmospherics with subsequent whistlers and empty piles atmospherics without subsequent whistlers. The variability of occurrence of whistlers is rather striking.

It is evident that employing the direction finding procedure in the study of lightning discharges simultaneously combined with accompanied whistlers is of greatest value if correlation is to be shown between the

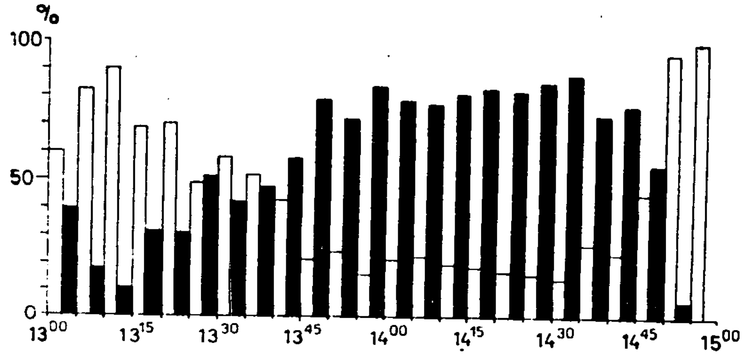

Fig. 7. Atmospherics productive of whistlers versus non-productive.

two phenomena. In the first place the method of analysis can be carried out after the following principles:

1. Comparison between the crest values of the electric field force of the atmospherics.
2. Comparison between the wave-forms of atmospherics.
3. Investigation by harmonic analysis.

8. Electric field variations of atmospherics in relation to whistlers

When it is a question of a comparison between the crest values of the electric field force of atmospherics, whether followed by whistlers or not, the whistler situation reproduced in Fig. 7 is especially valuable. It affords valuable material for comparison of the phases of development following on each other in whistler situations. The field force strength values have been directly determined by measurements from the original oscillograms in such a way that the values represent the highest amplitude difference between the two polarities.

The measured field strength values are, for a whistler situation on 28/6/58, graphically reproduced in Fig. 8, where a indicates the first period (79 observations) and b the second (119 observations). The field strength in volts/metre accompanied by whistlers is represented by filled circles and that without whistlers by empty circles. During the first half-hour of the whistler situation about 30 % of all oscillographic recordings gave subsequent whistlers within the actual sector fixed by the direction finder. During a later period 85 % gave subsequent whistlers. There is in Fig. 8 a very clear tendency to be seen for the relation of the field strength values to whistlers. In the area of the lowest field strength values atmospherics are not accompanied by whistlers. In a central area of the scale, atmospherics occur with or without whistlers. At the higher values on the scale all atmospherics are accompanied by whistlers.

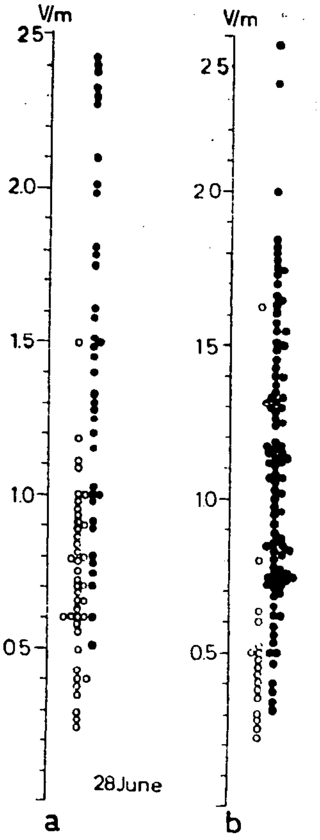

Fig. 8. Electric field of atmospherics related to whistlers.

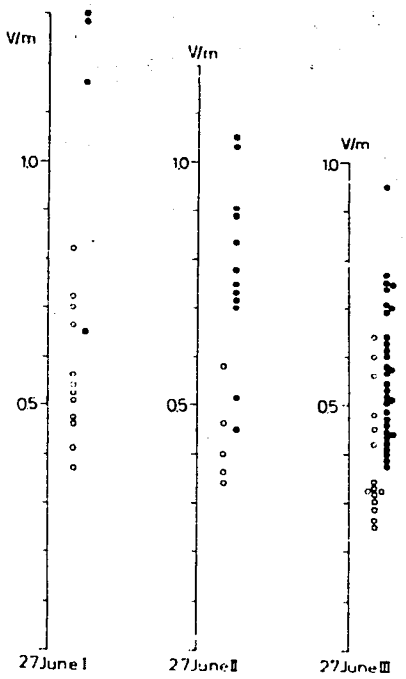

Fig. 9. Electric field of atmospherics related to whistlers.

Investigations on other whistler situations resulted in similar relations as obtained in Fig. 8. Another example of a characteristic situation from 27/6/58 is given in Fig. 9. The predominant occurrence of atmospherics producing whistlers at the groups of higher field-force values might to some extent be related to intensified current variations in the whistler-generating lightning discharges as compared with those lacking whistlers.

This indicates that the ionization in the channels when whistlers are produced has higher intensity values than in cases where no whistlers are produced. This fact is related to the typical preponderance of generating whistlers which, as will be demonstrated later, is characteristic of multiple lightning strokes. Another circumstance is related to the dependence of the transmission coefficient of the ionosphere in the very low frequency band from 1 to 5 kc, Wait (20, 21). As will be demonstrated further on, the frequencies around 5 kc are characteristic of lightning discharges followed by whistlers, and this must facilitate the entrance of the sferic signal through the ionosphere.

9. Wave-forms of atmospherics with or without whistlers

Evidently an attempt must be made to try to trace the characteristic variational quality factor in the lightning discharge which forms the prerequisite conditions for development of whistlers in a thunderstorm region. This problem will be treated by analysis of the oscillographic recordings of the atmospherics. During the 1958 observation period nearly 700 oscillograms of atmospherics have been recorded from whistler situations. Due to the large number of oscillograms at hand, it appeared especially suitable to divide up the plottable material by the use of the amplitude values of the field strength in conjunction with Figs. 8-9. In doing so three characteristic groups of amplitude variations of oscillograms from atmospherics were obtained:

(1) Oscillograms of atmospherics not producing whistlers.
(2) Oscillograms producing and not producing whistlers.
(3) Oscillograms of only atmospherics which produced whistlers.

As it is a question of comparison, the suitable group is the one which contains atmospherics both producing and not producing whistlers. According to Fig 9 there is such a group from a thunderstorm centre with bearing between 40° and 65° and a mean distance of 450-600 km.

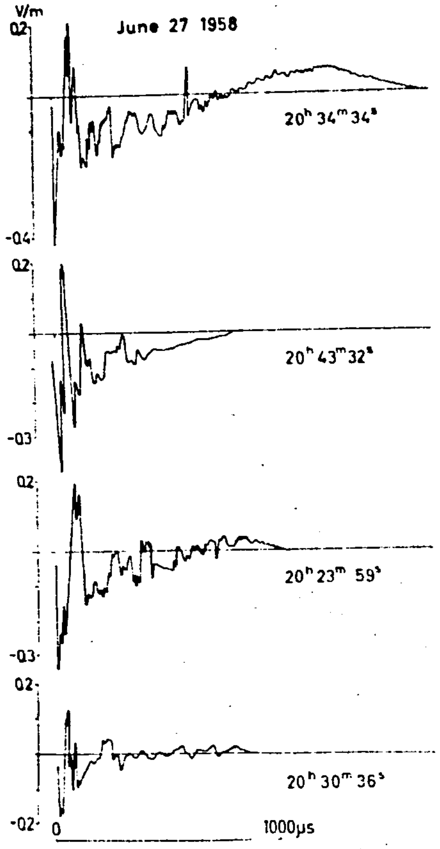

Fig. 10. Oscillograms of atmospherics not followed by whistlers.

Within this observation area a number of atmospherics not producing whistlers were received and are illustrated in Fig. 10. The oscillograms show typically irregular variational forms, where particularly regular frequencies are absent. Another very important feature is that the atmospherics have in common the fact that they have been generated by single lightning strokes, which means one must reckon with high resistance in the lightning path.

From our investigations in other connections it has been found by special oscillographic analysis (22) that lightning discharges without multiple channels, as compared with multiple ones, occur only in 10 to 15 % of all lightning discharges.

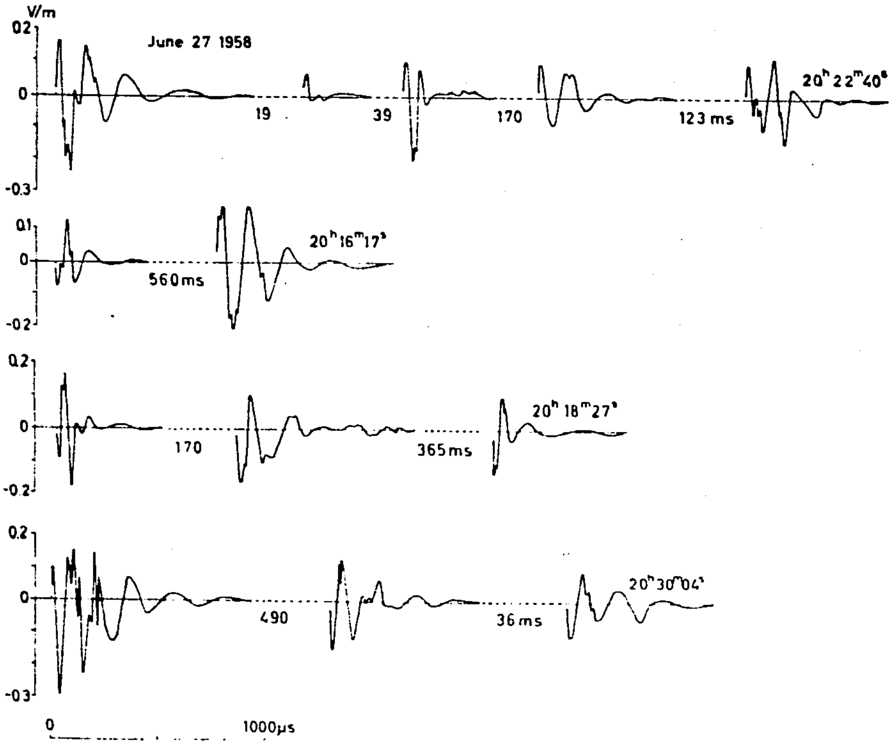

Fig. 11. Oscillograms of atmospherics followed by whistlers.

In Fig. 11 a number of whistler-producing atmospherics from the observation area are illustrated. Except in the initial stages these atmospherics are characterized by such very regular variational forms that they can, without further consideration, be designated as wave-forms, where the frequencies most nearly correspond to 5 kilocycles or to bands nearest this frequency.

The oscillograms reproduced in Fig. 11 are characterized by multiple discharges obtained by the method given in reference (11). The time intervals between the multiple discharges are given in milliseconds. In an oscillogram not reproduced in Fig. 11, only one single discharge was obtained with the same characteristic variational forms as given in that figure. Moreover, it is not out of the question that sometimes multiple strokes occur which do not appear in the recording because of their low amplitudes.

Multiple discharges which occur very often in the lightning path presuppose increased ionisation over that produced by single discharges both in the path and in the spaces within the thunderstorm atmosphere from which the large quantities of electric charges transformed into the the lightning discharges are fed. The consequence on the whole must be a smaller resistance in the lightning path than in the cases where the burst is characterized only by a single path.

This marked difference explains why only high-energy sferics appear capable of generating sferics, a fact thoroughly discussed by Hoffman (19).

10. Harmonic analysis of atmospherics with and without whistlers

In different connections, the necessary preponderance of frequencies around 5 kc has been mentioned as linked to the generation of whistlers. From this point of view it is obviously of special importance to compare the harmonic spectrum of lightning discharges followed by whistlers with that of discharges without whistlers. An indispensable condition for a comparison is that the lightning discharges occur during the same recording period and not very apart in time. This condition is very well fulfilled by an analysis of the oscillograms in Figs. 12-14.

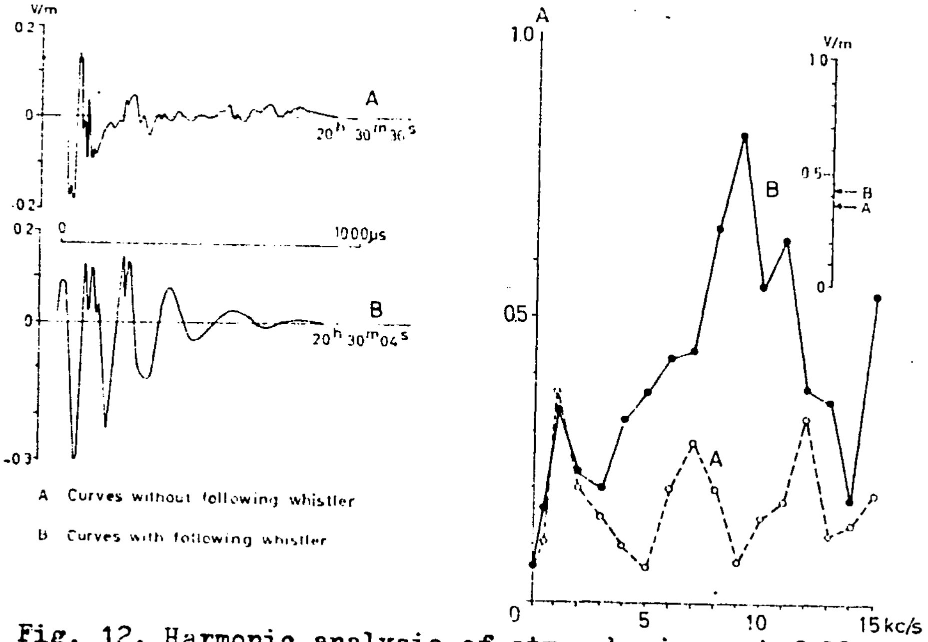

Fig. 12. Harmonic analysis of atmospherics not followed by whistlers, A, followed by whistlers, B.

Results of the harmonic analysis in these figures, where <u>A</u> represents oscillograms of atmospherics not followed by whistlers, and <u>B</u> oscillograms of atmospherics followed by whistlers. The harmonic analysis shows a striking predominance of frequencies in the region 5 to 8 kc for atmospherics followed by whistlers. Similar results have been obtained for other oscillograms in the same scale region of the field force. From the comparative analysis it follows that lightning discharges are followed by whistlers when the discharge contains a frequency distribution within the low frequency band as exemplified above. Evidently, a more exten-

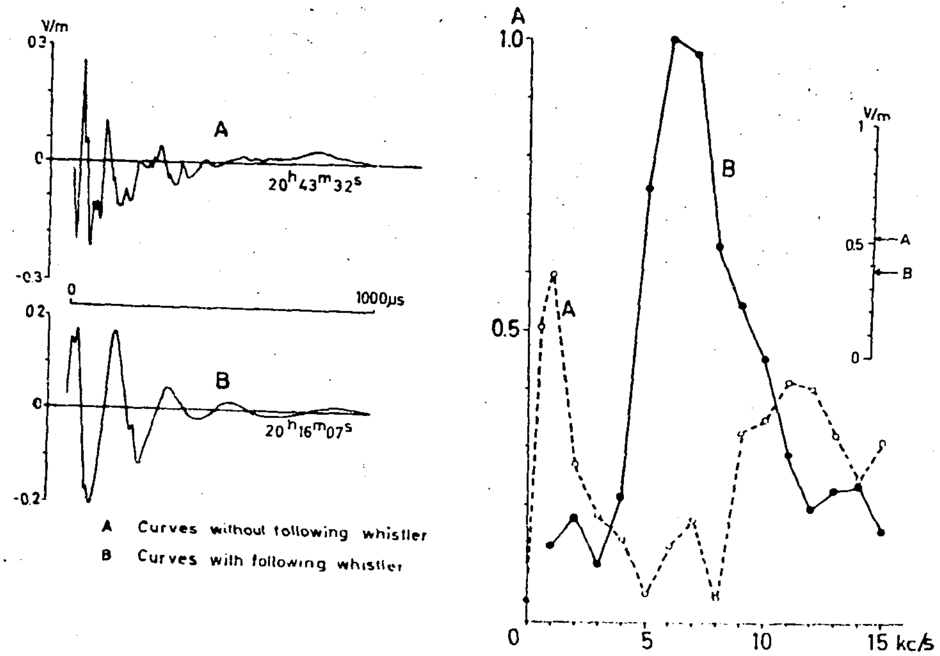

Fig. 13. Harmonic analysis of atmospherics not followed by whistlers, A, followed by whistlers, B.

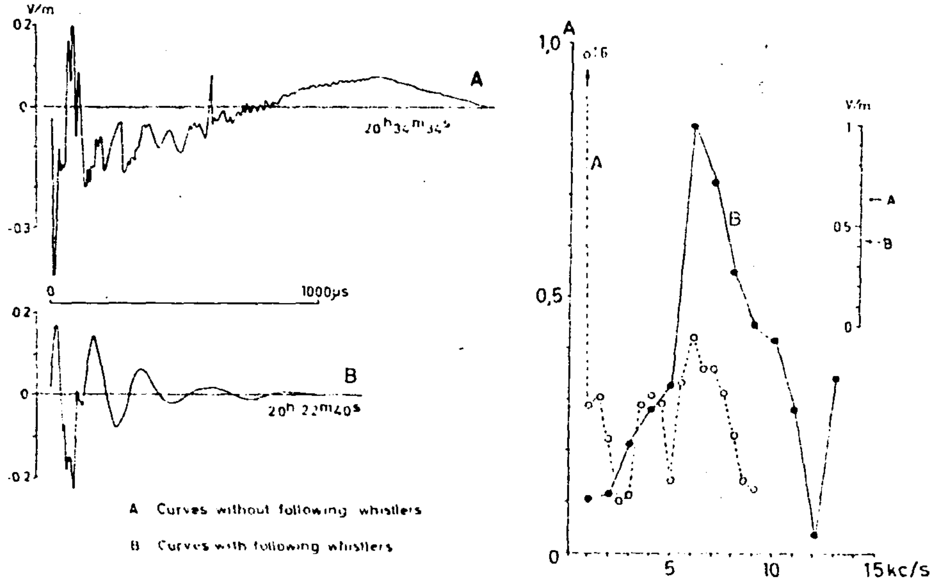

Fig. 14. Harmonic analysis of atmospherics not followed by whistlers, A, followed by whistlers, B.

sive comparative analysis is necessary, and such an analysis is already in preparation. A look at obtained frequency spectra of the extended comparison confirms agreement with what has already been shown in the above mentioned limited investigation.

11. Relations between multiple lightning discharges and multiple whistlers

In the previous discussion it was remarked that a lightning only followed by a single discharge does not in general produce whistlers. From our observations only about 10-15 % of all lightning strokes consist of a single discharge in the path. The reverse is very often true of multiple discharges in the path, and this difference is partially ascribed to the supposed higher ionisation in the paths of multiple discharges. Certainly it would be of special interest to examine more closely the occurrence of time differences of multiple whistlers passing in the same lightning channel. This is possible by frequency-time analysis using a suitable sound-spectrograph. For this purpose a Sonagraph of the Kay Electric Co design is especially well fitted. By the use of a narrow band filter and a heterodyne oscillator a record is obtained on a sensitized paper, a so-called sonagram. The frequency is given along the y-axis and the time along the x-axis. For multiple whistlers the time intervals are obtained on the sonagram. The only inconvenience is certain time uncertainties in the records of the sonagrams. This explains the time differences in intervals obtained by another more exact method.

An examination of the time intervals related to multiple whistlers can also in an exact way be obtained by simultaneous records on two cathode ray oscillographs (11, 22). The procedure allows a determination of the variational forms of successive discharges in the same channel here previously shown. It was also possible to obtain exactly, by cathode ray analysis, the time intervals between successive discharges in the channel. A comparative analysis of the time intervals of multiple whistlers is therefore possible.

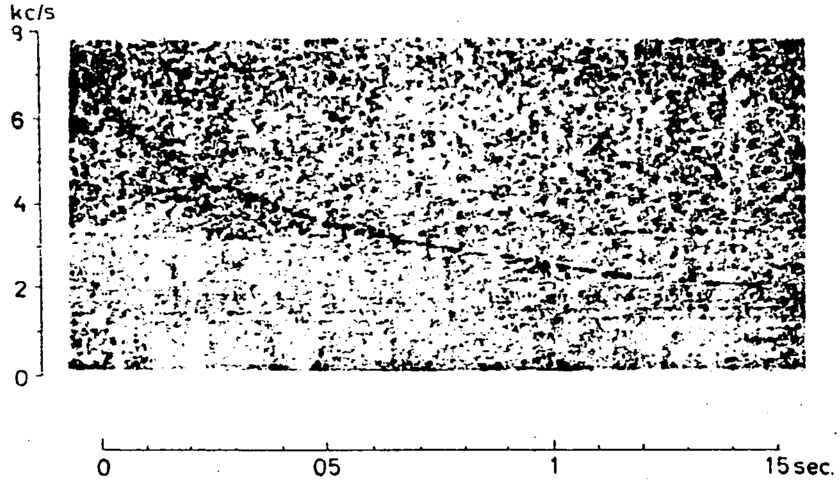

Fig. 15. Sonagram of a single whistler produced by a single lightning discharge in the channel.

In Fig. 15 is reproduced a typical sonagram of a whistler emitted from a lightning discharge which gives no indication by the oscillogram of more than one discharge having passed in the channel.

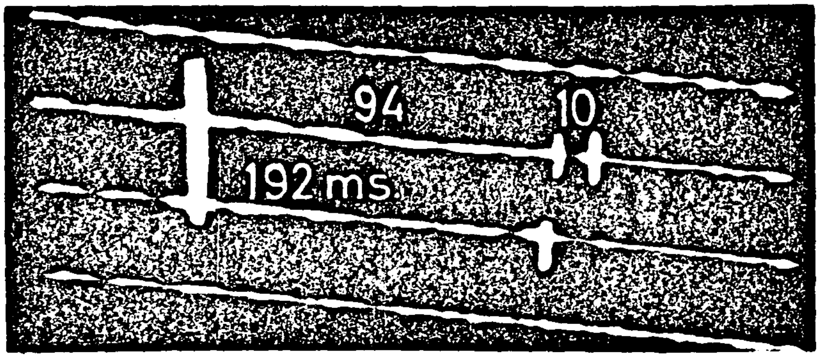

Fig. 16. Oscillogram of 3 multiple lightning discharges in the channel.

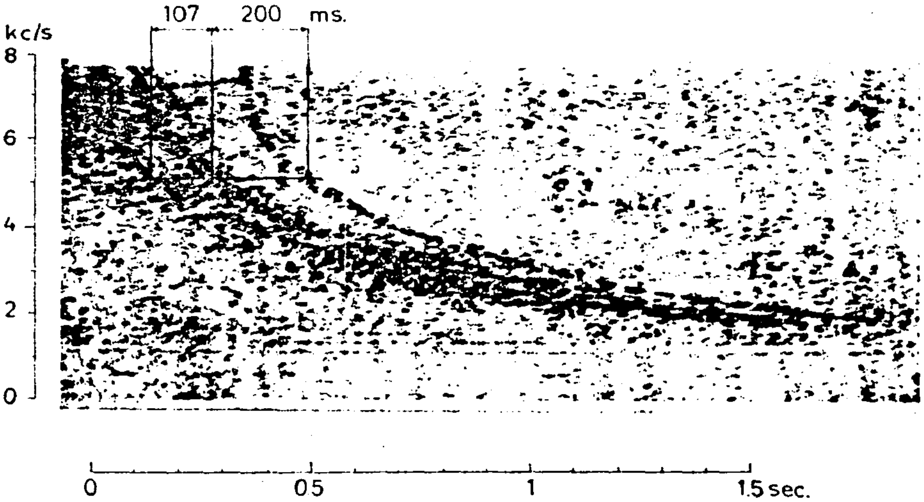

Fig. 17. Sonagram of 3 whistlers produced by multiple discharges in Fig. 16. Only 2 of the whistlers definitely visible.

An interesting case of a multiple-whistler situation is reproduced with oscillogram in Fig. 16 and with sonagram in Fig. 17. The differences in milliseconds between the oscillographed intervals of the discharges and the intervals in the sonagrams are ascribed to the mentioned uncertainty in time of the Sonagraph. Noteworthy is the long time intervals between the two discharges as compared with the third.

A contrary situation with more concentrated intervals are given in Figs. 18-19. The oscillogram shows 5 multiple discharges. Between two of them a very long time difference occurs as compared with the rest. A very dense accumulation of whistlers is shown in Fig. 20. This variation can be considered as a transition to the special variational type of condensed whistlers which is a typical transition to the form which has been

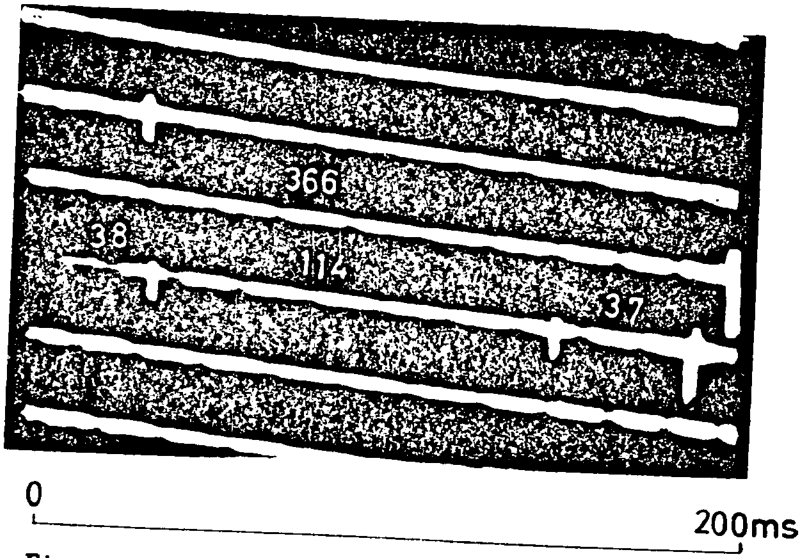

Fig. 18. Oscillogram of multiple lightning discharges with the first interval very long as compared with the following ones.

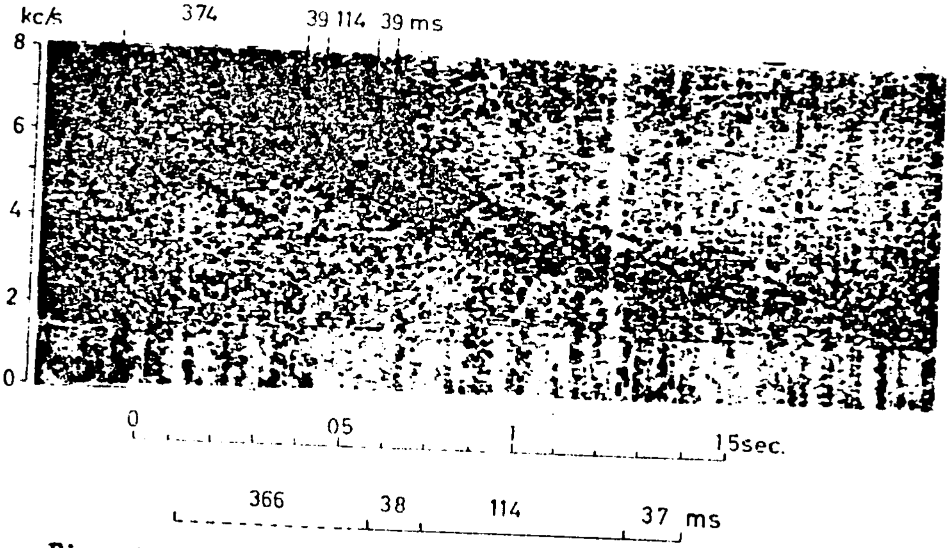

Fig. 19. Sonagram of 5 whistlers produced by the multiple discharges in Fig. 18.

called a swish shown in Fig. 21.

The haphazard occurrence of whistlers in local thunderstorms has up to now prevented the observance either vizually or by daylight photographs of lightning strokes followed by whistlers in separate channels. Nevertheless we have during two thunderstorm seasons (10, 23) samples of observations which in several cases show locally separated lightning strokes where the first has initiated the following ones. All strokes were bound together within time periods not exceeding 2 seconds. The occurrence of such locally separated lightning strokes can be accepted as indirect evidence that whistlers from adjacent separate lightning strokes will follow

separate propagation ducts. This opinion is supported by daylight photographs obtained in an earlier investigation (23).

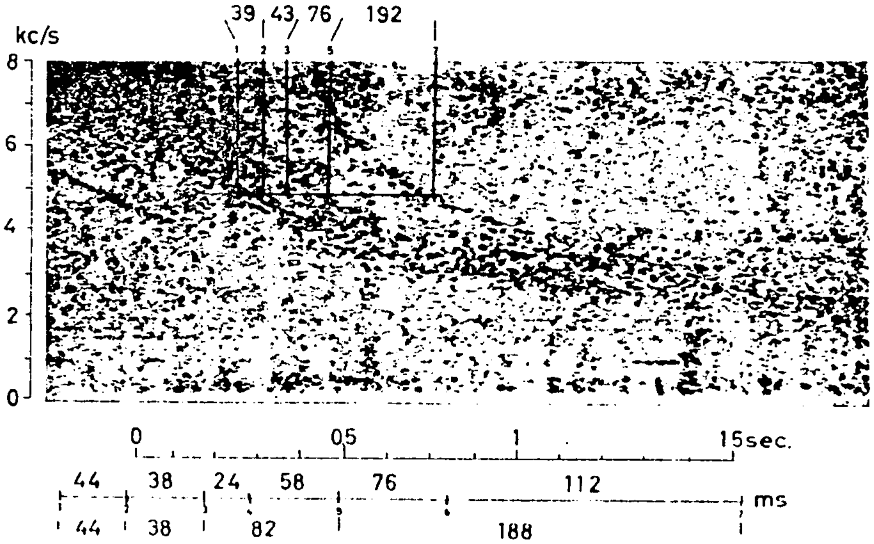

Fig. 20. Sonagram of 5 whistlers. Oscillogram shows 7 multiple discharges, 2 whistlers are missing.

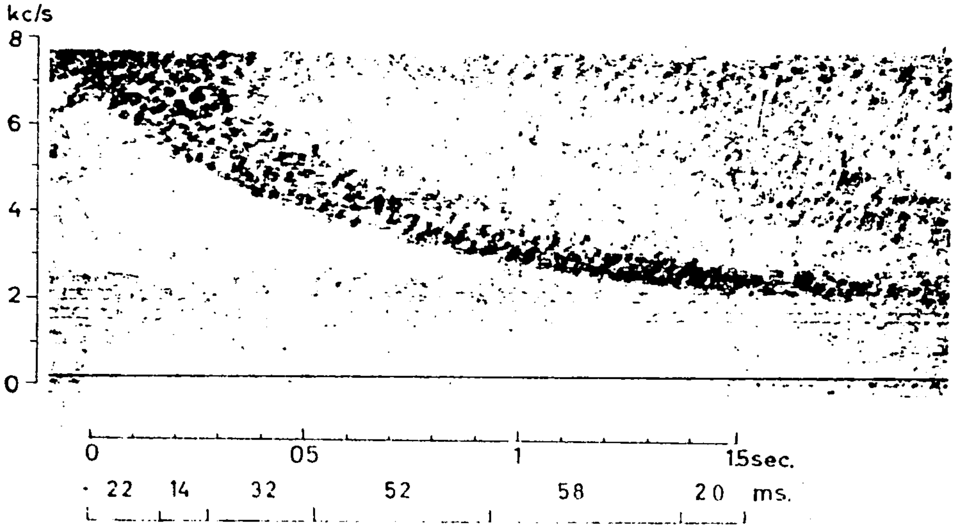

Fig. 21. Sonagram of a swish caused by 7 lightning discharges in the same channel.

12. Unusual musical atmospherics and their relations to lightning discharges

In the foregoing, musical atmospherics of the usual whistler type have been discussed. Different aural observations have shown that aside from usual whistlers other variational forms of musical atmospherics occur in great variety, a fact which becomes much more evident when whistler time-variations are resolved by a sound spectrograph. When in the following "variational type of whistlers" is used, it is meant the frequency-time variational type of musical whistlers obtained on sonagrams. Such unusual musical whistlers have received several suggestive names more or less well defined. Some of the most frequent are tweeks, single or multiple risers, hooks, constant frequency type, step type and combined types of some of the above mentioned.

As far as is known it has up to now only been possible to find a correlation between lightning discharges and usual whistlers and between lightning discharges and tweeks. It has been found to be of special interest to try to extend investigations of possible relations between lightning discharges and the quoted irregular variational types of unusual musical atmospherics.

In a publication (17) it was shown that several of the variational forms of musical atmospherics occur mainly in the day time. During the two thunderstorm seasons of 1958 and 1960 day-time observations of unusual musical atmospherics were carried out at the whistler station and about 700 individual observations that could be used as a basis for a special analysis (18) were obtained.

To this end during applied recording periods, continuous observations were carried out of the simultaneous occurrence of lightning discharges by means of the CRO direction finder and of musical atmospherics by the whistler-receiving set. Just as a whistler was taped, it was observed and noted if a correlation did or did not exist with a practically simultaneously recorded lightning discharge on the direction finder. A similar method applied in more southern latitudes with a comparatively high thunderstorm activity would no doubt lead to unreliable results. Because of the simultaneous occurrence of a considerable number of lightning discharges it would lead to some difficulties to correlate a musical atmospheric with an observed individual lightning discharge. Owing to the comparatively low thunderstorm activity on the latitude of the station it was easy to determine the correlation. Occasionally it happened that a limited thunderstorm area could be used for observation of the correlation for a period of up to 1-2 hours. During such a situation all musical atmospherics without exception were found with correlation. In another limited thunderstorm situation not one of the musical atmospherics was observed as correlated. To some extent this difference can be explained in such a way that only a limited part of the thunderstorm area had necessary conditions favourable for production of musical atmospherics.

The explanation for the occurrence of similar variational types of correlated musical atmospherics versus not correlated ones will be discussed later on. In the following examples of the variational types obtained by sonagrams have, with some exceptions, been reproduced types observed as correlated or not correlated with lightning discharges.

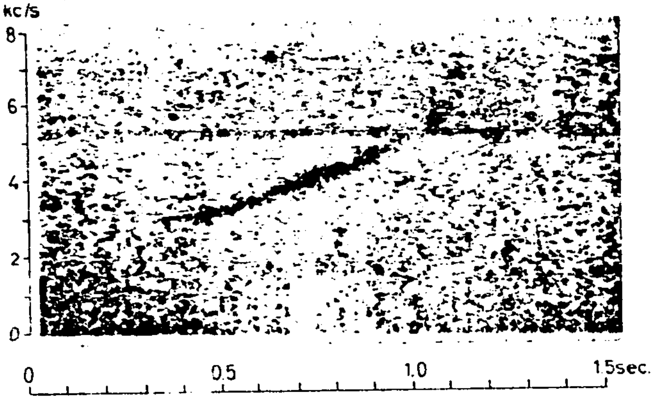

Fig. 22. Basic riser variational type, correlated.

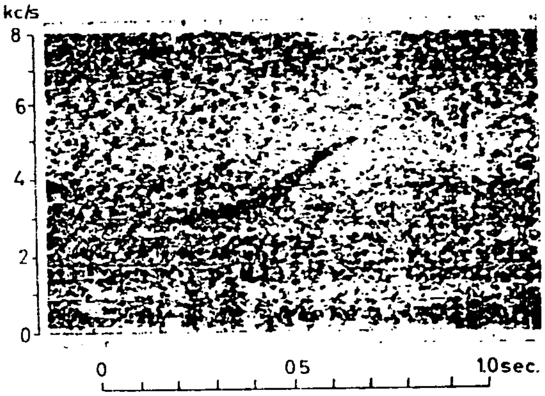

Fig. 23. Basic riser variational type, not correlated.

In Figs. 22-23 a type of single risers is reproduced with or without correlation, and the same is given for typical multiple risers in Figs. 24-25. A single hook with or without correlation is reproduced in Figs. 26-27, and in Fig. 28 there are exemplified multiple hooks with correlation.

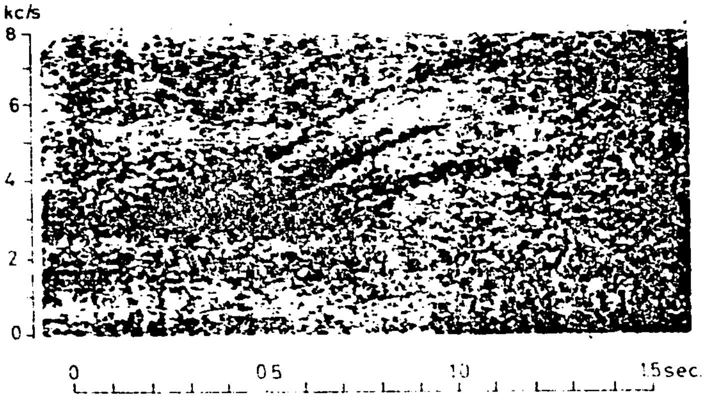

Fig. 24. Multiple risers of basic variational types, correlated.

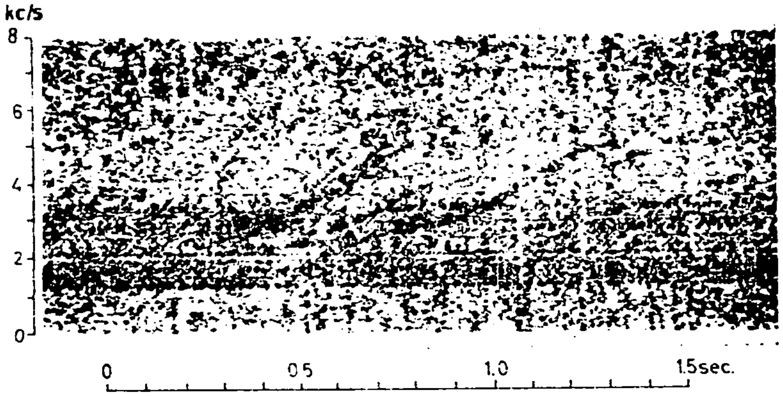

Fig. 25. Multiple risers of basic variational types, not correlated.

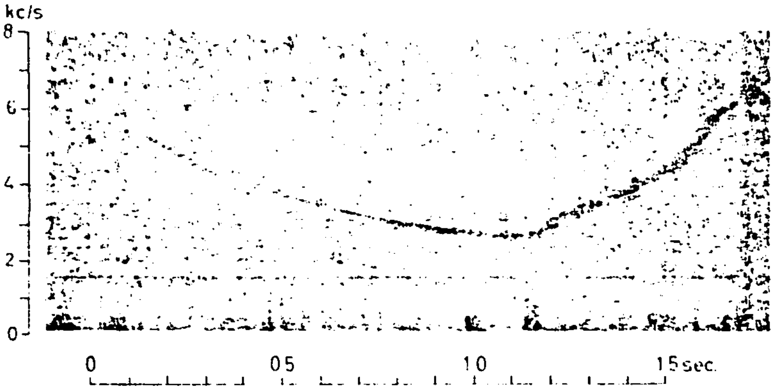

Fig. 26. Hook variational type, correlated.

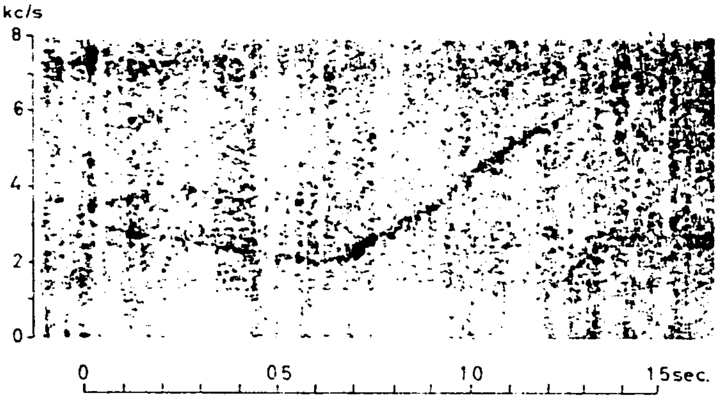

Fig. 27. Hook variational type, not correlated.

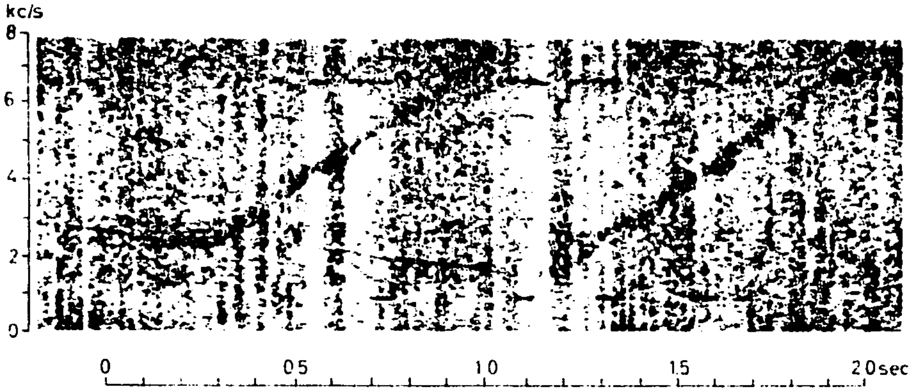

Fig. 28. Multiple hook variational types, correlated.

A nearly constant frequency variational type with or without correlation is reproduced in Figs. 29-30. A comparatively irregular variational type of frequency is reproduced in Figs. 31-32 with or without correlations. Multiple step variational types not correlated are given in Fig. 33, and in Figs. 34-35 single step variational types with or without correlation. Sometimes combinations of types were obtained, e.g. one or two risers preceding usual whistlers both correlated as exemplified in Figs. 36-37.

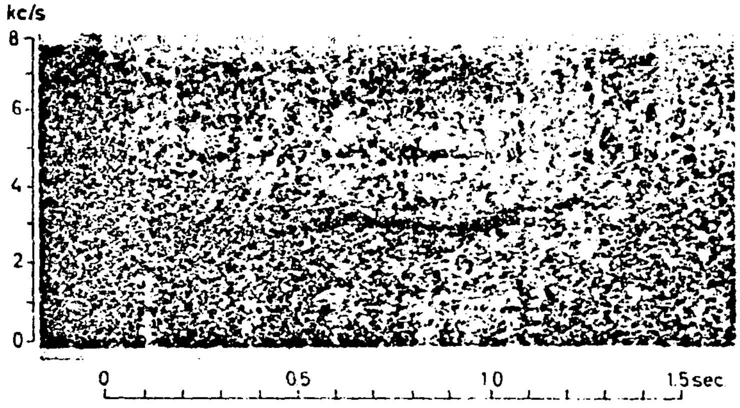

Fig. 29. Nearly constant frequency variational type, correlated.

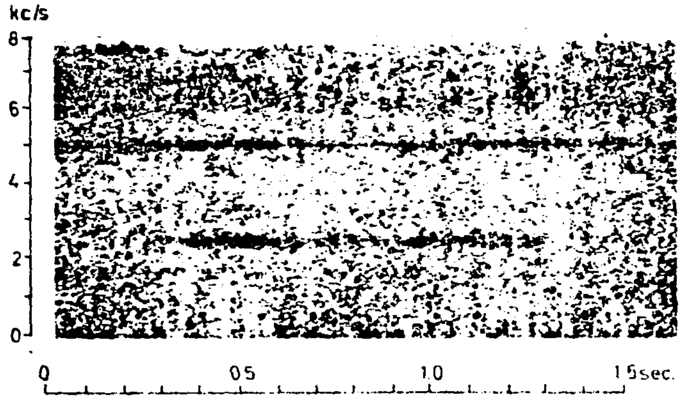

Fig. 30. Nearly constant frequency variational type, not correlated.

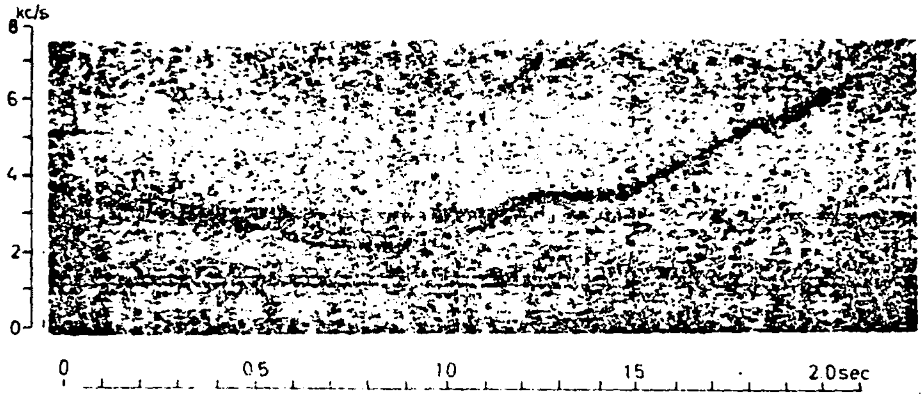

Fig. 31. Comparatively irregular variation of frequency, correlated.

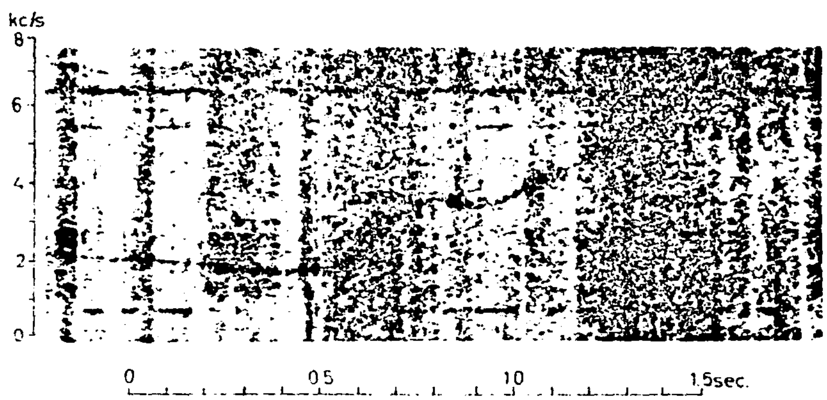

Fig. 32. Comparatively irregular variation of frequency, not correlated.

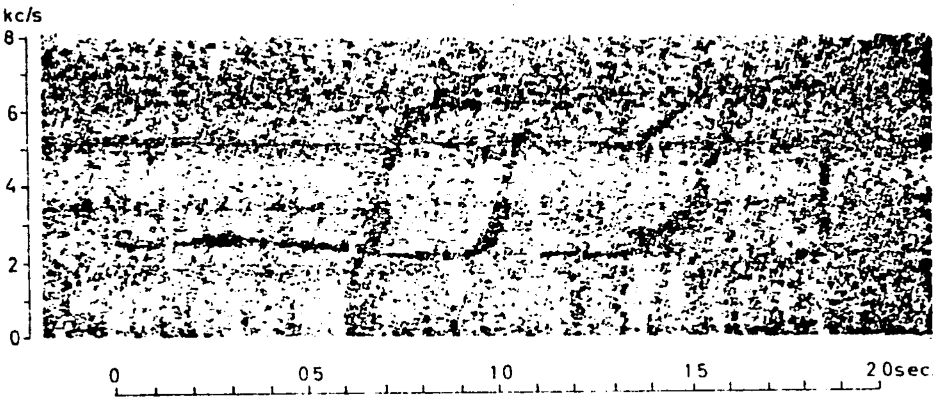

Fig. 33. Multiple step variational types, not correlated.

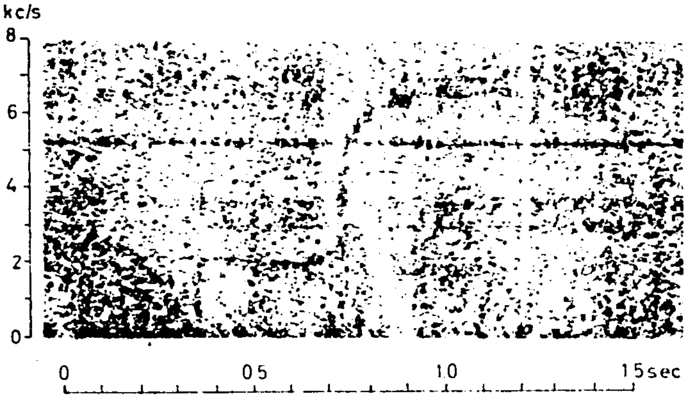

Fig. 34. Step variational type, correlated.

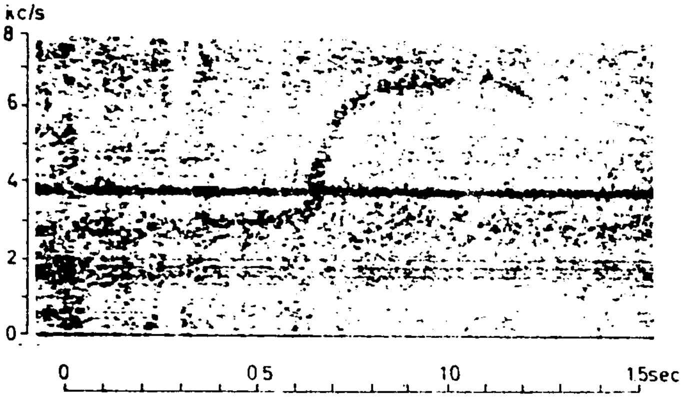

Fig. 35. Step variational type, not correlated.

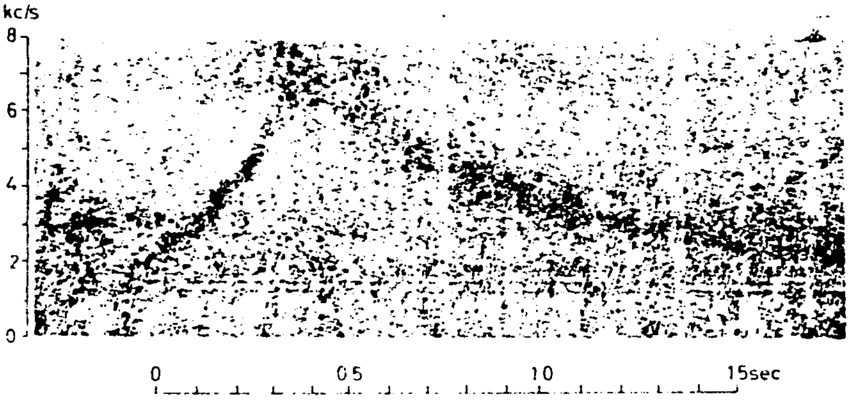

Fig. 36. Whistler of usual type preceded by one riser, correlated.

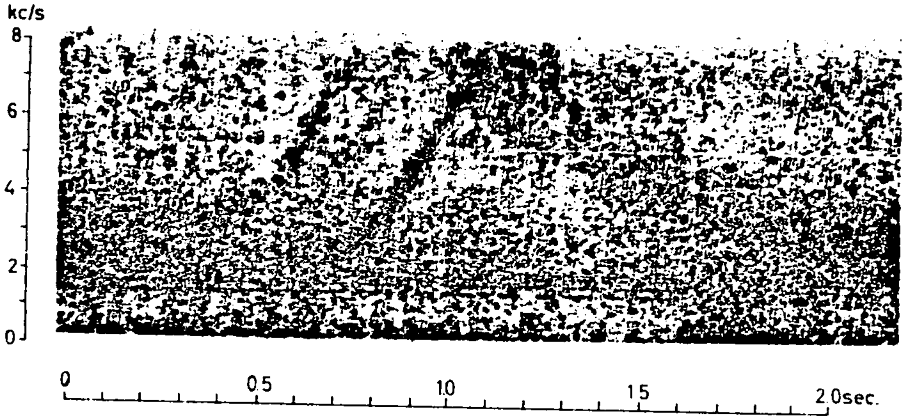

Fig. 37. Whistler of usual type preceded by two risers, correlated.

13. Special remarks of variational forms of unusual musical atmospherics.

The musical atmospherics of unusual types illustrated by Figs. 22-37 show plainly the most shifting variational aspects and forms. The conclusion must be that within the thunderstorm atmosphere there exist some very complicated, special modes of generation of unusual musical atmospherics. A theoretical explanation of the phenomena will for this reason require a more extended experimental analysis than has been obtained by the results presented here. It can only be confirmed that a theoretical treatment of the phenomena will be considerably more intricate compared with what was valid for musical atmospherics of the usual type.

It is especially striking that the analysed unusual musical atmospherics with or without correlation result in a conspicuous conformity in their characteristic variational forms. This shows that the unusual musical atmospherics originate from the same type of sources within the thunderstorm atmosphere. The conclusion is near at hand that the non-correlated musical atmospherics are also caused by lightning discharges.

The problem that non-correlated musical atmospherics have also been caused by lightning discharges without having been recorded as correlated has its explanation in the limitations of the equipment used with regard to distance sensitivity. For determination and recording of wave-forms have been used CRO recorders and for the determination of the distances CRO direction finders. The acceptable distances for an accurate determination were estimated to be 2000 km at best. It seems quite acceptable that musical atmospherics beyond that distance have sufficient propagation to reach the observation station and to be observed and recorded there as not correlated.

Another explanation of the existence of non-correlated musical atmospherics within the sensitivity limit of the station is possible. In a thunderstorm region lightning discharges might occur producing musical atmospherics characterized by effective propagation qualities. On the other hand, in spite of their location within the sensitivity limit of the station, lightning discharges have sometimes insufficient propagation effectivity to reach the station. This can very well explain why in special situations musical atmospherics have not been correlated.

Summary

A station for analysis of relations between lightning discharges and musical atmospherics of usual (whistler) and unusual variational forms has been operated for some years near Uppsala.

Recording cathode-ray oscillographs were used for the analysis of the lightning discharges whose relations to musical atmospherics were investigated. Cathode-ray oscillographic direction finders placed at two stations with suitable distances between them made it possible to determine the sources of the lightning discharges investigated.

Through comparative harmonic analyses it was shown that lightning discharges producing musical atmospherics of the usual type - whistlers - were characterized by a preponderance of frequencies around 5-8 kc. Multiple lightning discharges were found to be followed by multiple whistlers.

The recording method of the station allowed also of an investigation of correlations between lightning discharges and musical atmospherics of unusual and irregular variational forms. It was found that out of 700 unusual musical atmospherics about 70 % were correlated to lightning discharges and about 30 % were not. The striking variational resemblance between correlated and non-correlated short-time variational types of unusual musical atmospherics indicated that the non-correlated variational types must also emanate from lightning discharges.

Acknowledgements

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SESSION 2.1

Problems of Fair Weather Electricity; Introducing Remarks.

by H. Israël, Aachen

1. Introduction

It is a task of our conference to review our knowledge and to recommend further investigations on the different branches of atmospheric electricity.

When I try to do this for the field of the "Fair Weather Electricity" ("FWE") I have the feeling that some of you may think:

> Why still FWE? This is overdone! Moreover the results in this field are so complex and so contradictory that it seems senseless to continue!

But as scientists, I believe we should hesitate to use such an argument or to resign in view of difficulties. Besides there are quite different opinions concerning this question. Therefore let us examine critically the today's situation of the FWE.

The conception of "FWE" was the result of the old custom to consider only the fair weather values. These data seemed to be easier to explain than phenomena connected with disturbed weather. Today rather the opposite is true as we may see, e.g., when we look on the program of the present conference.

The division of the atmospheric electricity in the two parts; namely, the FWE and the "Disturbed-Weather Electricity," was justified afterwards by the dynamic conception of the atmospheric electricity: We have to distinguish generation - that is the disturbed weather electricity, or more precisely, the thunderstorm electricity, where the charges are separated - and consumption - even the FWE, where the separated charges will be neutralized. So the two parts are connected together very closely, having the same importance in the explanation of the whole picture.

If we look now on the fair weather electricity we first remember the fundamental discoveries of the last thirty years: We understand why we find everywhere and always an electrical field in the atmosphere characterized by typical periodical and nonperiodical variations. But these results emerge only if they are based on a large quantity of data, while for shorter series of observations the average picture is disturbed more and more by local conditions and meteorological influences. In other words: we got a climatological picture only, based on statistical evaluation.

However, this method is quite insufficient to relate, for instance, the atmospheric electric with the meteorological phenomena. Thus, in my opinion investigation in this branch is rather underdone than overdone.

II. Modern Problems in FWE

A. The Stratosphere

Let us look now on the modern problems in FWE. As you know, it is one of the most difficult problems in this branch that frequently the results are ambiguous because, in general, there are worldwide influences superimposed on local effects - especially if we evaluate measurements near the ground. Therefore, we have to look first for suitable methods to separate the two districts of influences.

This may be achieved when we try to separate the researches with respect to space: We have to distinguish at least two spheres of a quite different behavior, the troposphere and the stratosphere/mesosphere. Furthermore, we usually divide the troposphere in two regions, a lower one which is characterized by the vertical turbulent connection, and an upper one which is governed generally by a horizontal movement of the air.

It is evident that the processes and the problems we have to clear up are quite different in these three regions, from the meteorological point of view as well as from the electrical one:

The elctric behavior of the stratosphere/mesosphere is governed essentially by worldwide steering effects of the main generator and by variations of the ionization according to the latitude effect of the cosmic radiation only. On the other hand, tropospheric variations of the atmospheric electrical behavior are controlled by the influence of the "austausch" on the aerosol conditions.

Thus, I believe we can separate the "targets" of further researches in FWE in the two general groups of

(1) stratospheric researches of the electric field and the conductivity and of

(2) tropospheric results of the aerosol conditions.

Let me give some examples:

If we look on the first group, i.e. the stratospheric problems, we need first systematic measurements of the total potential difference V between the surface of the earth and the ionosphere and of their variations in time. Results of this kind can be obtained only by measurements in higher altitudes and at places not or less effected by the "austausch"! So we have there a special task for the aerological method of measurement as developed in the last time.

Two ways seem to be successful:

(a) Integration of field measurements by airplanes or radiosondes (O.H. Gish, 1944; J.F. Clark, 1956; J.H. Kraakevik, 1958; H.J. Fischer, 1962 et al.)

(b) Direct measurements of V and dV/dt in about 11 km altitude - by airplanes or constant level balloons with radiosondes -

as proposed by H.W. Kasemir, 1950.

Measurements of this kind promise a better insight into the mechanism of the worldwide atmospheric electrical circuit. I think there is no doubt that our basic hypothesis is correct, but up to now it is based only on mean results of a few polar expeditions and on those of the cruises of the Carnegie Institution. We are not able to control this in detail, e.g. to find out changes of the thunderstorm activity in different parts of the world - a target of special interest for the meteorology as well as for aviation. There are only first hints in this direction (H. Israël and E. Theunissen, 1957; H. Israël, 1957).

The aerological researches may be aided by continuous records of the atmospheric elements over the free oceans and at mountain tops. The first one could be done on the "weather ships" fixed now at different places of the oceans. Furthermore, I believe we should ask the permanent stations in the arctic and antarctic regions for atmospheric electrical records.

Another urgent question concerns the conductivity in the stratosphere/mesosphere. Here we have only scarce results up to now. The conductivity was measured directly, e.g. by radiosondes, up to about 30 km (C.G. Stergis, S.C. Coroniti, A. Nazarek, D.E. Kotas, D.W. Seymour, and J.V. Werme, 1955; R.H. Woessner, W.E. Cobb and R. Gunn, 1958). Furthermore the behavior of electro-magnetic waves in the higher atmosphere allows to measure the density of electrons or the conductivity respectively in the ionosphere, i.e. for altitudes above 80 km. In the interval between 30 and 80 km the conductivity values were computed (H. Israël and H.W. Kasemir, 1949; R.E. Bourdeau, E.C. Whipple, Jr. and J.F. Clark, 1959) and measured directly only once by a rocket sonde (R.E. Bourdeau et al., 1959).

This first experiment shows already a considerable discrepancy in both the computation and the measurement, especially for the region above 50 km of height. Therefore measurements of this kind should be continued.

Let us look into some of the most important problems in this field:

(a) In the region of 30 km to 70 km the electron concentration is influenced by the intensity of ionizing radiation, by the recombination processes, and by electron detachment and attachment rates. To understand which of these quantities prevail in physical processes throughout this region, it is necessary to determine the chemical, molecular, and atomic components and their density, including their change with altitude.

(b) In lower altitudes the conductivity of the atmospheres is determined by the density of the small ions, while in the ionosphere the conductivity is caused practically by free electrons. The transition is to be expected in the region between 30 and 80 km of height.

(c) More knowledge of this kind will give a better understanding of the lower boundary of the ionosphere.

(d) It also will yield more information on the global current circuit of atmospheric electricity, concerning questions such as the height distribution of the equalizing current, latitude effects, field gradients in horizontal directions, perhaps daily variations, etc.

(e) Finally we may find in this region connections to geomagnetic events, solar influences, aurora and similar phenomena.

It is true, measurements of this kind may be much more difficult to carry out than the usual atmospheric electrical measurements; however, I believe the adaptation of measuring equipment to rockets and satellites is a technical and not a principal problem.

B. The Troposphere

A quite different picture of the electrical behavior we meet in the troposphere; we find a group of problems of another kind.

To characterize the situation we may remember the opinion of Lord Kelvin 100 years ago - that in the future the forecast of the weather would be done with the electrometer. This prediction, of course, was a too optimistical one; however, the essential point which provoked that statement is the same up to the time being: All meteorological events are accompanied by characteristical changes of the electric parameters.

What we have to do is to explain these connections and to classify the electric variations. Maybe this is easier to say than to do because at the first sight the results up to now seem to give a chaotic picture. We remember, e.g., wide ranges of variation spectra of the different elements including fluctuations from the annual variations down to the so-called "noise," the different combinations of the "electrode effect" with the aerosol conditions, the radioactive influences, the movements of air masses, etc. Although we know many details in this field, it is hard to find an integral view up to now.

This, I believe, is the reason why some people voiced the opinion it would be senseless to continue researches of this kind. But in my opinion we have here no more difficulties than in the field of meteorology in general. Therefore, rather we should examine our measuring methods if they are adequate for the problems arising here.

As mentioned above in the troposphere we have to distinguish two regions of a quite different behavior, i.e. the "Exchange Layer" and the upper troposphere. In addition to this we have to separate a third region near the surface of the earth which is governed by the so-called "electrode effect."

The boundaries between these spheres are fluctuating according to the specific weather conditions, to the time of day, and to that of the season.

1. The Electrode Effect

The electrode effect is caused by the electric field in ionized air near the electrodes, i.e. here near the surface of the ground. Considering the atmospheric condtions one can compute that this effect will be essential up to an altitude of one or at most a few meters. This altitude is smaller if the content of condensation nuclei in the air is greater (J. Scholz, 1931), and the effect is depending on the ionization conditions near the ground. They may limit it sometimes to the first decimeters above the ground (A.R. Hogg, 1935; J.A. Chalmers, 1946 et al.)

Summarizing the results we find only a rough conception of this effect. Especially we miss researches of the meteorological influences. Therefore, I believe we have to see here a first important problem for our future researches.

> How will the electrode effect be influenced by the meteorological conditions, the radioactive conditions in the ground and in the air near the ground, the aerosol conditions etc?

Moreover the region of the electrode effect is accessible easily for all measurements and recordings we need. This enables us to examine the meteorologic-electrical connections in a small range, so to speak.

Of course, the usual measuring methods will be insufficient for researches of this kind. We have to measure at least the electrical field strength and the conductivity in small regions. Therefore, all kinds of disturbances should be avoided as much as possible as they occur due to the orographic situation, the installation or the working method, the equipment, etc. It is true, this will raise the claims for our measurements. However, I believe the problems we have to investigate in the region of the troposphere require urgently a new effort in our work.

2. The Exchange Layer

In this region of the troposphere we meet in general quite similar problems as mentioned before. However, the researches are more difficult because this sphere is much more extended in both the horizontal and the vertical direction. Therefore, we have to combine measurements both near the ground and in the free atmosphere.

Looking into these problems we have to find out above all the numerous influences of the "austausch" on the aerosol conditions. They will give us the key to understand most of the meteorological electrical relations.

The next step will be a systematical examination of the effect of air mass movements, considering their aerosol conditions, their content or radon, thoron, and decay products, maybe the content of fission products, etc.

Although the measuring methods are insufficient here, too, a lot of results came out already. I recall your attention, e.g., (1) to the explanation of the different types of diurnal variations of the electrical elements (J.G. Brown, 1930, 1935; H. Israël, 1948, 1950, 1952); (2) to the explanation of the so-called "sunrise effect" (H.W. Kasemir, 1956); (3) to the researches of the so-called "brightness effect" (G. Fries and H. Dolezalek, 1956); (4) to the "noise" of atmospheric electrical elements (H. Israël, 1958, 1959); (5) to the steplike variations of the atmospheric electrical elements at the upper boundary of the exchange layer (F. Rossmann, 1950; Callahan, Coroniti, et al., 1951) and to other ones.

However, these results yield with few exceptions, average values, describing the climatological behavior. This may be the reason why we miss a systematic picture of the connections between the weather and the atmospheric electricity up to now. Therefore, we have to look for a suitable extension of investigation. We shall see that here, too, the usual measuring customs must be changed.

"Off-hand-solutions" and "ad-hoc-theories," as they are tried sometimes, do not help us. They fail today as they failed in the days of F. Exner*.

3. The Upper Troposphere

The problems arising here may represent the last step in the new program for atmospheric electrical researches.

Since the aerosol content in the air above the exchange layer in general is unimportant, (see, e.g. R.C. Sagalyn and G.A. Faucher, 1954, 1955) we can expect to be confronted in this region, first of all, with the influences of air masses and their movements, with effects of variations of radioactivity, and with stratospheric influences.

Researches in this region will be done with airplanes, gliders, radiosondes, and constant level balloons. Furthermore, it will be very helpful to record the atmospheric electric parameters at mountain tops of sufficient altitude.

First, results and important hints for future researches will be found, e.g., in the papers of F. Rossmann (1950); R.C. Callahan et al, (1951); R.C. Sagalyn et al, (1954, 1955); C.G. Stergis et al. (1955); L. Koenigsfeld (1955, 1957, 1958); J.F. Clark (1956, 1958); J.H. Kraakevik (1958); K. Uchikawa

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*) so, e.g., the hypothesis of F.M. Exner (1886/1890) concerning a transport of charges by evaporation of water, which was refuted by H. Benndorf (**) and P. Lenard (1944); a revival of this hypothesis by R. Mühleisen (1958) was refuted by H. Israël and R. Knopp (1962; see also R. Knopp 1961).

**) H. Benndorf conducted in 1897/1898 field investigations in Siberia, which demonstrated that the mechanism as suggested by Exner is not verified.

(1961); G. Rönicke (1963); and other ones. For observations on mountain tops see, e.g., the researches of R. Holzer et al. (1955) in California and Hawaii and of H. Israël et al. (1957) in the alps.

III. The Measuring Methods

The researches proposed above require changes and improvements of the measuring methods.

First of all we have to look on the comparability of the results. For this the following demands must be fulfilled:

(1) It is known that the so-called "Reduction on the Free Plane" involves a considerable uncertainty, because it is impossible to include the influence of the space charges. Therefore the necessity to reduce the observed values must be avoided. In other words, all measurements near the ground - especially those of the electric field - should be done on an open plane of sufficient size. The rules of H. Benndorf (1900, 1906) may be used for the critical examination what means "sufficient." This should be applied also to measurements in mountain regions where we have to look for planes of sufficient size (plateaus, glaciers, etc.).

Of course by measurements with aircraft, radiosondes, etc., a computation factor concerning the geometrical forms is inevitable.

(2) Measuring techniques which disturb the natural conditions should be avoided as completely as possible. This concerns first of all the use of radioactive collectors for measurements near the ground. For airborne equipments the collector may be used provided that the aspiration is sufficient. When using radiosondes it is important to consider the researches of G. Rönicke (1962)

concerning the mutual influences of the two radioactive collectors.

(3) Different measuring equipments both for measurements near the ground and in the free atmosphere should be compared by simultaneous application at the same place and over a longer period of time.

(4) All researches should include simultaneous measurements of the three parameters of Ohm's law, i.e. the potential gradient (field strength), the conductivity (conductivities), and the air-earth current density.

(5) To avoid misunderstandings concerning the "sign," the remarks of H. Israël (1961, 1963) may be mentioned.

For synoptical researches as proposed by H. Israël (1954, 1955, 1961) and included in part II, B,2 of this paper the following difficulty should be considered.

(6) Synoptical researches near the ground will be disturbed by the electrode effect which may be different at different stations. In order to avoid this difficulty it was proposed by H. Israël (1962) to measure no more at the ground itself but in an altitude of at least two meters. If this proposition will be accepted the comparability may be improved. In this connection I like to refer to the researches of W.D. Crozier (1963). He tested a new method of field measurements which works with a minimum of disturbances.

IV. Some Indications for Practical Applications

Someone may ask for practical applications, if he thinks of the proposals given above for further investigation on Fair Weather Electricity, and the expense connected with it. It is true, scientific work will not be criticized from this point of view; but, I believe we can answer questions of this kind also. Let me give some examples.

(1) At first I like to mention here the method of M. Kawano (1958) to evaluate the "austausch" and its daily variation on the basis of atmospheric electrical measurements. Similar researches were done by W.B. Milin (1951, 1953, 1954). Researches of this kind will be very helpful for both climatological and meteorological purposes.

(2) Some results concerning the ionizing effect of artificial radioactivity in the air (see e.g., D.L. Harris, 1955; E.T. Pierce, 1959; G. Kondo, 1959; K.H. Stewart, 1960; A. Oster, 1963 et al.) suggest the application of atmospheric electrical observations for watching the fission product content in the air.

(3) Some years ago was discovered that the atmospheric electrical elements ondergo specific variations about 1 to 2 hours before the onset of fog and about 1/2 to 1-1/2 hours before the dissipation of fog (see e.g., H. Dolezalek, 1957; G.P. Serbu and E.M. Trent, 1958; L.H. Ruhnke, 1961 et al.) The application of this results to the forecast of fog and fog dissipation will be of special importance for the practical meteorological work (H. Dolezalek, 1962).

(4) Other possibilities for the application of atmospheric electrical results to practical problems came out from the researches of A. Gockel (1915) and others, concerning the prediction of thunderstorms; the results of J. Scholz (1935), concerning the prediction of blizzards; and the observations of G. Rott (1963)

concerning connections between the behavior of the electrode effect and the weather development during the day. - In all cases the prediction arised from observations during Fair Weather many hours before the event in question.

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Session 2.2

J. Bricard

Action of Radioactivity and of Pollution upon Parameters of Atmospheric Electricity

Table of Contents:

ACTION OF RADIOACTIVITY AND OF POLLUTION UPON PARAMETERS OF ATMOSPHERIC ELECTRICITY

by J. BRICARD

ABSTRACT

Placing ourselves at an altitude of several meters above the ground, in order to avoid the perturbations, we recall the characteristic elements of radioactivity and of atmospheric pollution. It is shown that their actions are in the first case the formation of small ions, in the second case their disappearance and the formation of large ions. From that we deduce the ionic density of the air under given meteorological conditions, studying separately the ions, corresponding to the recoil atoms, which come from radioactive disintegrations in the troposphere and in the lower stratosphere.

Finally we introduce the relations between the radioactivity and the other parameters of the atmospheric electricity, close to the ground and in the free atmosphere.

I. RADIOACTIVITY AND THE INTENSITY OF IONIZATION

1. Intensity of Ionization.

We call Intensity of Ionization (or q) the number of small ions of each sign (air molecules, having lost or attached an electron), created in one cubic centimeter of air per second. It is hence a fundamental parameter of the atmospheric electricity. Disregarding the action of cosmic rays, which produce continuously about two pairs of ions per cm^3 of air per second at the sea-level, we can practically say that at this altitude the natural radioactivity of the air is responsible for 80% of the intensity of ionization.

We call one Curie the quantity of a radio-element, producing 3.7 X 10^{10} of disintegrations per second. If we know the concentration of a given element in the air, expressed in Curies, for instance, it is easy to deduce from it the corresponding intensity of ionization in the case of a disintegration producing Alpha-Rays. The calculation is much more complicated and not always possible in the case of disintegration producing Beta- and Gamma-Rays (Section I3b). One Roentgen is the quantity of radiation, which per cm^3 of air at 0^o under the pressure of 1 atmosphere generates a quantity of electricity of each sign equal to 1 esu or 2.08 X 10^9 pairs of ions.

In spite of its importance it does not seem that the measuring of q by the method of ionization chambers were satisfactory as a whole. (Difficulties in measuring the ionization of particles α because of the recombination in columns and the absorption of radiations by the wall-effect. Necessity to introduce in the ionization chamber not only air, but also the aerosols it contains, responsible for one part of the radiaactivity α, and contributing by their charge to the saturation current. Absorption of β and γ on the walls of the chamber, etc.)

In spite of the improvements proposed (very thin walls of a known absorption [1] *, double-cage chambers [2]), we know but a few direct measurements of the intensity of total ionization. The instrument we applied for our calculations (double-cage) has not given so far sufficiently reliable results to allow us to use them at the present moment.

Thus, we are generally limited to indirect estimates of q, at least as far as α are concerned, made on the basis of the

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*) Numbers in brackets refer to the list of references.

content of radioactive products in the air and in the ground.

2. Intensity of Ionization Several Meters Above the Ground.

We shall suppose that the total intensity of ionization is on the order of 10 pairs of ions per cm^3 and second, 20% of which are of cosmic origin. It is then the production of 8 pairs of ions per cm^3 per second that we attribute to the radioactivity of the air and of the ground.

The radioactivity of the ground is about 3.5 pI/(cm^3sec); consequently the fraction of intensity of ionization, due to the radioactivity of the air, amounts to 4.6 pI/(cm^3sec). These values are divided in the following groups, according to their origin (Hess [3]:

Table I

-Radioactive substances of the air:

α	4.4	pI/(cm^3sec)	
β	0.03		
γ	0.15		
	4.58	pI/(cm^3sec)	(min 1.4 (max. 13.5

-Radioactive substances of the surface soil:

β	0.3		
γ	3.2		
	3.5	pI/(cm^3sec)	(min 2 (max. 6

We see that in the case of radioactive substances of the air the radiation α plays the biggest role, while γ is the most important in the case of radiation from the ground.

Above the oceans the total natural radioactivity is reduced to a few hundredths of its value above the ground.

3. Intensity of Ionization in the Altitude.

a. Radiation from the ground.

We see (table I) that the natural radioactive radiation of the surface soil, almost exclusively of γ origin, plays an important role in the lower layers. The following table (Israël) indicates its variation as a function of growing altitude.

Table II

Altitude above the ground	1m	10m	100m	500m	1,000m
% of radiation at the ground	97%	83%	33%	2%	0.1%

We may suppose an exponential law of absorption of this radiation in function of the thickness of the air-layer traversed. Let μ be the coefficient of absorption, supposed identical for all radiations. The intensity of ionization is proportional to the intensity of radiation in one given point. If we call q_{10}, its value in the immediate vicinity of the ground, we shall have in the altitude Z:

$$q_{1Z} = q_{10} \exp(-\mu z). \qquad (1)$$

The coefficient μ is in the order of $8 \times 10^{-3}\ m^{-1}$.

b. Derivates (Daughter-Products) of Radon and Thoron in suspension in the air.

In the case of natural radioactivity the distribution of concentration of Tn and Rn (we neglect the presence of Actinon), as well as that of their derivates, is connected with the state of turbulency of the air. Taking a soil with average internal characteristics and a coefficient of turbulent (eddy) diffusion K, independent of the altitude, of 8×10^4 cm^2 sec^{-1}, we find through calculations [4] for Rn and Tn ~~equal~~ concentrations at the ground level of 158×10^{-18} and 174×10^{-18} c/cm^3, respectively.

Difficulties arise, if we want to calculate the concentrations in various altitudes, due to the disintegration of the various daughter-products of Tn and Rn (it is necessary to know the state of equilibrium mother-daughter products), and due to the attachment of the daughter-products on the aerosols in the air, due to their coagulation and to their disappearance with time.

On the other hand we have to make a distinction between Rn and Tn. The first-one, whose half life-period is long (4 days), disintegrates slowly as it raises higher, while Tn (half life-period 10 sec.) and the ThA (period 0.2 Sec) disappear in the vicinity of the ground. Thus, in higher levels only ThB remains (half life-period 10 h). In the altitude Z above the ground the concentrations of Rn and ThB in the atmosphere are given respectively by the relations:

$$C = Co \exp(-Z \lambda^{\frac{1}{2}} K^{-\frac{1}{2}}) \qquad (2)$$

where Co represents the concentration of each on the ground level, K the coefficient of turbulent diffusion, and λ the radioactive decay constant, either of Radon or of ThB.

To simplify the reasoning, let us suppose that there exists a radioactive balance at any altitude between Radon on one hand and ThB on the other, and their daughter-products. This, of course, is very approximative, for if there actually exists a radioactive balance between Rn and RaA (3+ minutes period), it is not so for the other daughter-products, at least next to the ground. This is shown in the studies on the decrease in function of time of disintegration products of Radon, captured in the form of ions or aerosols. This is generally the case for ThB and ThC.- With the simplification we see that every disintegration α of Rn carries along simultaneously 2 α (RaA, RaC), and 2 β and 2 γ (RaB, RaC), and that every disintegration β and γ of ThB brings along simultaneously 1 β and 1 γ (ThC) and 1 α (ThC).

In order to obtain the corresponding value of intensity of ionization, it is necessary to know the number of pairs of ions, produced by each kind of disintegration, and to calculate the total at every altitude. This number is well-known for the α, which is monocinetic. It is poorly determined, however, for β and γ, whose spectra of distribution of energy we know little about at the present time. Table III represents the results, indicated by Israël, for a coefficient of turbulent diffusion $K = 8 \times 10^4 cm^2/sec$ and supposing a middle-value of 2×10^5 pairs of ions through disintegration α and 2×10^4 pairs of ions through disintegration β and γ. These values are supposed the same, independent of the source of radiation.

Table III

Altitude km	0	0.1	0.5	1	2	3	4	5	6	8	10
q from radio-activity	7.6	5.1	3.8	2.7	1.5	0.9	0.5	0.3	-	-	

It will be noticed that the values, indicated for the vicinity of the ground do not concord perfectly with those of Table I. This is explained by the very approximative mode of calculation used.

c. Lower Stratosphere

Fig. 1 represents variations of intensity of total ionization in function of the altitude. We see that it begins by decreasing, passes through a minimum at about 3 km, increases again, and above several kilometers the effect of the radioactivity becomes negligible as compared to that of cosmic rays. The effect of cosmic rays, very weak in the vicinity of the ground, increases progressively with increasing altitude up to about 12 kilometers, passes a maximum and decreases then for the higher altitudes.

In the lower stratosphere, between 10 and 20 km of altitude, we find RaD (period 22 years, source of β and γ) in very low quantities on the order of 10^{-19} c/cm^3. We find, in addition, radioactive elements originating in the action of cosmic rays upon the molecules of the air (principally Ar). Among them are Be_7 and P_{32}, which will be used later. The first one can also originate from atomic explosions. We find about 5×10^{-19} local c/cm^3 of Be_7, and 5×10^{-21} local c/cm^3 of P_{32}. As in the case of RaD, the resulting intensities of ionization are negligible as compared to the effects of cosmic rays.

4. Artificial Radioactivity.

With the exception of quite extraordinary conditions (vicinity of an nuclear station, or in the period after nuclear explosions [55]) the average content of artificial products in the air is now 2×10^{-18} c/cm^3 of sources exclusively of β and γ. This corresponds to intensities of ionization in the order of 3×10^{-3} pI/(cm^3 sec). In other words it is negligible as compared to natural radiation, except perhaps above the ocean, where the latter one is reduced to a few hundredths of its value above the ground. The situation is the same in the stratosphere layers, in spite of the accumulation of disintegration products manifesting itself there. At about 20 km of altitude we find maximum concentrations [5] of 10^{-17} and 10^{-18} c/cm^3, the average concentrations being 10^4 and 10^3 times weaker. Thus the effect is negligible as compared to that of the cosmic rays.

The situation is not the same, if there is an accumulation of these products on the surface of the ground after precipitations, sedimentation of dust etc. According to Israël [4], a rainfall of 10 mm containing 10^{-13} c/cm^3, if all the water remains on the ground-surface, would give in its vicinity an intensity of ionization on the order of 75 pI/(cm^3 sec). However, this is considerably minimized by the disappearance of water in the ground, and the effect is partially masked by the decrease of Radon exhalation during rainfall. Thus, it generally cannot be observed, yet it could become observable on a waterproof ground.

5. Qualities of Small Ions.

General Remarks. The small ions are generally present in the air in the order of a few hundreds per cm^3, the concentration (n') of the positive ions being by some 20% higher than that (n'') of the negative ions. Their difference (n' - n'') amounts to several elementary charges per cm^3. The concentration of the small ions, which is normally that of 300 to 500 per cm^3 next to ground, can be reduced to less than 10% of its value in highly polluted atmospheres and in the clouds. It increases with increasing altitude..

Physical characteristics of the small ions, whose dimension (some 10^{-8} cm) makes direct observation impossible, are the following:

Mobility. This is the speed the ion has in the atmosphere under given conditions of temperature and pressure, if it is exposed to an electric field of 1 V/cm. Under normal conditions the mobility of the positive ions is in the average in the order of $K' = 1.4$ cm^2/(V sec), that of the nagative ions a little higher, $K'' = 1.9$ cm^2/(V sec). (These are in fact the most probable values, the real values being dispersed around these average values). It varies with pressure and temperature according to the relation:

$$K(p,T) = k_0 \, (P_0 T_0) \, \frac{P_0}{P} \; \frac{T}{T_0} \qquad (2a)$$

Electric conductivity of the air, more easily accessible for direct measurement than the ionic concentration, is proportional to it and to the mobility of ions. It is given by the following relation, where e stands for the elementary charge:

$$\Lambda = (K'n' + K''n'') \, e \qquad (3)$$

On the ground level it is in the order of 0.5×10^{-16} to $2 \times 10^{-16} \, \Omega^{-1}$ cm^{-1}. It augments generally with increasing altitude under conditions depending essentially on meteorological circumstances. The figure 2, borrowed from Mühleisen, represent several examples of variation (Explorer II; Sagalyn and Faucher[7]). According to curve I we can consider Λ as notably constant between the ground and 2.500 m (strong turbulence under a marked inversion). This is not so in the other cases.

The density of the vertical conduction current is given by:

$$i = \Lambda E = EK'n'e + EK''n''e = i' + i'' \qquad (4)$$

where E is the electric field strength.

In good weather the vertical current is directed downwards, and we can suppose that its value is notably constant in the troposphere and in the lower stratosphere, whatever the spot the measuring has taken place may be. Its size is on the order of 2×10^{-16} A cm^{-2}. The constance of this current permits to bring into connection the electric field and the conductivity of the air, which are two quantities of different origin.

Diffusion Coefficient. Let there be $\frac{dn'}{dz}$ the gradient of concentration of the small ions, positive, for example, following a direction oz. The number of small ions traversing per sec. 1 cm^2 normal cross section at oz is equal to $D' \frac{dn'}{dz}$. D' stands for the coefficient of diffusion of the small positive ions. In principle, the same is valid for the negative ions. The coefficient of diffusion and the mobility are connected by the Einstein relation:

$$\frac{K}{D} = \frac{e}{kT} \qquad (5a)$$

k being the constant of Boltzman and T the absolute temperature.

On the average, D' and D'' are under normal conditions in the order of 3.7×10^{-2} cm sec^{-1} and 5.1×10^{-2} cm sec^{-1}, respectively [8].

Mean Free Path. In molecular dimensions, even if the charges are elementary, the electrical field produced by a small ion, animated by the Brownian movement, is sufficiently strong to polarize the neighboring molecules. Its trajectory, which is deviated by these charges between two successive collisions, is not straight, so that the results of the cinetic theory cannot be applied to it any more.

If we neglect this effect, we can calculate the mobility and the diffusion coefficient in function of the masses m of the ion and M of the gas molecules, from the average speed of thermic agitation of the ion and of the gas molecules and from a fictitious mean free path λ. Thus we obtain, for instance, the relation (1st formula of Langevin):

$$K = \frac{3}{8} e \, \lambda \sqrt{\pi} \left(\frac{m+M}{mM} \times \frac{1}{kT} \right)^{1/2} \qquad (5)$$

where k stands for the constant of Boltzmann.

If we take M = m and K = 1.5 $cm^2/(V\ sec)$ (normal conditions of temperature and pression), we find $\lambda = 1.3 \times 10^{-6}$ cm, a value notably different from the value, which corresponds to air molecules (6.4×10^{-6} cm), under the same conditions [9].

Recombination Coefficient. The small positive and negative ions recombine after their formation. A number of small ions of both signs disappear thus per sec. and per cm^3:

$$\frac{dn'}{dt} = \frac{dn''}{dt} = \alpha n' n''; \qquad (6)$$

α, standing for the coefficient of recombination, is given by the relation:

$$\alpha = \pi \vartheta \sqrt{2} \left(\frac{2}{3} \frac{e^2}{kT} \right) \varepsilon \qquad (7)$$

$$\varepsilon = \frac{\exp \frac{1}{4kT\ \delta / e^2}}{4 \left[1 - \frac{2}{9} \frac{\sqrt{2}}{\pi} \left(\frac{e^2}{3kT\lambda} \right) \left(1 - \exp \frac{3}{1 + 3kT\delta / e^2} \right) \right]} \qquad (8)$$

$$\delta = \frac{kT}{\lambda e^2} \left[\left(\frac{e^2}{6kT} + \lambda \right)^2 - \left(\left[\frac{e^2}{6kT} \right]^2 + \lambda^2 \right)^{3/2} \right] - \frac{e^2}{6kT} \qquad (9)$$

where k is the constant of Boltzmann and λ the mean free path, defined in (5), and ϑ is the average speed of thermic agitation. The expression (9), valid in a range of pressures between 10^2 and 10^5 mb is different from that of Thomson [8] and allows us to calculate the coefficient α under the various conditions of temperature and pressure. Under normal conditions we find [15] $\alpha = 1.6 \times 10^{-6}\ cm^3\ sec^{-1}$.

6. Small Radioactive Ions.

Every disintegration of Rn, of Tn, and of their daughter-products in the atmosphere is accompanied by the appearance of a recoil atom. Let C be the concentration of the element considered, expressed in Curies per cm^3. For Radon, for example, there will appear per cm^3 and per sec. next to the ground a number of RaA atoms in the order of:

$$q_{RaA} = C_{Rn} \times 3.7 \times 10^{-10} = 8 \times 10^{-6} \ \mathrm{pI}/(cm^3 \ sec); \qquad (10)$$

the same as for the other constituants. A certain number of these atoms is neutral (20% in the case of RaA), the others with a positive unitary charge, constitute the small radioactive ions.

Studying the decrease of these small radioactive ions, as a function of the time, properly sampled, we find that they consist almost exclusively of RaA, with a very weak fraction of RaB. A more profound study allows us to evaluate the life-span of these atoms in the atmosphere before they disappear in a process we shall deal with further on. This life-span is found to be on the order of 20 to 60 sec. [10] [11] [12].

It is easy to determine their concentration in the air by direct capturing, and by measuring the activity of the captured sample. We find in the vicinity of the ground that this concentration is on the average of 10^{-4} to 2×10^{-4} atoms of RaA per cm^3. Not having more precise results, so far(measurings are being carried out at the present time), we shall suppose that their mobility and their diffusion coefficient is the same as that of the ordinary small ions.

A study of the products of artificial disintegration, found in the lower stratosphere (accumulation zone) would lead us beyond the framework of this article. Without getting involved in the details, we can say that one part of the products of the explosions exists initially in the atomic form, neutral or electrically charged, as well as all the products of fissions of cosmic origin.

Let us take a simple example, that of Be_7 and P_{32}, generated by the fission of oxygen and nitrogen in the first case, of Argon in the second case. The period of the first (Be_7), which changes into Li_7 stable, is 53 days, that of P_{32}, which changes into S_{32} stable, is 14 days. All these are products, which are set free in the state of atoms, and they have probably an elementary positive charge.

Let us suppose at the altitude of 20 km [14] the concentration of 5×10^{-19} c/cm^3 of Be_7, and 5×10^{-21} c/cm^3 of P_{32}. They remain in the stratosphere for a sufficiently long time so that we can suppose that the radioactive equilibrium is reached. According to the relation (10), in one cm^3 of air and per sec. there will appear 2×10^{-8} atoms of Be_7 and as many of Li_7, as well as 2×10^{-10} atoms of P_{32}, with as many atoms of S_{32}. These atoms exist for a certain time in a free state in the atmosphere before they are attached to aerosols, present at this altitude (section II, 1), and it should be possible to detect them (section III 5 a).

II. AIR POLLUTION AND LARGE IONS

1. General Remarks

Natural aerosols, the aggregate of which constitutes the normal atmospheric pollution, are liquid or solid particles, likely soluble in water, neutral of electrified, whose constitution is, as yet, not well known and to which we will assign a spherical shape. Their dimensions are included between 7 X 10^{-7} and about 10^{-4}cm radius (see Table IV). They are also called condensation nuclei (see section II, 3).

Condensation nuclei, appearing at the ground, are carried upwards by turbulent (eddy) diffusion. They coagulate but slightly and fall back onto the ground by sedimentation, preferably at night, when turbulent conversion is less intensive, or they are collected during the fall of precipitations.

They may come from the ocean (sprays), or from human activities (combustions), and, owing to their slow falling speed with regard to air, they are apt to be carried far from their place of origin. Their chemical composition may vary greatly [16], [17] (chlorides, sulphates, nitrates, ammonium salts, sodium, magnesium). They are usually mixtures of various matters, since they coagulate, coming from simple nuclei initially formed.

Their concentration ranges about 10^3 to 10^5 per cm^3 at a few meters above the ground. It decreases with the increase of the altitude, said decrease being more or less steady (see Large ions, electric charge, section II, 4). Figure 3, borrowed from Israël [4], shows, according to Wigand, [18] the relative variations of atmospheric concentrations in aerosols as the altitude increases (measures made by a balloon). It may be seen that said distribution follows an experimental law, with a discontinuity corresponding to a temperature inversion. Towards 8,000 m it is reduced to $\frac{1}{10^4}$ of its value at the ground level, and it goes on decreasing as one goes up. According to Junge [19], there would be an increase of the concentrations, between 10 and 20 km; the concentration of particles averaging about 0.15 μ radius, going from 0.01 to 0.1 cm^{-3}, before decreasing again. But this concerns rather large particles and it does not seem that, at these altitudes, smaller particles have been numbered.

Let us finally mention the case of natural clouds, made up of droplets of water of some μ in diameter, a few hundreds of which may exists in a single cm^3. Some authors have mentioned, in addition to these droplets, the presence of particles inferior in size and much more numerous [20]. Above the altitude of 6,000 m, clouds are exclusively made of ice particles flat or elongated, over 0.5 mm in diameter. These crystals play an important part in charge generation in stormy clouds, but this will not be discussed here.

A direct observation of natural aerosols offers difficulties in particular with respect to their sampling. This is made either by collision (Konimeters), a method which does not seem to be applicable to small size particles under 10^{-5} cm or about; either by means of very fine threads (spider threads), which is possible only for liquid particles; either by electric precipitation of particles charged by corona effects, (particles with dimensions between approximately 0.2 μ and 0.8 μ escape more or less to that kind of precipitation); either by thermal precipitation (which is only good for solid particles); or by means of filters (one may moreover wonder how it comes that particles settle on the front surface of the filter and that, as a rule, only a few of them get inside the pores). On the other hand, particularly in the field of dimensions unattainable to an optical microscope, it will not be possible to use an electronic microscope for liquid particles, as long as there are no means available to realize supports liable to fix impressions of the droplets of these dimensions. In order to study condensation nuclei granulometry, we are compelled to use indirect methods based on their physical properties.

Their quantitative analysis in bulk in the air may be achieved directly by sampling on filters and by chemical analysis, or by radioactive computation. This prodeeding, justly crticized [43] on account of the inefficiency of filter sampling in some dimensional fields, particularly between 1.5 X 10^{-6} and 10^{-5} cm, seems now perfected. It has been controlled thanks to the use of extra-thin calibrated aerosols and of large natural ions, the size of which were known. Filters with an efficiency of more than 98% may thus be obtained, whatever may be the dimensional field of aerosols to be filtered.

2. Optical properties

Light is diffused by these particles and, at least in the case where their constitution is known, (index, reflection, and absorption factors), it is possible to compute a diffusion indicator for particles the dimensions of which are given. Reciprocally, the measurements of the flux diffused by a group of particles, allows to figure, at least approximately, the atmospheric concentration in aerosols; and the measure of the flux diffused by an isolated particle, correctly lighted, allows to know its dimensions without changing its constitution.

This method has been originally used for qualitative measures or for pollution detection, has been recently developed so as to become quantitative [20], [21]. It permits the access to dimensions bordering on the limit of the separative power of the optical microscope and we are now extending it to a field of lower dimensions.

3. Condensation

These particles, in a supersaturated atmosphere, act as condensation germs and give liquid droplets directly observable optically. The use of said property permits to determine their concentration in the air.

A droplet thus formed has a radius depending on its chemical nature, on the salt concentration or on the mixtures of salts of which it is formed and on atmospheric supersaturation. By measuring these droplets, under well defined conditions, it is possible to determine the primary dimensions of the corresponding germs in the air and to form an idea on the air pollution on the spot where they have been taken.

The following granulometric distribution may [22] be inferred from this:

$$\frac{dN}{d \log R} = \frac{C}{R^3} \qquad (11a)$$

in which dN represents the number of nuclei in a logarithmic scale of radius R, and C a constant. This expression seems valid for particles whose dimensions are at least equal to 10^{-5}cm (see section II, 6).

4. Electric Charges

These particles can carry charges usually very low, (ranging about one or several elementary charges), either by attachment of small ions, or by means of other chemical or thermal processes, in order to give large ions. The statistical study shows that, on an average, the atmospheric concentrations of large ions of both signs are very close, so that the average space charge corresponding to them must be low. However, in the course of the various operations resulting from human activity (combustion, condensation), very important differences between these concentrations, as well as a very pronounced space charge, either positive or negative according to circumstances, may appear.

Under undisturbed circumstances, the proportion $\frac{Z}{N' + N''}$ of the total number of nuclei, to that of charged nuclei, is very variable, depending on authors [23]. it is included between 1.61 and 5.4. It increases with the number of nuclei; the lowest value nearest to that stated by Mme. Thellier [24], seems to correspond to undisturbed average statistical conditions.

The large ions concentration, proportional to that of condensation nuclei, decreases also as the altitude increases, under conditions depending on the meteorological situation; and they disappear above 3000 or 4000 m. Fig. 4, borrowed from Sagalyn and Faucher [25], represents examples of their distribution in altitude.

5. Mobility and Diffusion Coefficient.

Due to their rather great dimensions, the above mentioned particles have mobilities and diffusion coefficients defined in the same manner as in the case of small ions, but much smaller. The maximum values, under normal conditions are, ranging in about 10^{-2} $cm^2/$ (V sec) and 3×10^{-4} cm^2/sec, respectively. These quantities, as in the case of small ions, are interrelated by relation (5a).

It is known that, in a viscous fluid, the strength needed to give a constant speed B to a particle with a radius smaller than 10^{-5} cm is expressed as follows (Stokes-Cunningham law):

$$F = \frac{6 \pi R \eta}{1 + b/pR} \qquad (12)$$

η is the air viscosity (at normal temperature and pressure η = 1.7×10^{-4} cgs), p is the atmospheric pressure expressed in cm of mercury, and b a constant, (b = 0.000617); R is the particle radius.

According to the mobility definition, we may write:

$$K = \frac{1}{6 \pi R \eta} \quad ne \left(1 + \frac{b}{pR} \right); \qquad (13)$$

e meaning the elementary charge and n the number of charges carried by the ion, said number being low and usually equal to the unit (see further down).

The following table IV gives an idea of the large ions mobilities and dimensions, derived from formula (8), a unit-charge carried by the ion being supposed.

Table IV

Small ions	$1,0 > k > 0,01\ cm^2\ V^{-1}\ sec^{-1}$	$6,6 < R < 78 \times 10^{-8}$ cm
Average large ions	$0,01 > k > 0,001$	$78 < R < 250 \times 10^{-8}$ cm
Langevin ions	$0,001 > k > 0,00025$	$250 < R < 570 \times 10^{-8}$ cm
Ultra large ions	$k < 0,00025$	$R > 5.7 \times 10^{-6}$ cm

The diffusion coefficient of large ions may be derived from relations (5a) and (13). We then find for $n = 1$:

$$D = \frac{kT}{6\pi R \eta} \left(1 + \frac{b}{pR} \right) \qquad (14)$$

k representing Boltzmann's constant:

For average large ions, for instance, D, under normal conditions, is included between 10^{-6} and 10^{-7} cm^2 sec^{-1}.

6. Coagulation

Suppose Z is the total number of nuclei, charged or neutral, per cm^3. It is proved that everything happens, with respect to coagulation, as if every nucleus was neutral [56]. Smolukowsky's [26] coagulation theory may be applied to them and we may write:

$$\frac{dz}{dt} = -\gamma z^2. \qquad (15)$$

With R the average radius,

$$\gamma = 8 \pi DR, \qquad (16)$$

D being given by (14).

For the large tropospherical atmospheric ions, we find [25] $\gamma = 1.6 \times 10^{-9}$ cm^3 sec^{-1}, which corresponds to an average radius of nuclei $R = 2.3 \times 10^{-6}$ cm.

The result is that the initial total volume of the nuclei, i.e. product ZR^3, keeps a constant value. In the field of small dimensions, under 10^{-5} cm (Holl [27] and Mühleisen [28]), we obtain:

$$\frac{dN}{dR} = \frac{C}{R^3}. \qquad (17)$$

Figure 5 represents, after Holl, the granulometry of natural aerosols, as a whole. The fixation of condensation nuclei by cloud droplets may be discussed as a coagulation process; it may yield an explanation for the smaller concentration of large ions inside the natural clouds than in the surrounding atmosphere.

7. Radioactive Condensation Nuclei.

These are particles identical to those which have been described above, but they differ on account of the fact that they attached not small ordinary ions, but small radioactive ions, studied in section I-6. Here we shall only study those originated from natural radioactivity decay (Ra and Th); especially the first one. On these we now have a few informations, taken in the vicinity of the ground.

We have seen that small radioactive ions are, as a rule, largely made of RaA atoms. Due to the long stay of the large ions near the ground (about 15 minutes according to Renoux' measurements [12]), those atoms, once attached to the large ions, decay, giving birth to daughter-products RaB and RaC. As this stay is not sufficient for the radioactive equilibrium to be attained (nearly three hours would, as a rule, be necessary), they are therefore constituted by accumulation products coming from the Radon, corresponding to 15 to 20 minutes [12].

Their destination by sampling and activity measurements is unreliable, since it involves information on the duration of that stay.

Let us suppose that the radioactive equilibrium is reached between the Radon and the RaA, (section I, 3,b), whatever its condition may be (free or attached to aerosols). We shall write:

$$\lambda \, n_{Rn} = \lambda_A \left(n_A + Z_A \right)$$

in which n_A and Z_A mean the atmospheric concentrations of small ions and nuclei having attached RaA. The concentrations of Radon being known (1 to 2 X 10^{-16} c/cm^3), we find that $n_A + Z_A$ averages 1 to 2 X 10^{-3} atoms of RaA/cm^3, wherefrom the Z_A value is deducted by difference, i.e., 8 X 10^{-4} to 1.8 X 10^{-3} particles per cm^3 under normal conditions [10] [11].

Their granulometric distribution is as follows:

__Table V__

(1)	(2)	(3)
$R > 1.7 \times 10^{-6}$ cm	$1.7 \times 10^{-6} < R < 10^{-5}$ cm	$R < 10^{-5}$ cm
55%	21%	24%

The 10^{-5} cm limit, actually under study, is not determined exactly. It seems well established that the greater part (60 to 70%) of the products responsible for natural radioactivity, is attached to the average large ions and on Langevin ions [11] [13] [39] [40].

Radioactive nuclei generated by the attachment of small RaA ions to neutral nuclei, carry a positive charge, but those generated by the attachment of RaA neutral atoms to neutral nuclei or of RaA positive atoms to negative nuclei are electrically neutral. Of the 55% of class (1) nuclei, 24% are charged, the remaining 31% are not [29]. These proportions are fairly the same as for neutral nuclei and for ordinary large ions.

Stratospherical particles (section II, 1) attach small radioactive ions (section I, 6) and it is due to them that the atmospheric radioactivity at high altitudes is determined. Furthermore, there are solid particles, entirely radioactive, generated directly by nuclear explosions.

8. Attachment of Small Ions to Charged and Neutral Nuclei.

Small ions, radioactive or not, sediment on condensation nuclei, charged and neutral, by diffusion and by electric action at the same time. Let us first suppose that nuclei are constituted by a monodispersed medium whose radius is equal to the average radius. The settling speed $\frac{dn'}{dt}$, $\frac{dn''}{dt}$ of the small positive and negative ions on the totality of nuclei, will be expressed as follows:

$$\frac{dn'}{dt} = -n'\left[\beta'_o N_o + \sum_{p=1}^{\infty} \left(\beta'_{1p} N'_p + \beta'_{2p} N''_p\right)\right] \qquad (18)$$

$$\frac{dn''}{dt} = -n''\left[\beta''_o N_o + \sum_{p=1}^{\infty} \left(\beta''_{p} N''_p + \beta''_{2p} N'_p\right)\right]$$

in which N_o, N'_p, and N''_p represent per cm^3 the number of neutral nuclei, large positive and negative ions, respectively, carrying p elementary charges. β'_{1p} is the attachment coefficient of small positive ions on nuclei having p positive charges, and β'_{2p} the corresponding coefficient between the same small ions and nuclei having p contrary sign charges, and the same goes for small negative ions.

The only experimental values available as far as for attachment coefficients, are those corresponding to neutral nuclei and to ions having a single charge (we shall see later how to calculate those corresponding to several charges). Let us mention the following scale of sizes:

Table VI

	$\beta'_{10} \times 10^{-6}$	$\beta''_{10} \times 10^{-6}$	$\beta'_{21} \times 10^{-6}$	$\beta''_{21} \times 10^{-6}$
Scrase [30]	0.58	1.07	2.35	2.96
Parkinson [31]	0.6	1.1	2.4	4.5
Mme Thellier [24]	2.6	3.2	5.8	7.2
Nolan and de Sachy [32]	6.8	7.6	8.7	9.7

A great dispersion is noted in the above results; in some cases it may be due to difficulties in measuring.

9. Attachment Coefficient Expression.

In order to simplify, let us first suppose that charges are symmetrical. We consider a condensation nucleus, having radius R, charged or not. Let us compute the positive ions flux for instance, entering a sphere having radius r, centered on it. It is supposed that the medium is sufficiently diluted, so that the presence of the other possibly charged nuclei has no effect on the value of n' and n", concentrations in small positive and negative ions, in the vicinity of the nucleus considered; and that the nuclei, due to their mass, are motionless. The number of small ions, positive for instance, crossing, by diffusion and by unit of time, the surface unit of the sphere and proceding towards the nucleus, will be $D \frac{dn'}{dr}$, D being the diffusion coefficient of the small ions.

The number of small ions of the same sign, crossing the same surface, under the same conditons, on account of the electric field, will be $Kn' \times \frac{dU}{dr}$, U representing the electric potential at the distance r from the nucleus center and K the mobility of the small ions; (it is supposed that the diffusion coefficient and the small ions mobility of both signs, have the same common value K and D). Under permanent normal conditions, there is no accumulation of ions and the ion flow ϕ crossing the sphere is constant and equal to the flow settling on the nucleus. Therefore we shall have:

$$\phi = 4 \pi r^2 \left(D \frac{dn'}{dr} + \frac{dU}{dr} Kn' \right) = Cte; \qquad (19)$$

p be the number of elementary charges e, positive for instance, carried by the nucleus, whose surface is supposed to be conductor. Keeping into account the image force of the small ion with regard to this, we shall write:

$$\frac{dU}{dr} = -e \left[\frac{p}{r^2} + \frac{R}{r^3} - \frac{Rr}{(R^2 - r^2)^2} \right] \qquad (20)$$

Let us write $r = Rx$ and $\eta = \frac{ke}{DR}$. The integral of relation (19) is expressed by:

$$n' = \exp \left[- \eta \left(\frac{p}{x} - \frac{1}{2x^2 (x^2-1)} \right) \right] \left[\frac{A}{DR} \int \frac{1}{x^2} \exp \left(\frac{1}{x} - \frac{1}{2\, x^2\, (x^2-1)} \right) dx + B \right]. \qquad (21)$$

a. Without Consideration of Small Ion's Mean Free Path.

Integration constants are determined by writing that n' is zero on the nucleus surface, supposed to be a perfect conductor, and that, far from the nucleus, limit densities have the same value n_o, since the medium is supposed wholly neutral, and n" is obtained by changing p to -p in relation (21).

Combination coefficients β_{1p} and β_{2p} of a nucleus carrying elementary charges of same sign as that of the small ions and of opposed sign, are expressed as follows:

$$\left\{\begin{aligned} \beta_{1p} &= \frac{1}{n_o} \quad 4\pi DR \left(\frac{dn'}{dr}\right)_{x=1} \\ \beta_{2p} &= \frac{1}{n_o} \quad 4\pi DR \left(\frac{dn''}{dr}\right)_{x=1} \end{aligned}\right\} \qquad (22)$$

from which

$$\beta_{1p} = \frac{4\pi DR}{I(R,p)} \quad \text{and} \quad \beta_{2p} = \frac{4\pi DR}{I(R,-\rho)} \qquad (23)$$

with

$$I(R,\rho) = \int_1^{\infty} \frac{1}{x^2} \exp \eta\left(\frac{p}{x} - \frac{1}{2x^2(x^2-1)}\right) dx. \qquad (23a)$$

Particularly, for neutral nuclei ($p = o$) β_{10} and β_{20} assume the form:

$$\beta_o = \beta_{10} = \beta_{20} = 4\pi DR. \qquad (24)$$

Such are the expressions obtained independently by Fuchs [33] and Bricard [34]. In fact, for particle sizes in the range of large ions ($R > 5 \times 10^{-7}$ cm), and neglecting a few hundredths, we may disregard the action of the electric image (Fuchs [33], [35]; Nolan and Keefe [36]), and write (Pluvinage [37], Gunn [38])

$$I(\eta,p) = \frac{e^{p\eta} - 1}{p\eta}; \quad I(\eta,-p) = \frac{1 - e^{-p\eta}}{p\eta}. \qquad (25)$$

Whipple's approximation [41] consists in supposing that the quantity of small ions deposited by diffusion, is the same for a particle with a given radius, whether the latter is charged or not. This means to neglect the action of the charge carried by a particle on the ionic density in its vicinity, and to write that it follows the same distribution law, whether the particle is charged or not.

A small ion, situated at a distance r from the center of a large ion, carrying an opposed unit charge, will support an attraction force $\frac{e}{r^2}$ and will proceed towards the large ion at a $\frac{Ke}{r^2}$ speed. So, for one unit of time, the number of small ions entering a sphere whose radius is r, centered on a large ion of contrary sign, by electric attraction, is $\frac{Ke}{r^2} 4\pi r^2 n = 4\pi Kne$. The difference $\beta_{21} - \beta_o$ is therefore equal to $4\pi Ke$. By replacing $\beta_o = \beta_{10} = \beta_{20}$ by value (24), Junge's relations are obtained [42].

Relations (22) and approximations stated above, which lead to fairly concordant results, when R is higher than 10^{-5} cm, show, if we take for the β the values mentioned on Table (VI), the radii R of about 10^{-6} cm, in full accordance with mobility measurements. However, they have been denied by Keefe, Nolan, and Rich [44], as when applied to smaller size nuclei. Keefe, Nolan, and Rich deny the validity of the theory, which has just been stated, and offer the following explanation: on account of their frequent collisions with small ions, condensation nuclei must go back to a state of equilibrium with them, as regards (at the same time) temperature and electric charge. Taking in consideration their electric energy, Boltzmann's distribution law can be applied to them. The concentration of particles carrying p elementary charges of both signs, may be written under the following form:

$$N_p = 2N_o \exp(-p^2e^2/2kTR) \qquad (26)$$

in which N_o represents the number of neutral particles per unit of volume, k the Boltzmann constant and T the absolute temperature. In fact, it does not seem that an equilibrium, in the Boltzmann meaning, can be established under these conditions and, as shown by Fuchs [33], [35], the expression (26) may be considered as an approximation to relations (25), when radius R is sufficiently great (section III A3). Figure 6 shows a comparison between the various theoretical results stated above, according to Keefe, Nolan, and Rich; the points marked are their experimental results. It may be seen that the concordance is satisfactory when $R > 10^{-5}$ cm and that no computation is also satisfactory for the lower values of radius.

b. Introduction of the Mean Free Path of Small Ions.

Suppose that λ is the mean free path of small ions, stated by relation (5). Suppose that Δ is the average distance from the particle surface, with which the small ion had its last collision. It is supposed that everything happens as if said distance would be constant, i.e. as if the collision had taken place at the distance $R + \Delta$ from the large ion center, and that the thickness shell, Δ, may be considered as a void space. A first approximation, (Arendt and Kallmann [45]) used by Lassen [46], consists in taking $\Delta = \lambda$. In a more accurate way, (Smolukowsky [35]), we shall take [47]:

$$\Delta = \frac{1}{3 R \lambda} \left[(R + \lambda)^3 - (R^2 + \lambda^2)^{3/2} \right] - R; \qquad (27)$$

which gives $\Delta = \lambda$ for very small values of R, and $\Delta = \frac{\lambda}{2}$ for great values.

It may be considered that, in the thickness zone Δ, between both surfaces, particles (in this instance small ions), move as in a vacuum and are impelled by thermic agitation speed v. Suppose that $n_{R+\Delta}$ is the small ion concentration on the outside surface of the shell. The ion flux reaching the particle (large ion or nucleus) is:

$$\phi_R = \pi R^2 v n_{R+\Delta}. \tag{28}$$

At equilibrium we shall write:

$$\phi_R = \phi_{R+\Delta} \tag{29}$$

or, according to (19):

$$4\pi(R+\Delta)^2\left[\left(D\frac{dn'}{dr}\right)_{R+\Delta} + \left(\frac{dU}{dr}\;Kn'\right)_{R+\Delta}\right] = \pi R^2 v n_{R+\Delta}. \tag{30}$$

In saying that the above relation is satisfied and that, very far from the nucleus, ionic densities have the same n_o value, we get A and B, integration constants of relation (21). Furthermore, we find that attachment coefficients β_{1p} and β_{2p} retain form (23) providing we write:

$$I = \int_{1+\frac{\Delta}{R}}^{\infty} \frac{1}{x^2}\exp\eta\left(\frac{p}{x} - \frac{1}{2x^2(x^2-1)}\right)dx + \frac{4D}{MvR}; \tag{31}$$

with:

$$M = \exp\left[-\eta\left(\frac{p}{x} - \frac{1}{2x^2(x^2-1)}\right)\right]_{x=1+\frac{\Delta}{R}} \tag{32}$$

If we disregard the electric image, we get a good approximation by writing:

$$\left\{\begin{aligned} \beta_{1p} &= \frac{\pi R^2 v p\,\frac{e^2}{kT}\exp\frac{-pe^2}{kT(R+\Delta)}}{p\,\frac{e^2}{kT} + \frac{v}{4D}R^2\left[1-\exp\frac{-pe^2}{kT(R+\Delta)}\right]} \\ \beta_{2p} &= \frac{\pi R^2 v p\,\frac{e^2}{kT}\exp\frac{pe^2}{kT(R+\Delta)}}{p\,\frac{e^2}{kT} - \frac{v}{4D}R^2\left[1-\exp\frac{pe^2}{kT(R+\Delta)}\right]} \end{aligned}\right\} \tag{33}$$

in which k represents always the Boltzmann's constant.

We find especially for β_o:

$$\beta_o = \frac{\pi R^2 v}{1 + \frac{v}{4D} \frac{R^2}{R + \Delta}} . \tag{34}$$

We see on figure 6, that the curve marked II, new theory calculated from (33) and (34), confirms the experimental points of Keefe, Nolan, and Rich, in a satisfactory way. Another argument in their behalf, is that relation (8), concerning the recombination coefficient of small ions, and equally proved right by experience, has been obtained through an argument identical to the above argument.

If r is greater than some 10^{-6} cm, relations (33) are simplified and become identical to those of Lassen [46]. For example we obtain for β_o:

$$\beta_o = \frac{4 \pi D R}{1 + \frac{4D}{vR}} ; \tag{35}$$

and if R is greater than 10^{-5} cm, we obtain relation (24), save for a few hundredths.

III. IONIC EQUILIBRIUM OF THE ATMOSPHERE.

We have studied, in chapter I, the radio-active origin of small ions and, in chapter II, the pollution characteristics, keeping strictly within the purpose of the Atmospheric Electricity viewpoint. We intend to study here the combined action of radio-activity and pollution, that is small ions versus condensation nuclei.

The consequences of the relations obtained, which are valid through the thickness of the entire atmosphere, will be studied circumstantially in the lower atmosphere, where experimental results are comparitively numerous. We shall state, furthermore, what may be their possible application to the problems of the higher atmosphere.

A. Eddy Diffusion is Disregarded.

1. Equilibrium Conditions. We suppose that the small ions, created in the air, disappear solely by fixation on neutral nuclei or on large icns having an opposite sign or the same sign; placing ourselves in a quiet atmosphere, free from turbulence, we disregard the nuclei coagulation (section II.6). At a given moment, at first we suppose that charges are symmetrical and that all the nuclei have the same radius (monodispersed medium), calling "N_p" the number of nuclei with the charge " + pe" (large positive ions); and "N_o" the number of electrically neutral nuclei. On account of the symmetry of the problem, the number per cm^3 of nuclei bearing the charge "- pe" is also N_p. Under these conditions we may write:

$$\frac{dn}{dt} = q - \alpha n^2 - n \left[\beta_o N_o + \sum_{p=1}^{\infty} \left(\beta_{1p} + \beta_{2p} \right) N_p \right] - K \frac{d(nE)}{dz} \qquad (36)$$

$\beta_o, \beta_{1p}, \beta_{2p}$ are defined by relations (33...). In the vicinity of the ground, the term depending on the re-combination coefficient α will be disregarded. This would not be allowable in altitudes where quantities $\beta_o N_o + \beta_1 N_1 + \beta_2 N_2 + \ldots$ are much lower. We shall also disregard the term $Kn \frac{dE}{dz}$.

We write for large ions:

$$\frac{dN_p}{dt} = n \left[\beta_{1,p-1} N_{p-1} - \beta_{np} N_p \right]. \tag{37}$$

We shall state that an equilibrium exists between the large ion production and their attachment on the nuclei, consequently:

$$\frac{dn}{dt} = 0 \qquad \frac{dN}{dt} = 0 \tag{38}$$

2. Required Equilibrium Time.

Let us suppose, in order to simplify, that there are no large ions having a charge greater than 1 elementary charge. If we consider the concentration of nuclei and large ions as constant, the concentration of the small ions at the time t will be written:

$$n(t) = N_o \exp(-\beta t) + (q/\beta) \left[1 - \exp(-\beta t) \right] \tag{39}$$

If the total nuclei concentration (i.e. Z) is constant, the concentration N of the large ions of both signs will be:

$$N(t) = \frac{Z}{(\beta_{21}/\beta_o) + 2} \left[1 - \exp(-pt) \right] + N_o \exp(-pt) =$$

$$= N_\infty \left[1 - \exp(-pt) \right] + N_o \exp(-pt) ; \tag{40}$$

N_o is the value of N at the time t = 0 and N the equilibrium concentration.

$$\Theta = \frac{1}{\lambda} = \frac{1}{{}_{o}N_{o} + \beta_{21}N_{1}} \qquad (41)$$

represents the average life time of a small ion, in a free state, that is the average time elapsing between the moment when it appears and the moment when it settles on a condensation nucleus.

In normal atmospheres, that quantity is included between 20 and 50 sec.

The quantity:

$$T = \frac{1}{p} = \frac{1}{(\beta_{21} + 2\beta_{o})n} \qquad (42)$$

represents the equilibrium time constant. Under normal conditions, it averages a few hundred seconds [4]. A direct measure of the average age of large radio-active ions, in the vicinity of the grounds, gives a value averaging 15 minutes. This represents the time of contact between large ions and small ions. The result is that in this time, as a rule, the ionic equilibrium corresponding to relations (38) is nearly reached, a few hundredths still missing.

3. Ionic Densities.

According to (36) we shall write to the equilibrium [49]

$$q = n\beta_{o}N_{o} + \sum_{p=1}^{\infty} (\beta_{1p} + \beta_{2p}) \; N_{p} \; . \qquad (43)$$

It is easily established, according to (37) and (38), that;

$$N_{p} = N_{o} \frac{\beta_{o}\beta_{1,1}\beta_{1,\,p-1}}{\beta_{21}\beta_{22}\beta_{2p}} = N_{o} \; ap \qquad (44)$$

wherefrom:

$$Z = N_{o} \; (1 + 2 \sum_{p=1}^{\infty} ap). \qquad (45)$$

These are relations whose numeric computation is in progress and which permit the determination of the distribution of charges in terms of the nucleus.

We may state that if R does not exceed 2×10^{-6} cm, particles carrying a double charge do not exceed 1% of those carrying only one charge; that particles carrying three charges do not exceed by 2% in number those carrying a double charge.

We find the repartition of charges attached to particles with greater than 10^{-5} cm in (37) and (38). In particular, it is shown, that the maximum charge attached to cloud droplets is in the order of a few tens of elementary charges.

Relation (44) may be written:

$$N_p = \frac{N_o \beta_o}{\beta_{1p}} \; \frac{\beta_{11} \; \beta_{1p}}{\beta_{21} \; \beta_{2p}}$$

or, according to (25)

$$N_p = N_o \frac{\exp p\eta - 1}{p\eta} \exp \left(- \sum_{i=1}^{i=p} \eta i \right)$$

$$= N_o \frac{\exp (p\eta/2) - \exp (-p\eta/2)}{p\eta} \exp (-p^2\eta/2).$$

If R exceeds 10^{-5} cm, the quantity $\dfrac{\exp \frac{p\eta}{2} - \exp \left(- \frac{p\eta}{2} \right)}{p\eta}$ is very near the unit, so that we may write (Fuchs [33]) for every sign:

$$N_p = N_o \exp \left(\frac{- p^2 e^2}{2\ RkT} \right).$$

The distribution of charges therefore follows, when the particles radius is not smaller than 10^{-5} cm, or so, a Boltzmann's law, as regards electrostatic energy, according to the hypothesis expressed by Nolan, Keefe, and Rich [44], (section II, 8a), which may be considered as an approximation to the results stated above.

If we disregard particles carrying several charges (i.e. β_{11}, β_{1p}) and if we suppose that (β_{21}/β_0) = 2, (in fact the average of this ratio amounts to 1.7 according to table (VI)), we find, according to (24) and (43):

$$q = nZ\beta_0 = nZ\,\frac{4\pi DR}{I\,(R,o)}\;; \tag{46}$$

R is the average radius of nuclei. This is Schweidler's formula which connects density of small ions and condensation nuclei with ionization intensity.

In a more accurate way, we shall write, according to (43):

$$q = nZ\,\beta \tag{47}$$

$$\beta = \frac{\beta_0 + \sum_{p=1}^{\infty}\left(\beta_{1p} + \beta_{2p}\right)ap}{1 + 2\left(\sum_{p=1}^{\infty} ap\right)} = \frac{4\pi DR}{I\,(R)} \tag{48}$$

Figure 7 represents [49] the variations of function I (R) in terms of R, in the case as expressed by relation (23a) and in the case as relations (33) are used. We see then that, except for very small values of R, function I (R) is very close to the unit.

Introducing the atmospheric electric conductivity, relation (47) is written:

$$\Lambda = \frac{2\,q\,I(R)\,Ke}{4\pi DRZ} \approx \frac{2q\,Ke}{4\pi DRZ} \tag{49}$$

Figure 8, borrowed from Sagalyn and Faucher [25], represents ionic density variations, computed according to the above relations. The points marked show the results of measures made in the exchange zone, which had a thickness of a few km above the ground.

Let us now consider the case of a medium whose granulometry follows relation (17). Relation (47) is written as follows:

$$q = n \int_{R_0}^{\infty} \beta \, f(R) \, dR = C n \, Z^{\frac{1}{2.3}}; \qquad (50)$$

C being a characteristic constant of the granulometry for a certain ionization intensity, that is for a certain stated atmospheric radioactivity; we shall then write:

$$n \times Z^{\frac{1}{2.3}} = C^{te}, \qquad (51)$$

an expression which is experimentally proven [27], [28].

4. Account is Taken of the Inegalities of Positive and Negative Mobilities [34].

Relations (47) will be expressed thus:

$$q = \frac{4\pi D' R Z n'}{I\,(R,\ p')} = \frac{4\pi D'' R Z n''}{I\,(R,\ p'')}; \qquad (52)$$

with

$$n' \approx \frac{q}{4\pi D' R Z} \qquad n'' \approx \frac{q}{4\pi D'' R Z} \qquad (53)$$

it results that:

$$\frac{n'}{n''} = \frac{D''}{D'} = \frac{K'}{K''}. \qquad (54)$$

According to the above relations, the space charge constituted by small ions, will be written as follows:

$$\rho_1 = e\,(n' - n'') = \frac{qe}{4\pi RZ}\;\frac{D' - D''}{D'\,D''} \qquad (55)$$

in which R is always the average radius of the large ions.

This quantity ρ_1 represents a positive space charge; for an average ionic density near the ground it averages to 50 to 100 elementary charges per cm^3, in accordance with the results which may be computed from direct measures of ionic concentrations of both signs.

As a rule, this represents only one part of the space charge, which, while preserving usually a near-by order of size, may be inversed in sign. Norinder's [50] results, valid at 8 or 9 m above the ground, show a negative charge (400 elementary charges per cm^3). Scrase [51] finds in case of marked turbulence, a charge always positive (under these conditions the electrode effect is masked); and negative in the first 5 meters above the ground, if the air is quiet; the average value measured ranging about 200 elementary charges per cm^3. From here it may be inferred that there is a surplus of charge born by other particles and especially by large ions in excess over that corresponding to small ions; and this may reverse the sign of the whole.

On the other hand, positive and negative conductivities are such that:

$$\left\{\begin{aligned} \lambda' &= K'\,n'e \approx \frac{q\,K'}{4\pi D' RZ}\;; \\ \lambda'' &= K''\,n''e \approx \frac{q\,K''}{4\pi D'' RZ}\;. \end{aligned}\right. \qquad (56)$$

It results from relation (54) that:

$$\lambda' = \lambda'' . \qquad (57)$$

According to relations (4) and (56) we find that the corresponding electric field of the earth is really proportional to the pollution and inversely proportional to the ionization intensity, which corresponds to the observations and permits particularly to explain the field variations related to radio-activity, on the ground as well as in altitude [55].

Finally, according to (23), (37), and (38):

$$\frac{N'_p}{N'_{p+1}} = \frac{N''_p}{N''_{p+1}} = \frac{I\,(\eta,\, p)}{I\,[\eta,\, -(p+1)]} . \qquad (58)$$

Particularly:

$$\frac{N'_1}{N''_1} = 1 . \qquad (59)$$

Relations (54), (57), (59) confirm usually stated experimental results. The following table gives a comparison with Mme. Thellier's experiments:

Theoretical Values	Experimental Values
$\frac{n'}{n''} = \frac{k''}{k'} = 1.25$	$\frac{n'}{n''} = 1.24$
$\lambda' = \lambda''$	$\lambda' = 1.42 \times 10^{-4}$; $\lambda'' = 1.40 \times 10^{-}$
$\frac{N'_1}{N''_1} = 1$	$\frac{N'_1}{N''_1} = 1.03$

According especially to relation (59), the space charge born by large ions should be zero, which results seems inconsistent with the results recalled above. However, we must not forget (section III A, 2) that the ionic equilibrium is usually reached only to a few hundredths. Let us take 5%. It corresponds to a possible excess of large ions of the same order. For a slight pollution (2000 large ions/cm^3), 100 elementary charges born by large ions may result, this being all the more marked when pollution is higher. We must furthermore add that artificial pollution causes important charges of a preponderant sign [6], which have no time to be neutralized by natural ionization, and whose action, superposing on that of natural pollution, alter ionic equilibrium equations.

5. The Case of Radio-Active Ions.

a. Computation of Concentrations. The following reasoning is prevailing and valid whatever the nature of the radioactive body present in the atmosphere may be, providing that elements of the range of molecular dimensions be present and not aerosols of larger dimensions. It will be applied to the particular case of the Radon near the ground, which seems to have been the more accurately studied until now.

Supposing that:

$$q_A = \lambda_{Rn} N_{Rn} \qquad (60)$$

is the number of RaA atoms appearing per cm^3 of air and per second, N_{Rn} meaning the atmospheric concentration of Radon and λ_{Rn} its radio-active constant. We will write relation (36):

$$\frac{dn_A}{dt} = q_A - \alpha n n_A - n_A \left\{ \beta_0 N_0 + \sum_{p=1}^{\infty} \left[(\beta_{1p} + \beta_{2p}) N_p + \beta_{1p} N_{pA} \right] \right\}. \quad (61)$$

n_A is the atmospheric concentration of small RaA ions, and N_{pA} that of the nuclei having attached RaA atoms.

Not knowing the exact value of the diffusion coefficient of neutral RaA atoms (mentioned in section (I,6)), which appear when the Radon disintegrates, we suppose as a first approximation, that every radio-active ion carries a positive elementary charge. The problem is then the same as that of the attachment of ordinary ions on condensation nuclei, with the difference that this concerns only positive ions.

Due to the fact that small radio-active ions have the same mobility as the small normal ions of the atmosphere, it results from relation (7) that they have also the same recombination coefficient as the small negative ions and we may, under normal conditions, disregard the quantity $\alpha n n_A$.

The β have the same meaning as in the previous section and the expression $\beta_{1p} N_A$ takes into account the formation of radio-active particles having a multiple concentration charge N_{pA}. The limit concentration reached at the equilibrium will be given by $\frac{dn_A}{dt} = 0$; that is, according to notations of section IIIA, 2 and disregarding multiple charges:

$$n_A = \frac{q_A}{\beta + \lambda_A}. \quad (62)$$

The quantity $\Theta = \frac{1}{\beta}$ represents, as in the case of relation (41), the average interval of time between the appearance of a radio-active atom coming from the Radon, disintegrated or not, and its attachment on a particle; it ranges therefore to about 20 to 50 sec, the same as for small normal ions.

This is, in fact, the order of magnitude corresponding to Renoux' direct measures [12], taken close to the ground (study of the decrease of disintegration products of small ions, directly collected in the atmosphere during a very short period). RaA atom concentrations, corresponding to the conditions of relations (62), are of the same kind as those mentioned in section(I.6) for β-values consistent with experience.

Relation (62) may also be applied to the computation of the concentration of stratospheric recoil atoms. At an altitude of 20 km, we may suppose for them: $D \approx 1$ cm^2 sec^{-1}; $R = 10^{-5}$ cm; and $Z = 0.1$ per cm^3. We find that β ranges at about 10^{-5}sec^{-1}, the attachment time for every present aerosol particle of these liberated atoms ranging at about 10^5 sec., about 3 hours. If we take the case of Be_7 and P_{32} considered in section I-6, whose period is long compared with this attachment time, according to (62), corresponding concentrations would amount to 2×10^{-3} and 2×10^{-5} of free Be_7 and P_{32} atoms per cm^3 of the atmosphere, respectively.

b. Neutral Radio-Active Nuclei [29] The whole of the Radon decay products is thus either free, in the form of small ions, mainly constituted by RaA, and by RaB and RaC in very small quantities, or in the form of radio-active condensation nuclei, electrically neutral, (coming from large ions originally negative), or of large radio-active ions (coming from neutral condensation nuclei), or fixed on dust particles.

Radio-active neutral ions can also appear by neutralization of large radioactive ions, by small negative ions, and disappear by attachment of small ions of every sign. We will disregard, in a first approximation, these minor reactions.

If the disappearance of large radio-active ion and neutral nuclei, exclusively of N_A and N_{oA} concentration, is exclusively attributed to their decay, we will write, for instance for the second concentration:

$$\frac{dN_{oA}}{dt} = n_A \beta_{21} N'' - \lambda_A N_{oA}; \qquad (63)$$

N" is the concentration of large negative ions. The same relation will be obtained for N_A.

If we suppose that there is an equilibrium:

$$\frac{dN_A}{dt} = \frac{dN_{oA}}{dt} = 0; \qquad (64)$$

and supposing a probable atmospheric ion concentration, we find for $n_A = 1.5 \times 10^{-4} cm^2$ (section I.6) that $N_{oA} = 5 \times 10^{-4}/cm^3$; $N_A = 4 \times 10^{-4}/cm^3$.

This corresponds to the experiments (section II.7).

However, (secondary reactions mentioned above), large negative radio-active ions should appear, originated by attachment of small ordinary ions, on neutral radio-active nuclei. In spite of all our efforts, we did not succeed in detecting the presence of these large negative ions in the atmosphere, which leads us to suppose that such a mechanism does not exist. It is, however, possible to realize it by the corona effect. An explanation could be the insufficient contact time between natural aerosol particles and Radon products.

c. Equilibrium Between Radioactive Small and Large Ions. [10], [11], [43]. Suppose that Z_A is the concentration of RaA atoms, corresponding to these two kinds of particle. Due to the small RaA period (3 min.), it may be supposed that the radio-active equilibrium is obviously reached between the Radon and the RaA resulting from its decay (10 minutes are indeed necessary to realize said equilibrium to 10%). We shall therefore write:

$$q_A = \lambda nRn = \lambda_A (nA + Z_A); \qquad (65)$$

and, starting from (62) and (65), we find that:

$$Z_A = q_A \frac{\beta}{\lambda_A} \qquad (66)$$

from which:

$$\frac{n_A}{Z_A} = \frac{\lambda_A}{\beta}. \qquad (67)$$

We see that the ratio $\frac{n_A}{Z_A}$ is independent of the quantity of Radon existing in the air.

Relation (67) shows for the RaA (period 3 min), near the ground, under normal conditions, ($\beta = 4 \times 10^{-2} \text{sec}^{-1}$), that $\frac{n_A}{Z_A}$ ranges at about 10%, which corresponds to the measures. These relations are also valid for stratospherical decay products. For Be_7 and P_{32} with $\beta = 10^{-5} \text{sec}^{-1}$, orders of magnitudes of 0.02 and 0.06 are respectively found for n/Z.

d. Granulometric Distribution of the Activity of Natural Aerosols [46], [49]. First, let us go back to the case of the attachment of small ions on natural aerosols, but in a polydispersed medium. According to (47) and (48), we may write:

$$q(R) = 4\pi Dn \int_{R_o}^{R} \frac{Rf\ (R)}{I(R)}\, dR. \qquad (68)$$

$f(R) = \frac{dZ}{dR}$ represents the granulometric distribution of the medium as given by the relation (17). Function q (R) is represented, in relative values, in fig.9 for two values: $R_o = 5 \times 10^{7}$ and $R_o = 10^{-6}$ cm of minimum radius R, corresponding to inferior limits, reasonable for large average ions: the maximum radius was chosen equal to 1 . The distribution, thus computed from relation (68), is practically identical with that computed by Lassen [46] from relation (35) for $R_o = 10^{-6}$cm.

On the same figure, a dotted line shows the distribution obtained by making I (R) = C^{te} in relation (68). We may see, especially for $R_o = 10^{-6}$ cm, that the corresponding distribution is very similar to the former, and that, due to the accuracy of measuring methods now available, this approximation is largely satisfactory, which justifies Mühleisen and Holl's [27], [28] arguments [I (R) = 1].

We derive from the curves that the average nuclei ($R \leq 2.5 \times 10^{-6}$ cm) attach 78 to 80% in the first case and 83% to 86% in the second; the remaining, i.e. about 15 to 20%, being attached by particles of larger size. These results define the role of these particles, the nature of which has been discussed before [34].

Relation (68) is general and applies to small radioactive ions derived from the Radon; for instance, attached to aerosol particles; n is to be replaced by n_A and q by q_A (R), which represents the accrued granulometric distribution of the activity attached to natural aerosol particles. Points marked in fig. 9 represent the experimental results directly obtained, corresponding to table V. We see that categories (1) and (3), table C, are well placed, (points marked c and d), with respect to the computed curves in fig. 9.

The experimental device used in these investigations does not permit to know accurately the value of the radius corresponding to class 2, which may be either a or b on fig. 9. However, even if we take the farthest, we are again in the neighborhood of the computed curve. We may then conclude, in consideration of the slight quantities measured and of the difficulties encountered in such experiments, that the experimental points thus obtained, constitute a first checking of the theoretical consideration stated above. They are also in agreement with the theoretical distribution foreseen by Lassen [46], concerning the attachment of Thoron by-products on artificial aerosol particles.

B. Introduction of Eddy Diffusion Coefficient. Kawano's Theory [52] [53].

1. Ionic Density.

In order to know the vertical distribution of ionic densities, we must introduce the eddy diffusion coefficient into the equilibrium equations. This allows to determine the distribution of the various electric parameters, depending on the altitude. Let n be the concentration of small positive ions, for instance, supposing that, as in (36), charges are symmetrical and that K is the eddy diffusion coefficient. The rate of variation of n with altitude Z will be expressed, on account of eddy diffusion, as follows:

$$\frac{dn}{dt} = \frac{d}{dz}\left(K \frac{dn}{dz}\right). \qquad (69)$$

The contribution of ions, coming from lower parts, adds itself to the production of ions by the various ionizing agents, considered in chapter I. Let q(z) be the corresponding total ionization intensity. Equations (36) and (38) become, at altitude Z*:

$$\frac{d}{dz}\left(K \frac{dn}{dz}\right) + q_z = \beta Zn - K \frac{d(nE)}{dz} + \alpha n^2. \qquad (70)$$

Account may be taken of possible variations of K with the altitude (Miline [54]), which complicates the computations. We will merely consider K as constant (Kawano) and disregard possible variations of the conduction current, as well as the small ions recombinations, which leads to relation:

$$K \frac{d^2n}{dz^2} + q_z = \beta Zn. \qquad (71)$$

The ionization intensity is the sum of 3 terms:

$$q_z = q_{z1} + q_{z2} + q_{z3}. \qquad (73)$$

The first term, q_{z1}, represents the action of the γ-radiation from the ground. At z altitude, it is given by relation (1). The second term represents the action of radio-active gases and of their active decay products suspended in the atmosphere. By limiting ourselves, in a first approximation, to the Radon daughter-products and

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*) K is not well known close to the ground. However, we shall suppose, that the value of K as well as that of dn/dz is much smaller at ground level than in some height. This justifies the equations (37) and (38).

by reverting to the reference level h, we will write, according to (2):

$$q_2(z) = q_{2h} \exp - \left[\sqrt{\frac{\lambda}{K}}\,(Z - h) \right]. \qquad (73)$$

where λ is the Radon radio-active constant. (It would be easy to take into account the other radio-active bodies, possibly present. They would reveal themselves through a sum of terms of the above type).

Relation (70) will then be written under the form mentioned by Kawano:

$$K \frac{d^2 n}{dz^2} + q_{10} \exp(-\mu z) + q_{2h} \exp - \left[\sqrt{\frac{\lambda}{K}}\,(z-h) \right] + q_3 = B\,Z\,n\,; \quad (74)$$

Zn; (74)

q_3 is the cosmic radiation contribution, supposed constant, in terms of the altitude.

The integration of the above relation has been made by KAWANO, in the case when product $B\,Z$ is constant with the altitude. It is evident that this condition is in contradiction with the other conditions brought in relation (74), (other characteristics variable with the altitude), as well as with experience, (section II,1). Therefore, the expression of n thus obtained can only be very approximative and would most probably be improved if Z would be given an exponential form. However, with the following limit conditions:

$n = n_h$ at $z = h$

$n = n$ at $z = \infty$

we obtain:

$$n = \left[n_h - \frac{q_{1h}}{BZ-\lambda} - \frac{q_{20}}{BZ - K\mu^2} - \frac{q_3}{BZ}\right] \exp -\left[\sqrt{\frac{\lambda}{K}}\,(z-h)\right] + \frac{q_{1h}}{BZ-\lambda}$$

$$\exp -\left[\sqrt{\frac{\lambda}{K}}\,(z-h)\right] + \frac{q_{20}}{BZ-K\mu^2} \exp(-\mu z) + \frac{q_3}{BZ}\,. \qquad (75)$$

This expression allows numerical calculation of the ionic density with these simplifying hypotheses and according to (3), the conductivity, resistivity, etc., at various altitudes.

2. Other Electrical Parameters.

By calling E the earth's electric field supposed vertical and ρ the charge density at altitude:

$$\frac{dE}{dz} = -4\pi\rho \qquad (76)$$

or, according to (4):

$$\rho = \frac{i}{4\pi\Lambda^2} \quad \frac{d\Lambda}{dz}. \qquad (77)$$

i is the density of the vertical conduction current.

Starting from (3), (75), (76), and (77), we may therefore bring in the pollution and radio-activity on all other atmospheric electricity parameters, and especially on the space charge and the electric field. Let us write $q_{20} + q_3 = q_2$ and $\mu = 0$, which means to disregard ground radiation absorption (table III). Noting that $\lambda = 2.09 \times 10^{-6}\,\mathrm{sec}^{-1}$ is negligible compared with BZ (whose order of magnitude under low pollution is nearing $10^{-2}\,\mathrm{sec}^{-1}$), we obtain, according to (75), (76), and (77), a relation between the electric field E and space charge density at the height h, which is written

$$E_h = 4\pi \varsigma_h \frac{n_h K^{\frac{1}{2}}}{(BZ)^{\frac{1}{2}} \left(n_h - \frac{q_{1h} + q_2}{BZ}\right)} , \qquad (78)$$

At zero altitude, if we take $K = 4 \times 10^4 \text{ cm}^2\text{sec}$, $B Z = 10^{-2}\text{sec}^{-1}$, $q_h = 10 \text{ pI cm}^{-3}\text{sec}^{-1}$, and $n = 1000 \text{ cm}^{-3}$ according to (46), we find that E ranges about 0.3 esu/m, i.e., about 100 V m^{-1}, normal size range. Relation (78) allows to explain, in a satisfactory way, the electric field local anomalies.

IV CONCLUSIONS

Although the relations established in the course of this report are general, their application to problems of atmospheric electricity is restricted, as regards the equilibrium between small ions and natural aerosols, at altitudes higher than a few km. Above, ionization intensity of radio-active origin and atmospheric pollution play a negligible part, compared with ionization intensity of cosmic origin and re-combination between small ions. In other words, relations (70) and (72) remain valid, providing all other terms besides q_3 and αn^2 are disregarded even in the stratospheric accumulation zone.

We have shown that ionic equilibrium conditions may also be applied to the attachment of ions or radio-active atoms on natural aerosol particles. Although their concentrations are extremely low, compared with those of large and small natural ions, their experimental study is already well in progress, in the neighborhood of the ground. It presents an interest in the exchange layer where pollution and radio-activity are still noticeable, but seems useless between the latter and the tropopause. On the contrary, in the accumulation zone, towards 20 km in height, where exist at the same time, radio-active atoms (fission and artificial radio-activity) and an appreciable quantity of pollution, it presents certainly an interest and could constitute a new stage in the study of the atmospheric radio-activity.

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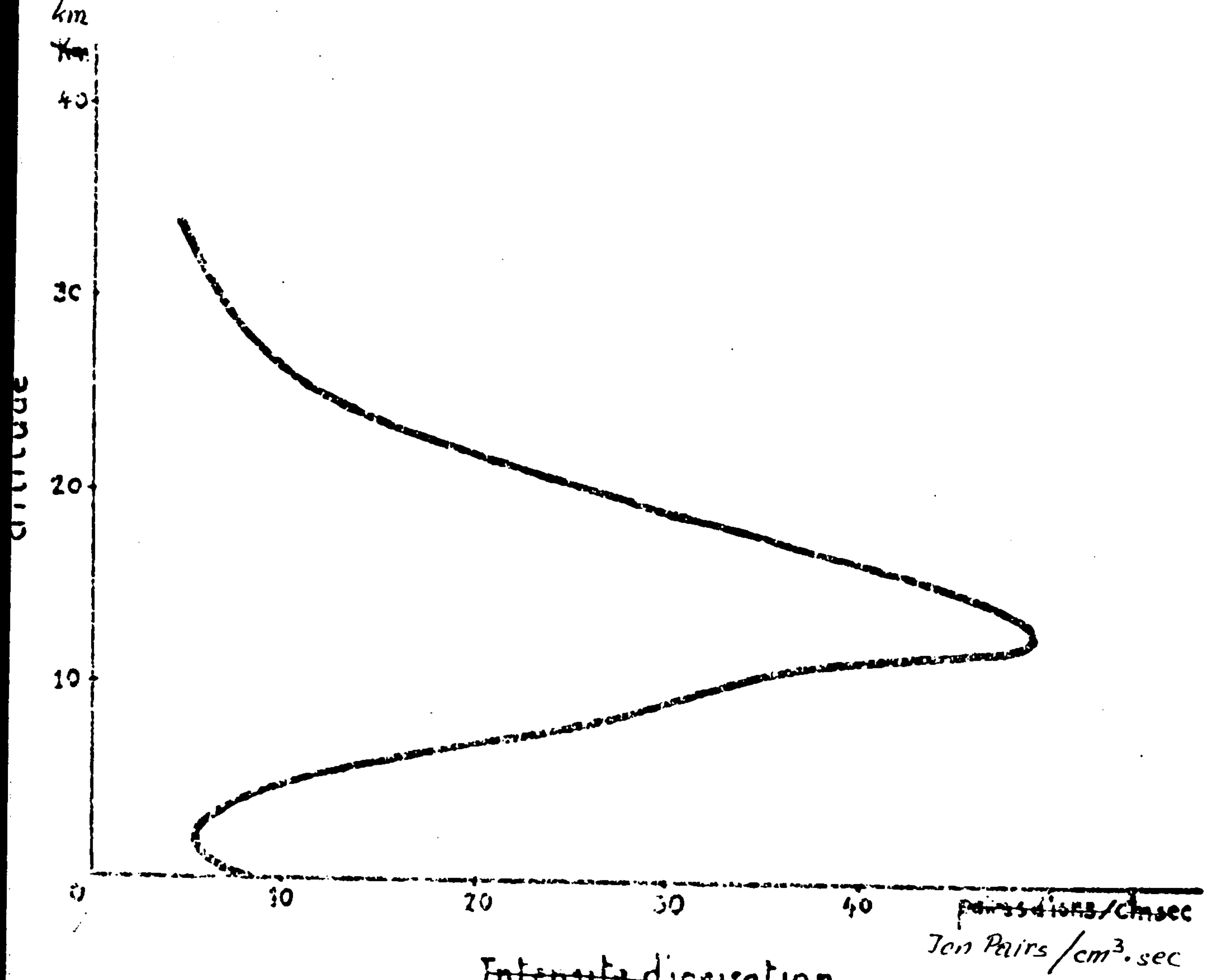
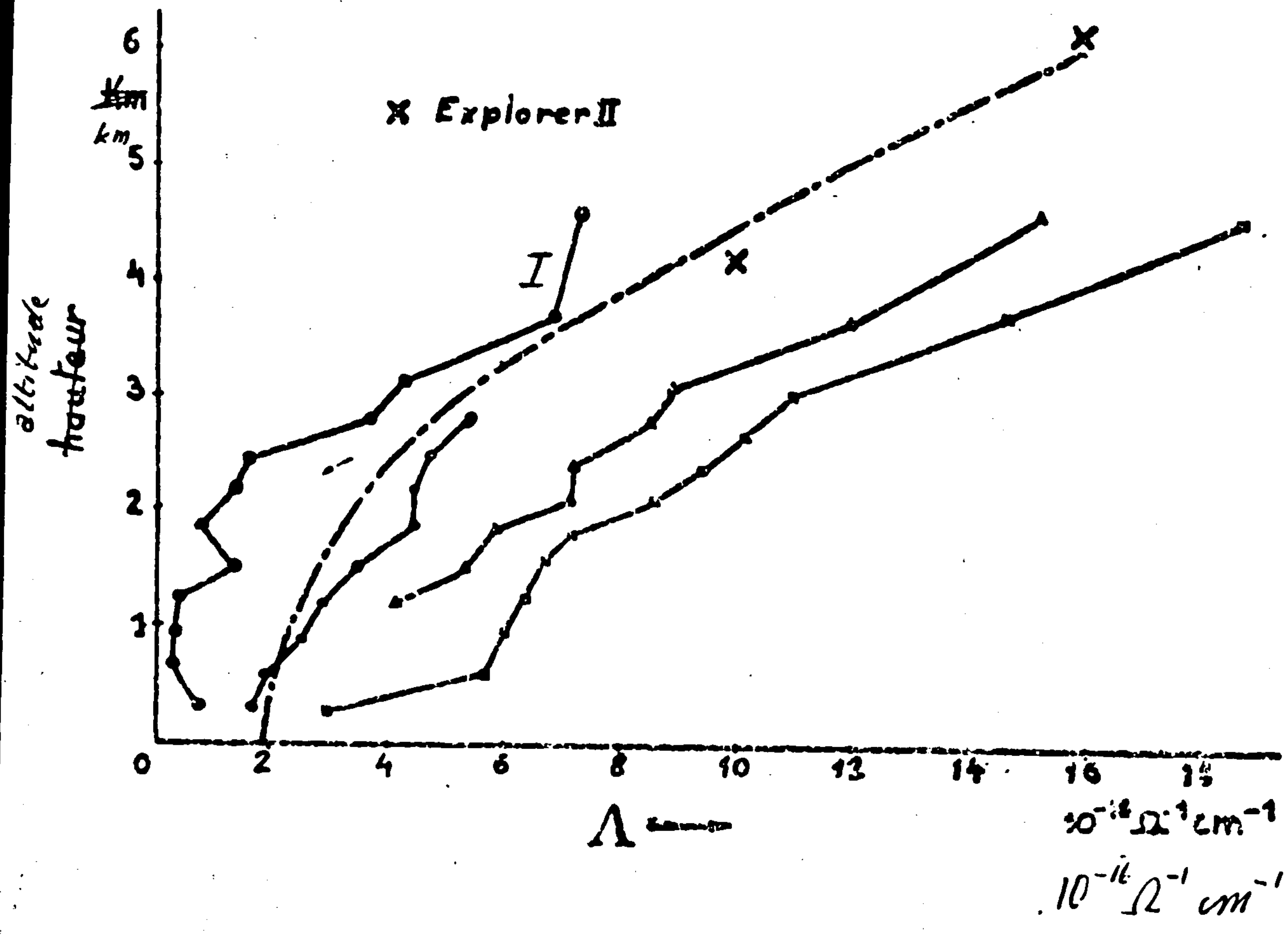


~~Intensité d'ionisation~~
Intensity of Ionisation

Fig. 1


6
~~km~~
km 5
4
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× Explorer II
I
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6
8
10
12
14
16
18
Λ ⟶
10⁻¹⁶ Ω⁻¹ cm⁻¹
10⁻¹⁶ Ω⁻¹ cm⁻¹

fig. 2

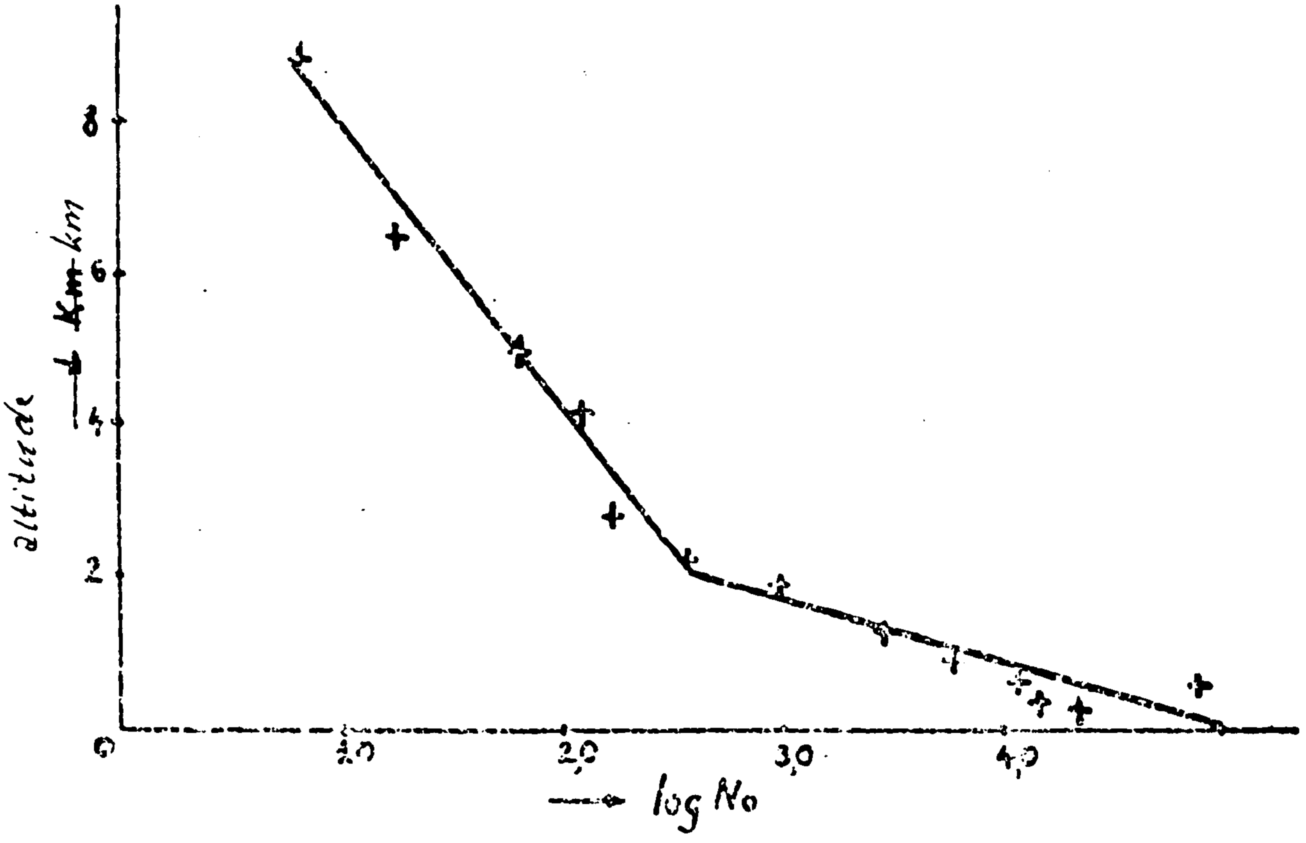

Fig. 3

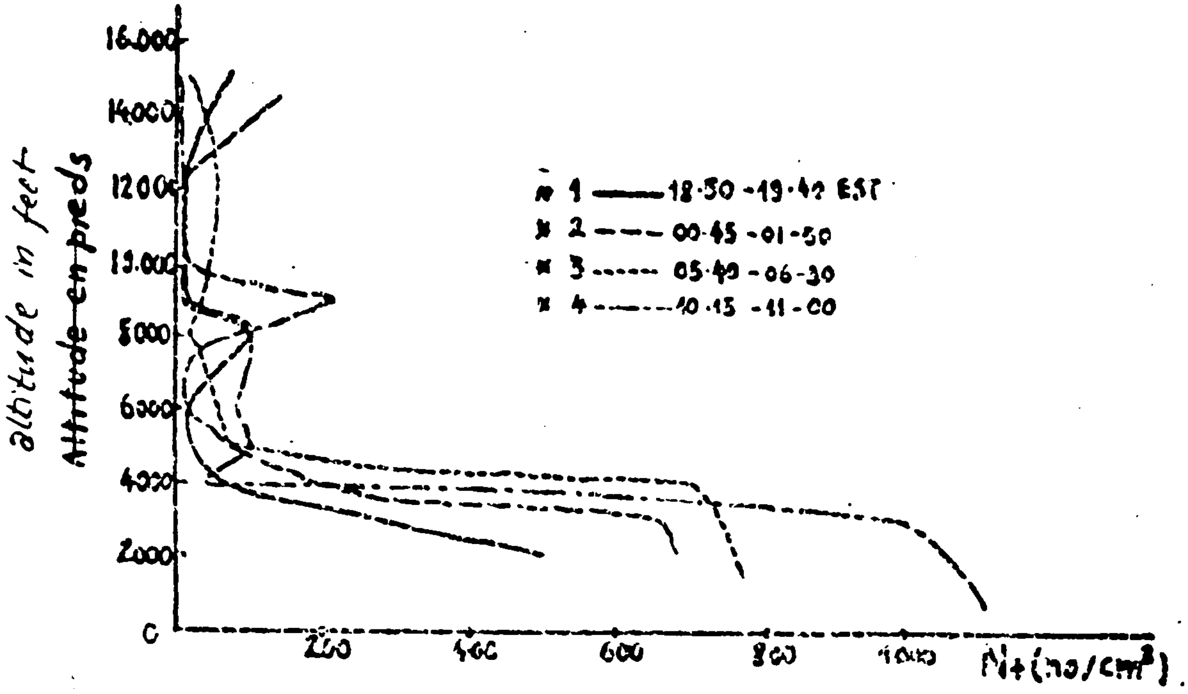

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fig. 4

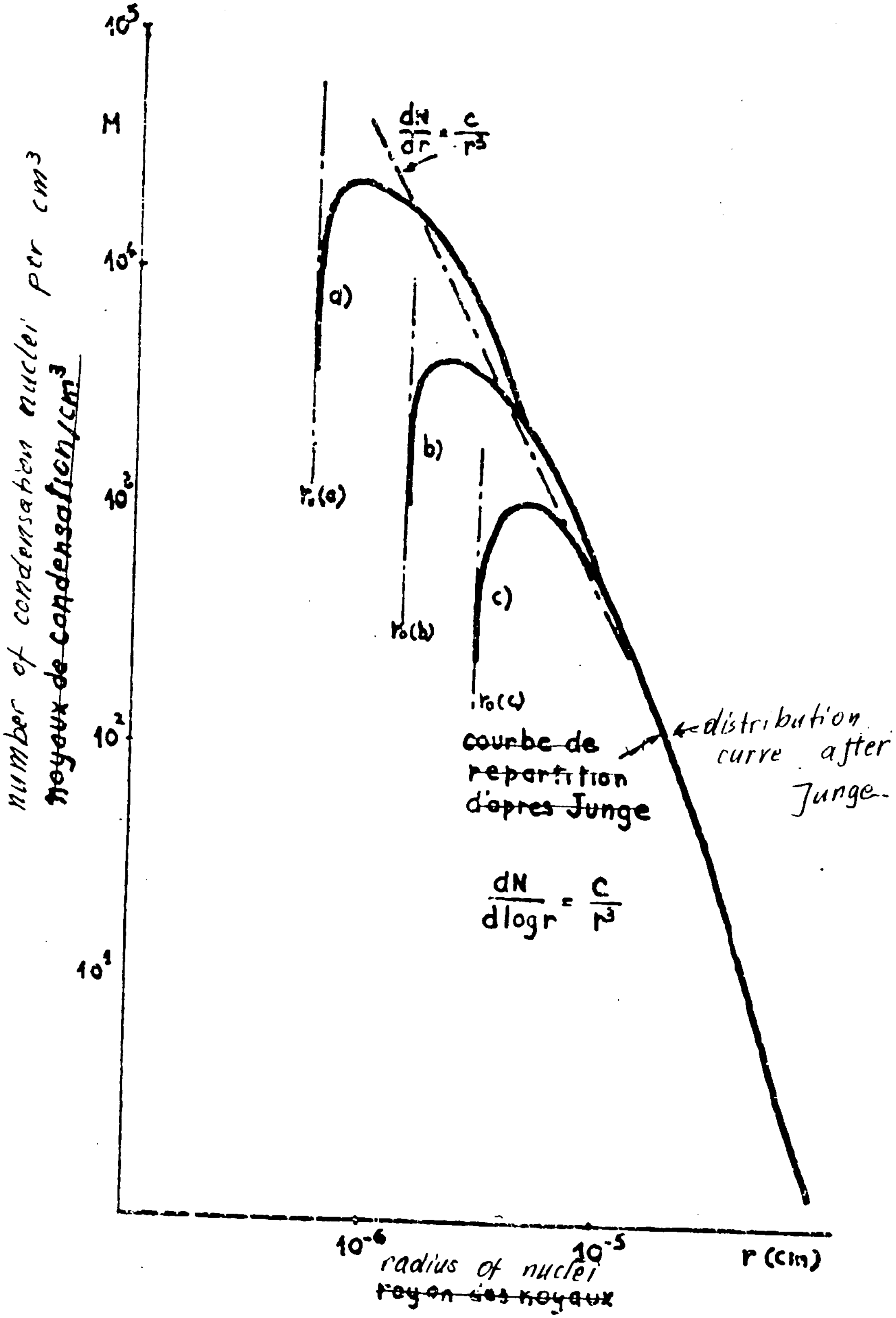
10^5
M
10^4
10^3
10^2
10^1
$\frac{dN}{dr} = \frac{C}{r^3}$
a)
b)
c)
$r_0(a)$
$r_0(b)$
$r_0(c)$
~~courbe de repartition d'apres Junge~~
distribution curve after Junge
$\frac{dN}{d\log r} = \frac{C}{r^3}$
number of condensation nuclei per cm3
~~noyaux de condensation/cm³~~
10^{-6}
10^{-5}
r (cm)
radius of nuclei
~~rayon des noyaux~~

fig.5

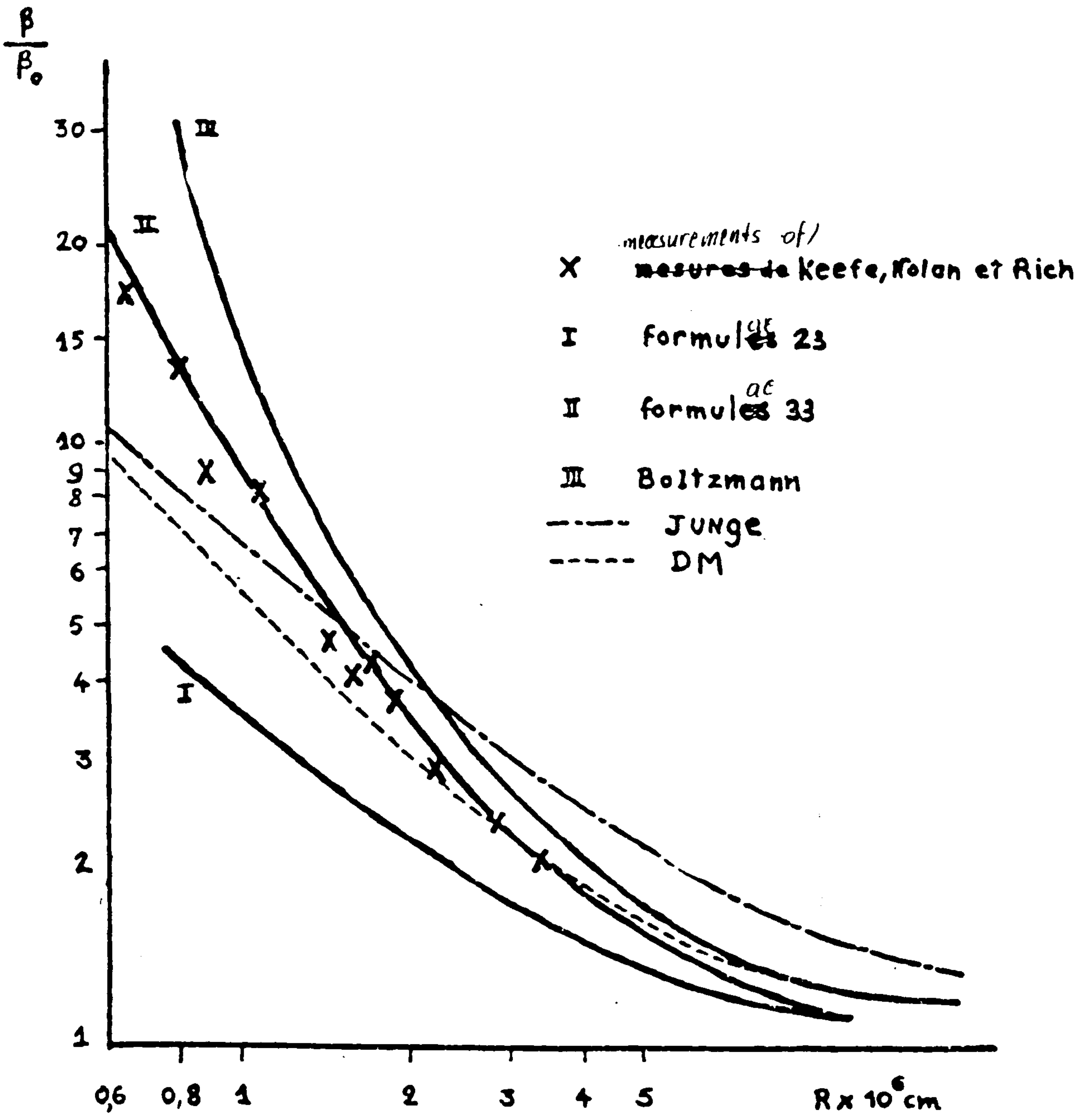
$\frac{\beta}{\beta_0}$
30
20
15
10
9
8
7
6
5
4
3
2
1
0,6
0,8
1
2
3
4
5
R x 10⁶ cm
I
II
III
X measurements of/ ~~mesures de~~ Keefe, Kolan et Rich
I formul~~es~~ ae 23
II formul~~es~~ ae 33
III Boltzmann
—·—·— Junge
- - - - - DM

fig.6

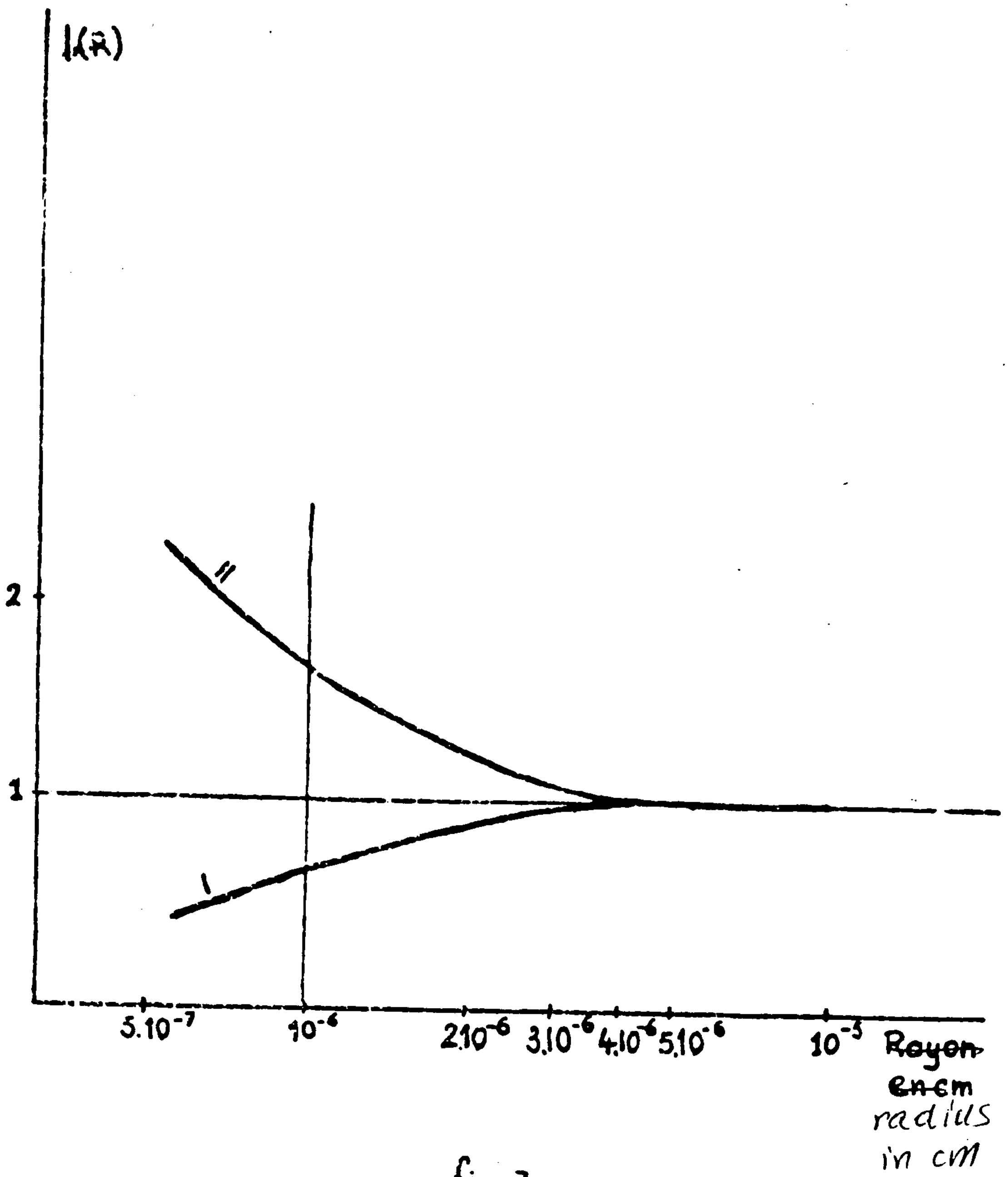
I(R)
2
1
II
I
5.10^-7
10^-6
2.10^-6
3.10^-6
4.10^-6
5.10^-6
10^-5
~~Rayon en cm~~
radius in cm

fig. 7

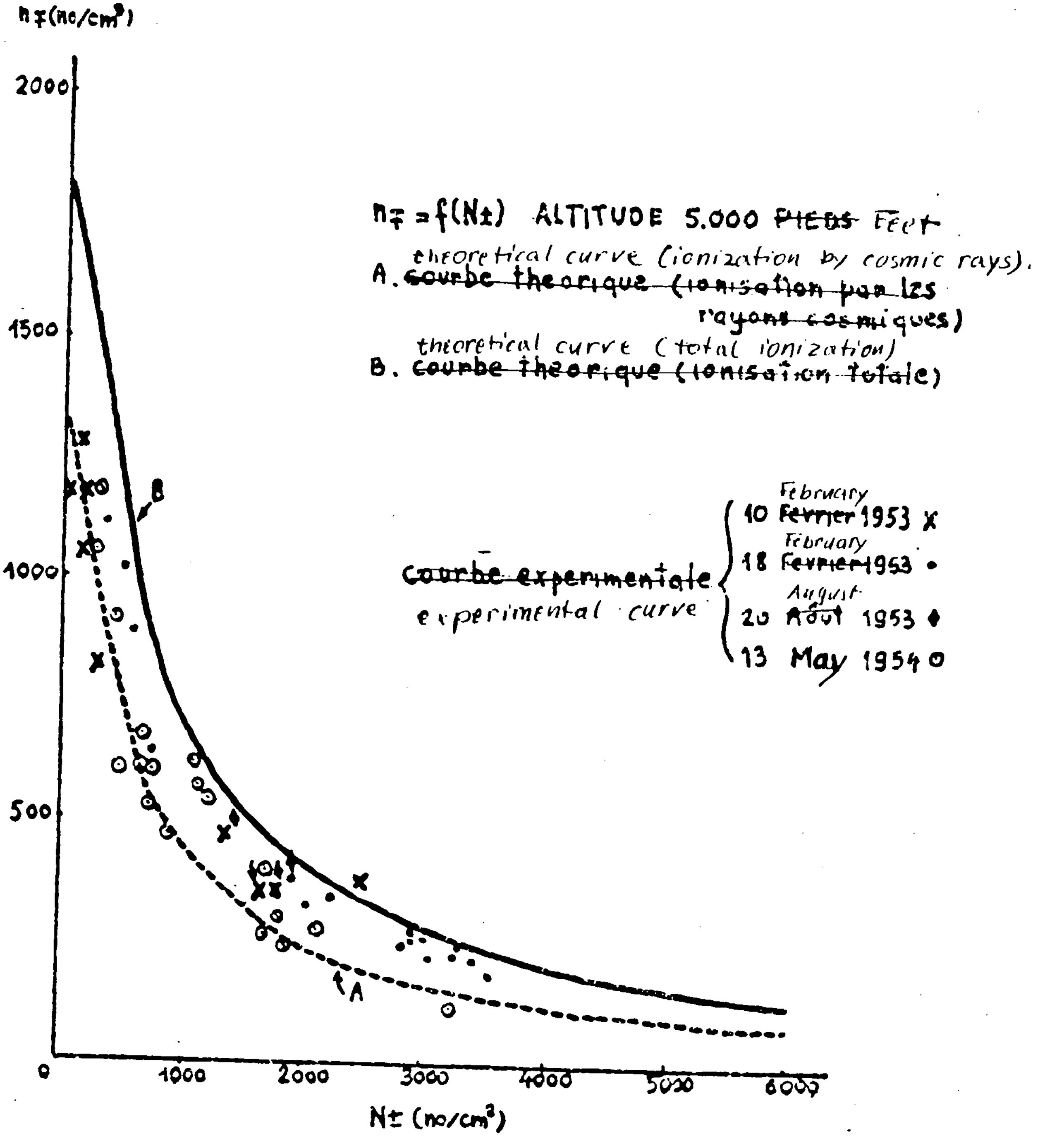
n∓(no/cm²)
2000
1500
1000
500
0
n∓ = f(N±) ALTITUDE 5.000 ~~PIEDS~~ Feet
A. theoretical curve (ionization by cosmic rays).
~~courbe theorique (ionisation par les rayons cosmiques)~~
B. theoretical curve (total ionization)
~~courbe theorique (ionisation totale)~~
B
A
~~courbe experimentale~~
experimental curve
10 February ~~Fevrier~~ 1953 X
18 February ~~Fevrier~~ 1953 •
20 August ~~Aout~~ 1953 ♦
13 May 1954 ○
1000
2000
3000
4000
5000
6000
N± (no/cm²)

fig. 8

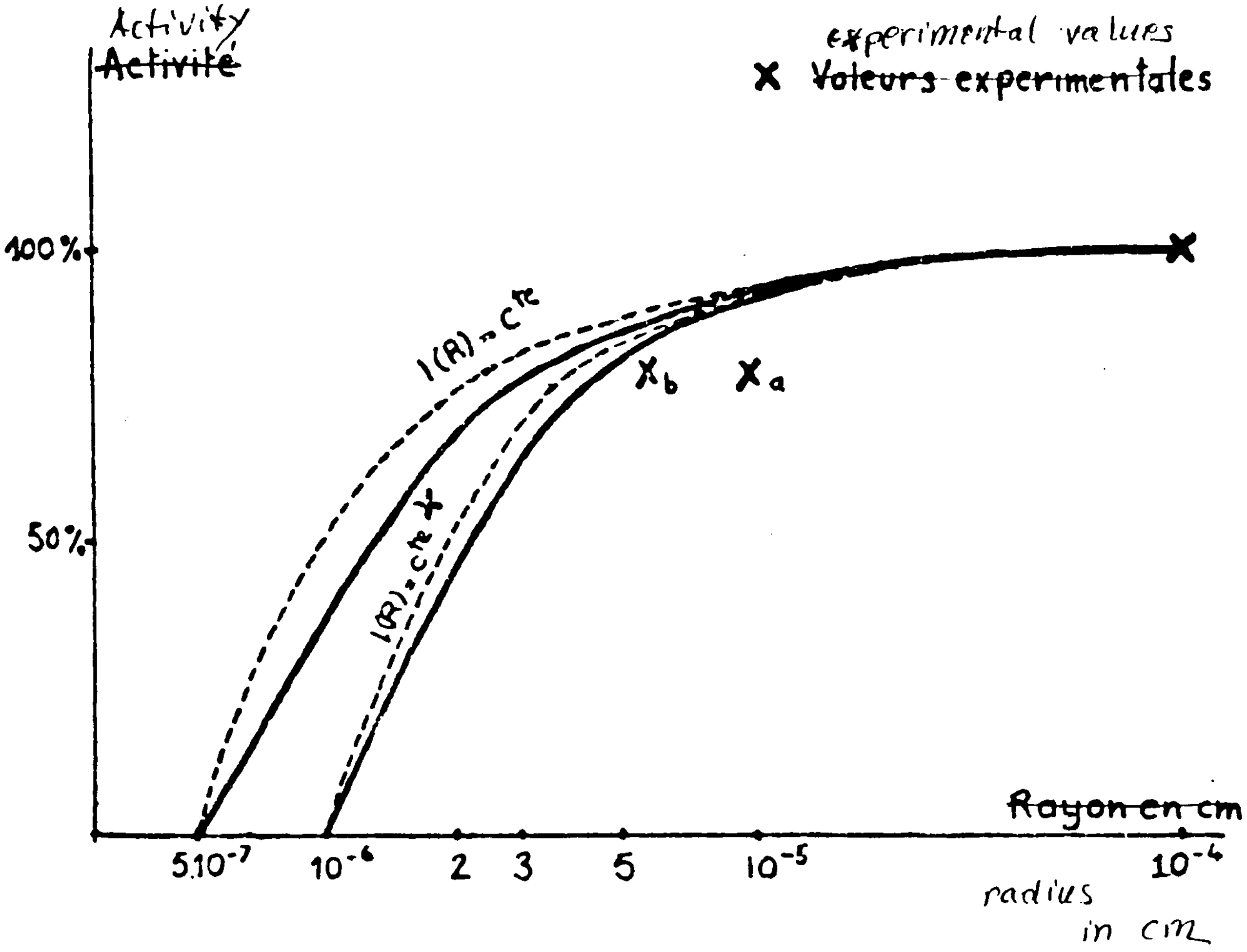
Activity
~~Activité~~
experimental values
X ~~Valeurs experimentales~~
100%
50%
I(R) = C^{te}
I(R) = C^{te}
X_b
X_a
~~Rayon en cm~~
5.10^{-7}
10^{-6}
2
3
5
10^{-5}
10^{-4}
radius in cm

fig. 9

Ii

SESSION 3.1

Generation of Electric Charges Outside Thunderclouds

by

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1. Introduction

It can scarcely be denied that the most important processes of electrification in the lower atmosphere are those within thunderclouds, but nevertheless there are many other electrical processes at work in various regions of the atmosphere that [illegible] have been discovered and that will have small or large effects on the electrical state of the atmosphere.

It is hoped that, at the risk of becoming a mere catalogue, something can be said about most of these processes, though naturally there will be more that can be discussed about some than about others.

As in the thunderstorm, it is possible to distinguish between two stages in the generation of charge, first the actual separation of the two charges of opposite sign from previously neutral matter and, second, the segregation of these two charges in such a way that they reach different places. In some of the processes discussed, the separation is that which produces the natural conductivity of the atmosphere, namely the ionization of the atmosphere by cosmic rays and by radioactivity. And in some processes the segregation is by the ordinary process of electric conduction in the electric field that is present, moving charges of opposite sign in opposite directions.

2. Point Discharge

Point discharge can be considered as a generator of charge, since the breakdown separates charges from neutral matter and the electric field segregates them.

When an earth-connected point exists above the surface of the earth, the lines of electric force in the atmosphere concentrate on the point and the local field strength is greater than that of the earth's surface. In the simple case of an isolated point, this local field strength would depend on the potential difference between the point and its surroundings, i.e. the free atmosphere at the same level, and so on the height of the point and the potential gradient in the atmosphere; for a point which is one of a number at comparable heights, the other points modify this simple approach.

When the potential gradient in the atmosphere reaches a certain value, the field strength near the point becomes sufficiently large for local breakdown, involving ionization by collision, to occur, and, as the potential gradient increases, breakdown can occur over wider volumes and for more points. The local breakdown near points has been studied under laboratory conditions as "corona discharge", but the details need not concern us here.

The result of the local breakdown is to produce ions of both signs; those of the same sign as the potential gradient move quickly into the point and form a current to earth, while those of the opposite sign remain in the atmosphere and form a space charge, ultimately moving upwards to the cloud which is the origin of the potential gradient. The presence of the space charge near the point diminishes the actual field strength at the point and under suitable circumstances the discharge may occur in pulses; averaging effects over periods of time long compared with the pulses, it is easy to see that, in steady conditions, there will be an adjustment to give a steady current and space charge, the local conditions near the point providing just sufficient current for the purpose; it is then unnecessary to discuss details of the actual processes at work near the point, just as, in an analogous case of the Langmuir-Child law for thermionic emission, the details of the emission process need not be discussed.

With a particular point and one value of the potential gradient, it follows that the current would be altered only if the space charge is altered, and this is achieved only by wind removing it from the neighbourhood of the point. An approximate theoretical calculation of the current in its dependence on potential gradient and wind speed for an isolated point has recently been made (Chalmers, 1962) and work is progressing on an attempt to carry out a more accurate computation with a computer. The theoretical problem of a point which is not isolated, but one of a number similarly or differently situated remains to be tackled.

On the experimental side, the earlier measurements of the relation between point-discharge current and potential gradient did not recognise the part played by wind, but the more recent work has shown that this must be included and the results are in fair agreement with the approximate theoretical calculations.

The work so far discussed has been carried out by simply erecting a metal point in the atmosphere and connecting it to earth through a measuring instrument; this, therefore, does not give a great deal of information about the effect of natural point discharge, which must take place largely through trees. The problem therefore arises as to how closely a metal point and a tree correspond in regard to point-discharge currents.

Schonland (1928) cut down a bush, typical of the neighbourhood, mounted it on insulators and measured the current through it; while this was an approach to natural conditions, it did not reproduce the conditions of a living tree. More recently, Maund and Chalmers (1960) attempted to measure the current through a tree, not directly but by measuring the effect of the space charge on the potential gradient downwind; the results suggested that a tree in leaf gives less current than a point at the same height. Milner and Chalmers (1961) inserted electrodes into a tree, so as to short-circuit the current down the tree through a galvanometer and found smaller currents than for a point. Quite recently, with the same apparatus, Chalmers (1963) found that, at the time of a close lightning flash, the tree and a neighbouring metal point gave appreciably different currents, showing that the tree does not behave like a simple conductor. It would be very desirable if such measurements could be attempted in the parts of the world where thunderstorms are frequent.

The question of the effect of the presence or absence of neighbouring points on the current through one particular point is another which requires further investigation. Chiplonkar (1940) and Chalmers and Mapleson (1955), using natural point discharge, found that the total current through a number of points close together was less than if they were replaced by a single point, but Belin (1948), in a laboratory experiment, found that each point of a group gave the same current whether the others were present or not.

3. Non-Stormy Rain and Snow Clouds

Although the electrical effects in non-stormy clouds are less than those of thunderclouds, they are still appreciable, and some processes of charge separation must be present.

One of the important problems in this field is the discussion as to whether the charge-separation processes in non-stormy clouds are the same as in thunderclouds or not. If they are the same processes, then the problem is why the magnitude of the charge separation is so different; what are the conditions in the thundercloud that make the processes so much more efficient there than in the non-stormy cloud? It should perhaps be pointed out that the difference is much greater than the mere difference in intensity of precipitation. If, on the other hand, charge separation in the non-stormy cloud takes place by totally different processes, then these processes must be such that they are not much magnified by the change from non-stormy to stormy conditions, and, further, the processes in the thundercloud must be such that they cannot operate significantly in the non-stormy cloud. These considerations are a strong justification for increased study of nonstormy cloud electrification, particularly when it is realised that such clouds are much more frequent in many parts of the world than thunderclouds and conditions are much steadier and more amenable to measurement.

In this connection, an important principle has been used, namely that of the quasi-steady state, so that one can assume that the total vertical electric current is the same at all levels. This assumes that there is no differential horizontal electric current at any level, and it might be profitable to consider this question in more detail, particularly in the case of warm-front clouds where the movement of the air is much more horizontal than vertical.

An important result in the measurements of the effects of non-stormy clouds is the difference of both potential gradients and precipitation currents as between rain and snow. Unless there are effects at the earth's surface, or near to it, this seems to indicate that there must be electrical effects in the process of melting, since most of the precipitation concerned has started as ice particles and, if finally falling as rain, has melted later. The simple discussion of the quasi-steady state lends to the conclusion that the potential gradient above a cloud would alter in sign when the precipitation changes from rain to snow or vice versa; it would be most desirable if this conclusion could be confirmed or refuted by actual observations above the clouds.

4. Non-Raining Clouds

The charges in warm clouds which are not precipitating have been measured by a number of workers and, although there is some disagreement, the general results appear to be that the larger droplets more often carry positive charges and the smaller negative, the actual charges being only a few electronic units.

Some laboratory experiments by Barklie, Whitlock and Haberfield (1958) have shown that these charges are directly related to the presence of ions and this is in accord with theoretical work by Gunn (1955).

Though these effects provide the only separation of charge in clouds of this type, it seems unlikely that similar processes could be appreciable, compared with others, in clouds which give precipitation.

Another effect in non-raining clouds is that which is termed the "traffic-jam effect". Since the conductivity within a cloud is less than that outside, in order to maintain continuity of current across a cloud boundary, there must be a greater potential gradient within the cloud than outside, and this, in turn, means a region of space charge at the boundary.

5. Precipitation

Precipitation, as it reaches the ground, is usually charged; if the charge it carries is that which it has received in the cloud, then this is not to be considered separately from the problems of charge generation within the cloud; but if the charge on the precipitation has been altered as it falls, then the processes by which this occurs must be considered as separate. If precipitation is an important factor in charge generation in thunder clouds, then there must be a large change of charge during fall, since it is certain that the precipitation current reaching the ground is much smaller than it would be in the charge-generating region of the cloud.

When precipitation leaves the cloud, the only ways by which it would seem possible that it could acquire charge would be 1) melting 2) capture of ions and 3) shattering.

The fact that the charges and the potential gradients during snowfall differ from those during rainfall (see, for example, Chalmers 1956), show that it is likely that something occurs during melting and it is very desirable that more should be found out about this, both by observations during precipitation and, if possible, by laboratory measurements.

The "inverse-relation" between precipitation current and point-discharge current (Simpson 1949) can be explained if the precipitation acquires charge from the point-discharge ions and a more detailed consideration of this (Chalmers 1951) has shown fairly satisfactory results. For the correlation of rain current with potential gradient when there is no point discharge, the matter does not appear so simple and further work is required. At the time this is being written, work is in progress on the measurement of rain current simultaneously at the top and foot of a 60-foot tower; results and conclusions may be available by the time of the Conference.

Kelvin (1860) and Chauveau (1900) have found a change of sign of the potential gradient at the top and foot of a tower on certain occasions during rain, and this requires a negative space charge in the air below the top of the tower; measurements of charges due to splashing cannot entirely explain these results and it might be that shattering of rain drops occurs in this region.

6. The Electrode Effect

It is perhaps questionable whether the electrode effect should be included as a charge-generating process, since the actual charges concerned are only the ions produced by cosmic rays and radioactivity. But recent work has suggested that the electrode effect, and the convection of the charges separated by it, are of appreciable importance in the atmosphere.

The electrode effect comprises a space charge near an electrode, in the case of the atmosphere the earth's surface, and arises because there can normally be no ions leaving the electrode, so that the conductivity at the surface of the electrode is due to ions of one sign only. In normal fine-weather conditions, the electrode effect would give a positive space charge near the earth's surface; this is, in fact, found only in special conditions, e.g. over the Greenland ice-cap (Ruhnke, 1962) or over water (Mühleisen, 1961); in other cases it is reduced or absent because of higher ionization close to the earth.

7. Other Natural Sources of Charge

There are several other natural phenomena which give rise to charges in the atmosphere.

In blizzards, there are charges generated by, presumably, the impact of snow particles on one another and on the snow on the ground (Simpson 1919) and the same occurs in drifting snow. Obstacles such as wires become charged in a blizzard (Barré, 1953).

Dust-storms give rise to quite large electric potential gradients, sometimes even giving lightning (Rudge, 1914), and volcanos also give considerable effects to be ascribed to frictional effects of the ash (Hatekayama and Uchikawa, 1951).

It has long been known that positive charge is generated by the splashing of water, e.g. at waterfalls (Lenard, 1892); Mühleisen (1958) has found charge separation with change of humidity; there is evidence (Mühleisen 1959) for positive charges originating at the sea-shore in the breaking of the waves. Blanchard (1961) has found that positively charged particles move upwards from the sea surface, produced by the breaking of air bubbles in the sea.

It is probable that only the last two of these are likely to be of appreciable importance in the whole balance of charges in the atmosphere, but there is scope for more investigations of all these phenomena.

8. Artificial Sources of Charge

Mühleisen (1953) has investigated in detail the generation of charge by burning and other industrial processes and has found that different processes produce different signs of charge; the amounts of charge taken into the atmosphere may be quite appreciable. An earlier example of the same was the positive charge arising from locomotives (Kelvin, 1860).

Chalmers, (1952) found that negative charges can be liberated into the atmosphere from high-tension cables in conditions of high humidity when the insulation partially breaks down; sufficient charge is liberated to produce negative potential gradients several km. downwind.

Another example of an artificial source of charge is the observation of Moore, Vonnegut, Semonin, Bullock and Bradley (1962) who found positive space charge downwind of a television tower in fine weather; this they explained as due to the removal by wind of a space charge formed at the top of the tower by the electrode effect.

Deliberate attempts to produce space charges in the atmosphere by electric discharge have been made by Vonnegut and Moore (1958), Vonnegut, Maynard, Sykes, and Moore (1961) and Vonnegut, Moore, Stout, Staggs, Bullock and Bradley (1962).

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Session 4.1

CHARGE GENERATION IN THUNDERSTORMS

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Introduction

It is proposed that the principal mechanism of thunderstorm electrification involves the accretion, freezing and splintering of supercooled droplets on pellets of soft hail. Gravitational separation of the small positively-charged ice splinters and the much heavier negatively-charged hail pellets then produces an electric field of the observed polarity.

Evidence in support of this theory comes from: (i), observation of the disposition of electric charges and fields in thunderclouds; (ii), observed correlations between the appearance of soft hail and strong electric fields; (iii), laboratory observations that riming elements acquire a negative charge as positively-charged splinters are ejected from freezing drops; (iv), the discovery that this separation of charge arises from a basic property of ice, viz a protonic thermo-electric effect which has been investigated experimentally and theoretically in some detail; (v), application of the laboratory results on the rate of charging of artificial hail pellets to a model thunderstorm which reveals that the proposed mechanism is capable of producing and separating charge at the rate required by observations on lightning flashes while other mechanisms appear to work much too slowly. These arguments will now be presented in more detail, but first it seems worthwhile to list the more important and relatively undisputed features of the thunderstorm with which any satisfactory theory of electrification must be consistent.

2. Requirements of a satisfactory theory of thunderstorm electrification

The theory must explain quantitatively how electric charge is generated and separated in a thundercloud at a rate equivalent to that at which it is dissipated in lightning flashes. It must account for the observed polarity of the thunderstorm and be consistent with what is known about the electrical and dynamical structure of the storm, the nature of the electrical field changes accompanying lightning, the size and duration of the storm, and the nature, scale and intensity of the precipitation processes which are generally considered to be closely correlated with the electrical activity. More specifically, the theory must be consistent with the following facts:

(i) The average duration of precipitation and lightning from a typical single thunderstorm cell is about 30 min.

(ii) The average electric moment destroyed in a lightning flash is about 100 C.km, the corresponding charge being 20-30 C. A typical cell produces flashes at intervals of about 20 sec so the average lightning current is about 1 amp.

(iii) The magnitude of the charge which is being separated immediately after a flash, by virtue of the falling speed of the precipitation elements, is of order 1,000C.

(iv) In a typical cell this charge is generated and separated in a volume bounded by the 0 and -40°C levels and having a typical radius of 2 km and therefore a volume of about 50 km^3.

(v) The negative charge is centred near the -5°C level, while the main positive charge is situated some kilometres higher up; a subsidiary positive charge often exists near cloud base where the temperature is usually a little warmer than 0°C.

(vi) Sufficient charge must be generated and separated to supply the first lightning flash within 10-20 min. of the first appearance of precipitation particles large enough to produce a radar echo.

In round figures, the requirement is to generate about 1000 C of charge in a volume of about 50 km^3 in a period of about 20 min. i.e. at an average rate of 1 $C/km^3/min$.

3. Observational evidence for an ice mechanism

(i) Lightning is usually accompanied by heavy precipitation although, in warm, dry climates, this may not reach the ground. Most theories on the origin of the electric charge have assumed that the precipitation plays an important role, and as the main charge centres appear at levels in the cloud where the temperature is below 0°C, it is natural to associate that generation with the presence of supercooled water and/or the ice phase.

(ii) Kuettner (1950), from observations made inside thunderclouds capping the Zugspitze in Germany, reported that solid precipitation elements were predominant in the greater part of the thundercloud and were present on 93% of the occasions. Snow pellets and pellets of soft hail were the most frequent form of hydrometeor being present on 75% of occasions but large hail was relatively rare.

(iii) Fitzgerald and Byers (1962), using aircraft fitted with electric-field meters, have reported that the actively building regions of thunderstorms are regions of excess negative charge. The strongest fields, of up to 2300 V/cm, were associated with regions of heavy precipitation. In particular, a large hail shaft produced a strong, smoothly increasing field indicating a negative charge on the hail.

(iv) Malan and Schonland (1951, a, b) find that, in South African storms, the negative charge is often distributed in a nearly vertical column which may extend up to but not beyond the -40°C level. This is consistent with the charge being generated by growing hail pellets because supercooled droplets exist at temperatures down to, but not below -40°C.

4. The charging of rime deposits

In recent years, several workers have reported that when supercooled water droplets impinge and freeze on an ice surface, the resulting layer of rime acquires a substantial charge. The experimental results, which have been reviewed by Mason (1957), may be summarized as follows.

Findeisen (1940, 1943) formed a rimed layer by spraying water droplets on to a cold metal surface and found that it acquired a positive charge. The charging ceased if the surface became smooth and glassy, as was the case if the drops froze slowly, or if it became wet. Rather stronger charging was obtained with a natural supercooled cloud than with an artificial spray, the difference being ascribed to more rapid freezing of the smaller cloud droplets. The rate of charging in the cloud was 3×10^{-13} C cm^{-2} s^{-1}.

In a later investigation, Kramer (1948) found the rime deposit acquired a <u>negative</u> charge which increased in proportion to the impact velocity of the droplets. With a velocity of 0.5 m s^{-1} the charging rate was 2×10^{-14} C cm^{-2} s^{-1} and, for a velocity of 5 m s^{-1}, ten times larger.

Lueder (1951 a,b) made experiments in natural supercooled clouds on a mountain top in order that the contaminants in the water should be those occurring in nature. He states that the growing rime deposit acquired a negative charged, an equal positive charge being communicate to the air, probably on the parts of the drops which were flung off without freezing. Unfortunately, it is difficult to interpret his experiments and to deduce the actual rate of charging.

Meinhold (1951) measured the electric field strength at the surface of the fuselage of an aircraft flying at 80 m s^{-1} through a supercooled cumulus congestus cloud. The deposition of rime was accompanied by a rapid rise in the field strength in a sense which indicated that the aircraft was acquiring a negative charge, and the rate of charging was calculated to be 5×10^{-12} C cm^{-2} s^{-1}.

The charging of a rime deposit on a cold metal surface was also studied by Weickmann & aufm Kampe (1950). Water droplets in the diameter range 5 to 100μ were sprayed at velocities varying from 5 to 15 m s^{-1} on to a metal rod of 5 mm diameter in a cold room kept at either -5 or -12°C; they were therefore slightly supercooled on reaching the rod. The rate of charging, which was not sensitive to the presence of dissolved salts, increased with increasing velocity of the air stream, and for a velocity of 15 m s^{-1}, attained a value of

5×10^{-12} C cm^{-2} s^{-1}. When water at temperatures slightly above $0^{o}C$ was sprayed on to the rod it acquired a slight positive charge. Later the authors indicated that the results of these experiments may have been seriously affected by electrification associated with the production of the spray.

The balance of the evidence from all these experiments points to the acquisition of a negative charge by a growing layer of rime, Findeisen's result being an outstanding contradiction. In light of the recent experiments of Latham and Mason (1961), described below, it now appears that some of the differences between the results of different workers may be ascribed to the use of differing drop sizes, temperatures, and impact velocities, while spurious effects may arise from initial charging of the spray droplets and electrification produced by the splashing of droplets on the ice surface.

5. The splintering and electrification of freezing water drops.

Some evidence for the production of charged splinters by a growing rime deposit was obtained by Kramer (1948), and their production during the freezing of individual water drops was investigated in detail by Mason and Maybank (1960).

Nucleation of a water drop, at temperature $-T^{o}C$, is followed by rapid solidification of a fraction T/80 of its mass in the form of an ice shell. Subsequent freezing of the liquid interior now proceeds at a rate determined by the dissipation of the latent heat to the surroundings. The expansion which accompanies this freezing sets up stresses in the ice shell which may disintegrate to produce a number of ice splinters. Mason and Maybank found that, for drops suspended in still air, the number of splinters produced was almost independent of the drop diameter in the range 0.1 to 2 mm but that for drops of diameter $< 60\mu$, splinter production was much reduced. They also measured the charges on the residues of fragmenting drops. If only a minor fraction of the drop was blown off the residue was invariably negatively charged. Typically, a drop of 1 mm diameter freezing at -5°C produced about 20 splinters and acquired a negative charge of about 10^{-4} e.s.u.; a similar drop freezing at -15°C produced about 5 splinters and acquired a charge of about 3×10^{-5} e.s.u. The average positive charge per splinter was therefore 5×10^{-6} e.s.u. These experiments suggested an explanation for the electrification of growing rime deposits and that a similar mechanism operating during the growth of hail pellets might be an important factor in the electrification and ice-crystal economy of clouds.

6. Charging associated with the growth of soft hail pellets.

Latham and Mason (1961) measured the electrification of artificial pellets of soft hail as they grew by the accretion of supercooled water droplets, and determined how this varied with the temperature, size and impact velocity of the drops.

The experiments were conducted in a cold room, at air temperatures ranging from 0°C to -17°C, with the apparatus shown in Fig. 1.

The hailstone, simulated by a 5 mm diameter, electrically insulated, copper sphere coated with a $\frac{1}{2}$ mm layer of ice, was suspended in the centre of an earthed vertical brass tube through which the air stream carrying the droplets could be drawn at velocities ranging from 0 to 30 m s^{-1}. Water drops of uniform diameter in the range 20 to 90μ produced by the spinning-top apparatus of Walton & Prewett (1949), or rather larger drops produced by an atomizer, were allowed to fall several feet in the cold room where they became supercooled to very near the air temperature before reaching the hailstone target. For a given droplet size and air-stream velocity, the flux of droplets hitting the target was determined by allowing them to strike, for a given time, a Formvar-coated glass sphere of the same dimensions, and counting the droplet impressions under the microscope. The impaction and freezing of the droplets was accompanied by the ejection of ice particles from the target surface; their number and sizes were determined by inserting Formvar-coated slides just beneath the hailstone and later examining the plastic replicas of the crystals.

The electric charge accumulating on the hail pellet during the freezing of droplets on its surface was measured by a Vibron vibrating-reed electrometer of resistance $10^{12}\Omega$ and time constant 200 s. The minimum detectable charge was about 5×10^{-4} e.s.u.

The surface temperature of the target, measured by a thermocouple, was higher than that of the surrounding air because of the latent heat released by the freezing drops and could be raised artificially by irradiating the surface with the beam of a 50 W tungsten lamp.

The experimental operations, which could be performed from outside the cold room, consisted of setting the cold room (air) temperature, the air-stream velocity and the drop size and reading the electrometer after the target had been exposed to the droplets for a known time, usually 10 s. Then the effect, on the rate of charging, of raising the surface temperature of the hailstone (this being previously calibrated in terms of the air speed and the current supplied to the lamp) was investigated. Meanwhile, slides for collecting the ice crystals shed by the target were inserted at regular intervals. The whole procedure was then repeated for a different set of conditions.

The freezing of droplets of distilled water on the surface of the hailstone caused it to become negatively charged and was accompanied by the ejection of small ice splinters. The manner in which the average charge and number of splinters produced per drop varied with the drop diameter, impact velocity and air temperature is shown in figures 2, 3 and 4.

In a typical experiment, with the air temperature at -15°C and the air stream moving at 10 m s^{-1}, 10^4 drops of diameter 80μ struck the hailstone within 10 s and produced a total charge of 4×10^{-2} e.s.u., i.e. an average charge of 4×10^{-6} e.s.u. per drop. On average, each droplet produced 12 ice splinters; their mean diameter on collection was 20μ but they were probably smaller on ejection and had grown in the meantime.

Droplets of $d < 30\mu$ produced few splinters and little charging. Figure 2 shows that the production of both was enhanced as the droplet diameter was increased to about 50μ, remained fairly constant for diameters between 50 and 80μ, and fell again for still larger drops. These results are in fairly good agreement with those which Mason and Maybank (1960) obtained for individual droplets suspended on fibres except that they did not observe a reduction in splintering for large drops. This tendency, in the present experiments, may be explained by the fact that, in impinging at several metres per second, the larger drops shattered before freezing and that splashing communicated a positive charge to the ice target in the manner observed originally by Faraday and more recently by Gill & Alfrey (1952). Positive charging of the target at high impact velocities is shown in figure 3; this occurred although there was still a considerable production of splinters.

As shown in figure 4, the rates of charge and splinter production are almost independent of the air temperature in the range -6 to -17°C but both fall off rapidly at higher temperatures and, in our experiments, were no longer detectable at -2°C. The explanation is as follows. The impacting droplets can be frozen only at a rate determined by the rate of dissipation of their latent heat to the environment; at air temperatures close to 0°C the rate of freezing was slow and consequently the hailstone surface became wet and, as the replicas showed, considerable splashing occurred as the drops struck it.

A number of tests were carried out to make sure that charging of the hailstone was due entirely to the collision and freezing of the droplets. No detectable charging occurred when the air stream carried no droplets and when droplets, impacting at very low velocity, froze on the surface without producing splinters. The parallelism between the curves of charge and splinter production in figures 2 to 4 is, perhaps, the strongest evidence for the one being a consequence of the other.

Irradiation of the hailstone by the lamp caused a reduction in the rate of charging. For example, with the air temperature at -12°C, raising the surface temperature of the hailstone by 2°C reduced the rate of charging by about 20%; when the surface was warmed by 5°C, the charge production was halved; but, in both cases, the rate of splinter production was not appreciably altered.

When the impinging water droplets were contaminated with sodium chloride in concentration corresponding to the average found in cloud water (3.6 mg/l.), the rate of charging was decreased by about 20%.

These experiments appear conclusive in showing that the negative charging of the hailstone is caused by the ejection of small splinters of ice during the freezing of droplets on its surface. The influence of droplet size and the presence of salt are in fair agreement with the observations of Mason and Maybank apart from the effects which were produced by splashing of large drops.

In a later paper, Latham and Mason (1962) reported that when the above experiments were repeated in the presence of an external electric field the charging rates of the hailstones were altered by only about 10 per cent by application of fields of $\sim 1000 \text{ V cm}^{-1}$. The inference is that the charging of hailstones will not be greatly accelerated by the cumulative build-up of polarizing fields in thunderstorms.

7. Application of laboratory results to computation of the production of charges and electric fields in a model thundercloud.

We consider a thunderstorm in which above a level Z_o the updraught U contains an exponential size spectrum of hailstones such that the concentration of stones within the radius interval R to R + dR is

$$N(R)\,dR = N_0 \exp(-\Lambda R)\,dR, \qquad (1)$$

where N_o and Λ are constants indepdndent of position in the updraught.

Since splinters and charge are produced only by the freezing of droplets on the surfaces of hailstones which remain dry, we write the fractional volume $F_D(z)$ swept out per unit time by the dry hail at level z as

$$F_D(z) = \int_0^{R_c(z)} \pi R^2 \, V(R,z) \, N(R) \, dR, \qquad (2)$$

where V is the hailstone fallspeed and $R_c(z)$ is the critical radius at which a hailstone becomes wet at level z. We now assume that this flux of dry hail encounters a concentration n(z) of supercooled droplets of radii greater than 25μ; smaller droplets produce few splinters and little charge. Since these droplets are continually being swept up by the entire spectrum of hailstones, their concentration will decrease with increasing height according to

$$n(z) = n_0 \exp\left(-\int_{z_0}^{z} \frac{F(z)}{U(z)} \, dz\right), \qquad (3)$$

where n_0 is the concentration of drops at z_0 and F(z) refers to the entire hail spectra.

The total rate of charge production between levels z_0 and z owing to the impaction, freezing and splintering of large cloud droplets on dry hail is then given by

$$\frac{dQ}{dt} = A n_0 q_d \int_{z_0}^{z} F_D(z) \exp\left(-\int_{z_0}^{z} \frac{F(z)}{U(z)} \, dz\right) dz, \qquad (4)$$

where A is the mean cross-sectional area of the updraught and q_d is the average charge produced by the freezing of a drop of $r > 25\mu$.

We have seen that a typical single-cell storm generates about 1000 coulombs of charge in about 20 min., i.e. at an average rate of about 1 amp. Putting $\frac{dQ}{dt} = 1$ amp $= 3 \times 10^9$ e.s.u., $A = 9\pi \times 10^{10}$ cm^2 (a mean radius of 3km for the cell), $q_d = 4 \times 10^{-6}$ e.s.u. (Latham and Mason 1961), and values of F_D and F based on the observations of Atlas and Ludlam (1961) for a storm having an updraught increasing linearly with height according to $U(z) = 5(z-1)$ m sec^{-1} with z measured in km and a liquid water content of 3 gm^{-3}, we find $n_0 = 5$ cm^{-3}.

This does not seem an unreasonable value since droplets of $r > 25\mu$ have been found in concentrations exceeding 1 cm^{-3} in rather small cumulus (Durbin 1956), while concentrations of 5 cm^{-3} in Cb have been observed by Weickmann and aufm Kampe (1953).

The corresponding concentration of splinters, assuming a freezing drop to produce on average, 10 splinters, is calculated to be about 1 cm^{-3} between the -20°C and -30°C levels (Browning and Mason, 1963). This, too, seems a reasonable figure.

The rate of building of the vertical electric field E by separation of the hail pellets and ice splinters is given by

$$\frac{d^2E}{dt^2} + \beta\frac{dE}{dt} = -4\pi n q_d \sum^{\ell} \pi N(R) R^2 V^2(R) \qquad (5)$$

$$= -3\pi (p/\rho_i)(\bar{V}/\bar{R}) \qquad (5a)$$

where β represents the leakage of charge through point-discharge and conduction currents, p the precipitation intensity, ρ_i the average density of the ice particles, $\bar{V}$ and $\bar{R}$ are respectively weighted mean values for the fall speed and mean radius of the hailstones. For particles sizes ranging from R = 0.1 mm to 1.0 mm, $\bar{V}/\bar{R}$ = const = 8500. If we assume that the precipitation intensity increases rather rapidly with time at first, and then levels off at a value p_m which is maintained for several minutes, we may write $p = p_m(1 - e^{-\alpha t})$ and Eq 5(a) becomes

$$\frac{d^2E}{dt^2} + \beta\frac{dE}{dt} = \delta(1 - e^{-\alpha t}), \qquad (5b)$$

where $\delta = -3\pi \times 8500 \times \left(\frac{n_d q_d}{\rho_i}\right) p_m$.

The solution of (6) with the conditions E = 0 and $dE/dt = 0$ when t = 0 is

$$E = \delta\left[\frac{t}{\beta} - \frac{\alpha+\beta}{\alpha\beta^2} + \frac{1}{(\beta-\alpha)}\left(\frac{e^{-\alpha t}}{\alpha} - \frac{\alpha}{\beta^2}e^{-\beta t}\right)\right]. \qquad (6)$$

Taking $\beta = 2 \times 10^{-3}$ e.s.u. and $p_m = 5$ cm hr^{-1}, $\rho_i = 0.5$ g cm^{-3} $\frac{1}{\alpha} = 600\,s$, $n_d = 1$ cm^{-3} and $q_d = 4 \times 10^{-6}$ e.s.u., Eq (6) predicts that the field will reach a value of 9400 V cm^{-1} within 10 min of the appearance of precipitation elements. But, before large-scale fields of this magnitude are reached, lightning discharges will almost certainly occur and destroy the field. However, it appears that the accretion, freezing and splintering of supercooled droplets on hail pellets can readily account both for the production of charge in thunderstorms and for the generation of large-scale fields of several thousand volts per cm during periods of about 10 min.

If the field were destroyed by a lightning flash but the soft hail continued to fall at a steady rate ρ_m , the field would recover at a rate given by

$$\frac{d^2E}{dt^2} + \beta \frac{dE}{dt} = \delta \qquad (7)$$

or

$$E = \delta\left(\frac{t}{\beta} - \frac{1}{\beta^2}\right) + \frac{\delta}{\beta^2} e^{-\beta t} \qquad (8)$$

With β and δ taking the same values as above, the field would build up again to 4000 V cm^{-1} in 30 s, which is about the average interval between lightning flashes from a modest single-cell storm.

8. The basic mechanism of charge-separation during the freezing and splintering of droplets.

The fundamental problem is to explain how the electric charge can be separated during the bursting of a freezing drop and why the splinters are ejected with a positive charge leaving a negative charge on the hailstone. Mason and Latham (1961) have proposed that this is a manifestation of a protonic thermo-electric effect in ice by which the hydrogen and hydroxyl ions formed by the dissociation of a small fraction of the ice moleculees become separated under the influence of a temperature gradient.

The process depends essentially on two facts. One is that the concentrations of positive and negative ions increase quite rapidly with increasing temperature; the other, that the hydrogen ion (proton) diffuses much more rapidly through the ice crystal than does the hydroxyl ion (Eigen and de Maeyer, 1958). Thus, if we imagine a steady temperature difference maintained across a piece of ice, the warmer end will initially possess higher concentrations of both positive and negative ions. The more rapid diffusion of H^+ ions down this concentration gradient leads to a separation of charge, with a net excess of positive charge in the colder part of the ice. A detailed theoretical treatment by Mason ~~and Latham (1961~~) leads to the following expression for the potential V produced by a temperature difference T across the ends of an ice specimen

$$V = \frac{k}{2e} \frac{(\upsilon_+/\upsilon_- - 1)}{(\upsilon_+/\upsilon_- + 1)} \left\{ \frac{\phi}{kT} + 1 \right\} \Delta T \qquad (9)$$

$$= 1.86\, \Delta T \qquad \text{millivolts}$$

where υ_+, υ_- are respectively the mobilities of the H^+ and OH^- ions, $\upsilon_+/\upsilon_- = 10$, e the electronic charge, k Boltzmann's constant, $\phi = 1.2$eV the activation energy for dissociation in ice and T is the absolute temperature. Latham and Mason (1961) have measured the potential differences across specimens of pure ice and find excellent agreement with Eq. (9). Moreover, the potentials are not markedly affected by the presence of dissolved salts and gases in the ice.

When two pieces of ice at different temperatures are brought into temporary contact and separated, the warmer piece acquires a negative charge and the colder one an equal positive charge . Theory indicates that there should be a maximum charge separation of $5 \times 10^{-5} \Delta T$ e.s.u. between each cm^2 of contacting surface when the surfaces are separated after about 0.01 sec. If they are left in contact for longer times, the charge separation will be decreased as the two pieces of ice become more nearly equal in temperature. These conclusions have been confirmed by experimental measurements that show that very little charge separation occurs if the contact period exceeds 0.5 sec.

The electrification of freezing water droplets is explained by the preferential migration of protons down the temperature gradient established across the ice shell. During the early stages of freezing, a radial temperature gradient is established across the ice shell, the inner surface being held at $0^{\circ}C$ by the water that is still liquid inside, the outer surface cooling towards the air temperature. According to the above theory, protons will migrate preferentially down this temperature gradient and produce an excess positive space charge in the outer layers of the ice. When the droplet bursts by the expansion of the centre as it freezes, splinters ejected from the outer layer will tend to carry away a positive charge and leave the remainder of the drop negatively charged. This is in accord with the experimental observations.

It is difficult to calculate the temperature gradient across the ice shell, which varies with time, and therefore the space charge density in the outer layers at the time of rupture. During the formation of the initial shell, the temperature of the drop is everywhere 0°C; as freezing of the interior proceeds, a temperature gradient is built up; when freezing is completed the droplet finally assumes the air temperature everywhere and again the temperature gradient disappears. However, near the end of the freezing process, when the centre of the drop is still 0°C and the temperature of the outer surface close to that of the air, we may take the average temperature gradient across the ice to be T_a/r. In fact, shattering usually occurs before this late stage but we may use this value of the gradient to calculate a minimal value for the separated charge. According to Eq. (9), this will be $4\pi r^2 \cdot 5 \cdot 10^{-5} T_a/r$ e.s.u. If $T_a = -15^\circ C$ and $r = 40\mu$, this becomes 4×10^{-5} e.s.u. If r = 0.5 mm, the charge becomes 5×10^{-4} e.s.u. Thus the measured charges of 5×10^{-6} e.s.u. and 3×10^{-5} e.s.u. could be accounted for by the fragmentation of one-tenth of the surface area of the drops.

The Reynolds-Brook Charging Mechanism

Reynolds (1954), Reynolds, Brook and Gourley (1957), have attributed the negative charging of hailstones not to the freezing and splintering of droplets but to collisions between the hailstones and much smaller ice crystals. Laboratory experiments in which an ice sphere was rotated in a mixed cloud of ice crystals and supercooled droplets showed that the sphere acquired a negative charge;

but if the cloud was composed entirely of droplets or entirely of crystals, there was negligible charging.

Reynolds believed that charging was caused by rubbing contact between the simulated hail pellet and the ice crystals which bounced off with a positive charge, and that the sole function of the freezing droplets was to warm the rimed surface and to create a temperature difference between it and the colliding crystals. It was estminated that, with a temperature difference of a few degrees, the average charge carried away by a crystal of radius 50μ was 5×10^{-4} e.s.u.

Following up these ideas, Reynolds, Brook and Gourley (1957) investigated the electrification which resulted from rubbing contact between two rods of ice of different temperatures. When both pieces of ice were formed from distilled water, their resistivity being about $10^8\ \Omega$ cm, the warmer became negative after rubbing. If, however, one of the ice specimens was made from a 10^{-4} molar solution of NaCl it became negative even though it was 25°C colder than the 'pure' ice. This reversal of potential was attributed to the formation of a liquid layer during rubbing and, on refreezing, a selective incorporation of Cl^- ions into the colder ice. Later, Brook (1958) investigated the potentials developed when two pieces of ice of different temperatures are brought into temporary contact and separated with a minimum of frictional contact. The sign of the charging was related to that of the temperature gradient, for both 'pure' and 'salty' ice, in the same manner as before, but the potentials were an order of magnitude smaller than those developed during rubbing contact.

These phenomena have been re-investigated by Latham and Mason (1961, a, b). They found, in agreement with Reynolds et al, that when two pieces of highly purified ice were brought into temporary contact (with minimum friction) and separated, the warmer acquired a negative charge. A theoretical calculation based on the protonic thermo-electric effect, indicated that a maximum charge transfer of $3 \times 10^{-3}\ \Delta T$ e.s.u. cm^{-2} should occur with a contact time of about

1/100 sec. and that it should thereafter decline as the two pieces become more nearly equal in temperature. The theoretical value for the charge developed for a contact time of ~ 1/100 sec. was well confirmed by experiments which also showed that very little charge separation occurred if the contact period exceeded ½ sec. Contamination of the ice with CO_2, HF, and NaCl in concentrations of up to 50 times that normally present in rain-water, did not greatly influence the electrification.

Latham and Mason also investigated the charging of a simulated hailstone by collisions with ice crystals. In order to eliminate charging by the freezing of supercooled droplets, these were rigidly excluded from the cloud, and the surface temperature of the hailstone was controlled by an internal electric heater or by irradiating its surface. Charging of the hailstone by the colliding crystals was measured as a function of their temperature difference, and of the size and impact velocity of the crystals. The sign of the charging was directly proportional to the temperature difference but rather insensitive to the size (diameter ranging from 20μ to 50μ) and impact velocity (1 to 30 m sec^{-1}) of the crystals. With a temperature difference of 5°C, a rebounding crystal of diameter 50μ produced, on average, a charge of 5×10^{-9} e.s.u.

This is five orders of magnitude smaller than Reynold's value of 5×10^{-4} e.s.u.!

Reynolds' value may be questioned on two grounds. First, the field produced by such a charge at the crystal surface would exceed 10,000 V cm^{-1}; surely a discharge would occur between the pointed crystal and the hail pellet before the charge on the crystal could build up to this value.

Secondly, the charge of 5×10^{-4} e.s.u. is about 1000 times greater than that of all the charged carriers that would be present in the ice crystal if this were pure ice! Additional carriers might be produced as the result of local frictional heating of the ice at the points of contact but even if the <u>whole</u> ice crystal fall in a vertical electric field and collide with the much smaller cloud-droplets that they overtake. The raindrop will be electrically polarized by the field; in a downwardly directed field such as exists in the atmosphere in fine weather, the lower half of the drop will carry a positive charge and the upper half an equal negative charge. Elster and Geitel suggested that, after collision, some of the cloud particles would rebound from the underside of the raindrop, carry away some of its positive charge, and leave the raindrop with a net negative charge. The falling drops, in carrying their negative charge towards the base of the cloud, would enhance the original field, and so the whole electrification process would build up rapidly. A detailed mathematical treatment of the problem shows that if only one per cent of the cloud droplets striking the lower half of the raindrops were to bounce off, and if this percentage were independent of the electric field strength, the field would grow exponentially with time and, in a cloud producing rain at the rate of 1 cm/h, would reach 1000 times its initial fine-weather value in only 10 minutes.

Now laboratory experiments indicate that, in the absence of an electric field, the fraction of cloud droplets that actually rebound after striking raindrops is small; the great majority of collisions result in coalescence. However, no experiment sufficiently accurate to detect non-coalescence to the extent of only a few per cent has yet been performed. This problem, which becomes complicated further by the presence of electric fields and of free charges on the drops, is now being studied by the author. It has been found that although droplets of 50-100 μ diameter may rebound after striking an uncontaminated plane surface of water or a much larger drop, they can always be made to coalesce by applying vertical fields of only about 10 volts per cm. The droplets become distorted as they approach the water surface, small protuberances develop at their ends in the direction of the field, and complete coalescence occurs, probably because small electric discharges occur at the protuberances and cause rupture of the intervening air film. This suggests, perhaps, that once fields of about 10 V/cm are established in the cloud, coalescence between colliding cloud droplets and raindrops is assured. In this case the Elster-Geitel charging mechanism will cease long before fields strong enough to initiate lightning are produced.

At the present time we are unable to suggest a mechanism that would convincingly account for the origin of lightning in clouds consisting wholly of liquid water. But there is strong evidence in favour of the riming-hailstone mechanism being the dominant one in the typical large thunderstorm.

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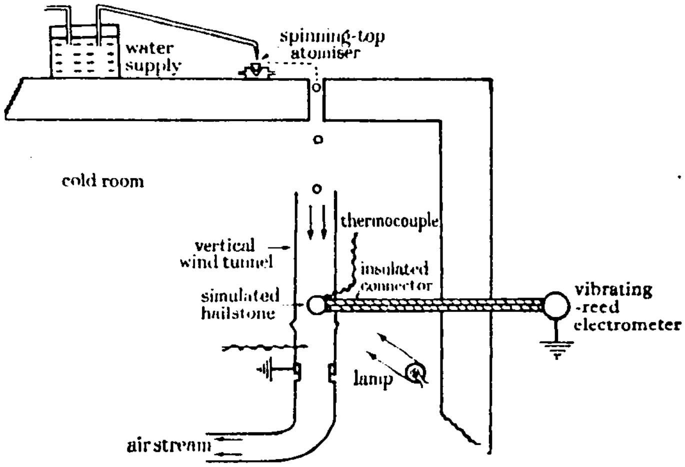

FIGURE 1 Apparatus for measuring the charge on hail pellets growing by riming.

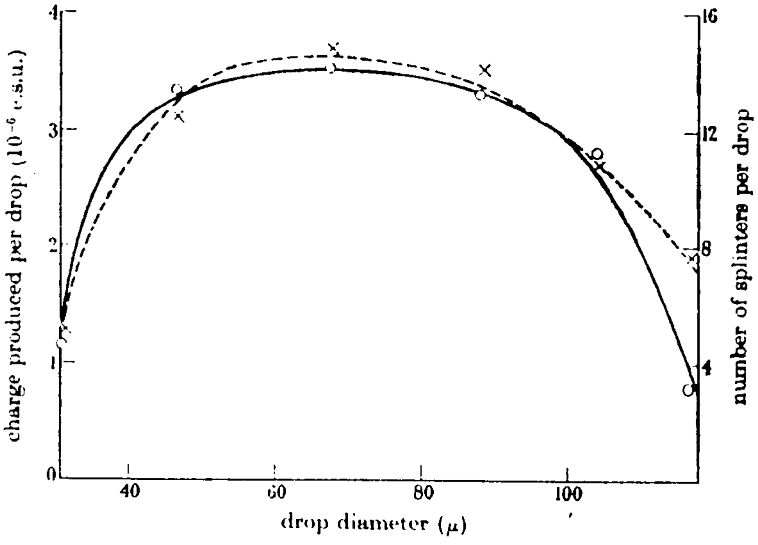

FIGURE 2 The production of ice splinters (×) and electric charge (○) as a function of the diameter of the freezing droplets. Air temperature, −15 °C; air velocity 10 m/s.

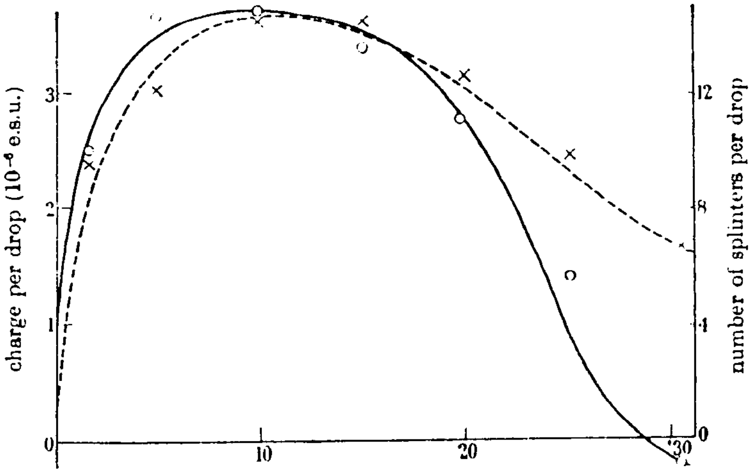

FIGURE 3 Splinter (×) and charge (○) production as a function of the impact velocity of the droplets. Air temperature, −15 °C; drop diameter, 70 μ.

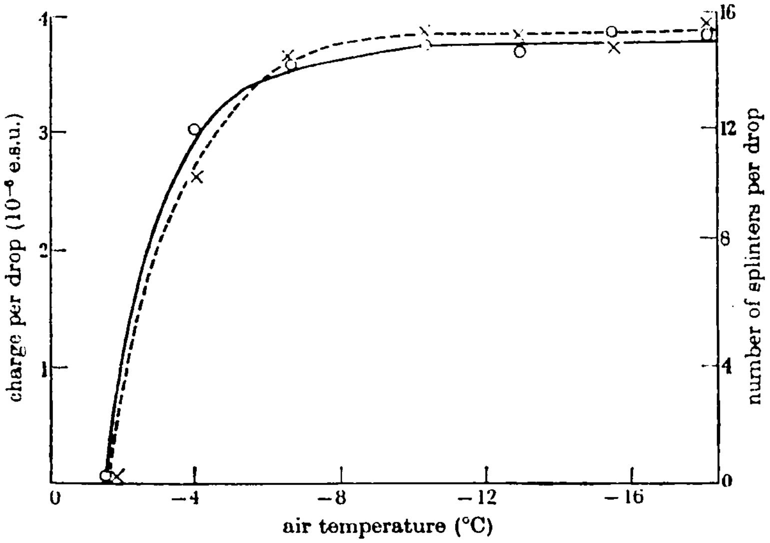

FIGURE 4 Splinter (×) and charge (○) production as a function of the air temperature. Air velocity 10 m/s; drop diameter, 70 μ.

SESSION 7.1

THE THEORY OF LIGHTNING

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The title of this discussion covers a very wide field since a discussion on any aspect whatsoever of the lightning discharge or its manifestations involves a certain amount of theorizing.

I shall confine this talk firstly to the theory of the stepped leader, and shall then discuss discharge processes taking place inside and above the cloud.

Experimental data on the latter processes are extremely scanty so that the suggested mechanisms are mostly speculative and as such fall in the realm of theory.

THE THEORY OF THE STEPPED LEADER.

Very little new information based on photography of the stepped leader of a lightning flash has materialized since its discovery about thirty years ago. Photographic studies of laboratory sparks on the other hand have yielded a large amount of new information but difficulties arise when attempts are made to apply the knowledge gained to the leader of a lightning stroke. A case in point is the recent work of Stekolnikov and Shkilyov (1962) who used an image converter tube to photograph negative rod-to-plane sparks. They state that the bright steps they photographed

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are impulse corona discharges and are not preceded by a pilot streamer, from which they conclude that the leader process in laboratory sparks is different from that of natural stepped leaders.

Apart from the observation that the bright step is not accompanied by a pronounced steplike electrostatic field change, electrical studies of lightning have given little information which can be usefully applied to stepped leader theory.

In studying the radiation fields of flashes in the distance range of 50 km., both Clarence and Malan (1957) and Kitagawa (1957) found that when the stepped leader approaches the ground, radiation pulses follow one another at intervals of the order of 10 μsec. Kitagawa ascribes these pulses to short interval leader steps. Clarence and Malan, however, conclude that since the radiation field comes from the whole lightning channel, intracloud streamers which take part in supplying current to the advancing leader also contribute to the radiation pulses. The evidence for this conclusion is based on the observation that of the numerous stepped leaders photographed by us, none except perhaps the last step, show intervals as short as 10 μsec between steps. Furthermore, we also argued that because exactly similar short interval pulses are often observed to precede strokes subsequent to the first, it is evident that all the pulses need not necessarily originate in a stepped leader process.

The question now arises: which explanation of the

profuse /.....

profuse radiation pulses is the correct one? The answer to this question is important from the point of view of stepped leader theory. It is especially necessary to have conclusive evidence showing whether dart leaders are propagated by short steps or continuously.

The latest attempt to formulate a stepped leader theory known to the speaker is that of Wagner and Hileman. The theory of these authors is a sort of combination of the well-known earlier theories of Schonland, Bruce and Komelkov. Wagner and Hileman distinguish between the channel which consists of a 2 mm. diameter highly conducting arc plasma and a surrounding corona sheath of diameter about 30 m. When the channel is arrested a space charge develops in front of it, being fed by a multitude of filamentary streamers. At some instant the current in one of the filaments reaches a critical value of 1 ampere when an arc plasma begins to develop from the tip of the channel. This filament now robs the other space charge filaments of their charge and emerges as the new channel (or step).

According to Wagner and Hileman the intensity of the current at any point along the advancing step rises suddenly when the tip of the newly formed arc plasma reaches that point and thereafter remains constant until the tip has reached its maximum extension. The current which remains at about 1 ampere at the starting point of the step increases uniformly along the new channel to reach a maximum value of about 7000 amperes at the tip of the fully

developed /.....

developed step. At any point the product of current and duration of current flow is constant during the advance of the step.

The assumption that the current which flows in the plasma channel during step formation is mainly derived from the surrounding space charge can explain why the bright step produces practically no sudden electrostatic field change although it carries a heavy average current.

THE POSSIBLE EFFECT OF HEAVY RAIN ON THE STEPPED LEADER PROCESS.

It has been postulated that the preliminary electrical breakdown in the base of the cloud takes place by the mechanism of filament formation on large water drops. In a heavy thundershower the base of the cloud virtually extends down to ground level. The question now arises as to what extent, if any, heavy rain is likely to affect the stepped leader breakdown to earth.

Let us first consider the information available from the radiation fields occurring immediately before first strokes of flashes to ground. When using very high amplification, radiation pulses which may be ascribed to stepped leaders, can be detected in practically all cases. For a very large percentage of flashes the radiation pulses are surprisingly small, however. Does this indicate that the breakdown process for flashes in rain is a hybrid between the ordinary stepped process and the filamentary process, or can the effect be wholly attributed to the low

radiation /.....

radiation propensities of stepped leaders in general, or as first suggested by Pierce, are stepped leaders totally absent ?

Let us now consider the photographic evidence. Under favourable conditions for photography all flashes show stepped leaders. By favourable conditions it is meant that the flash is not obscured by rain or that the stray light scattered from rain has not caused overall blackening of the picture. It is obviously almost impossible to photograph a faint stepped leader in heavy rain, except perhaps when the flash is very near indeed.

Berger has taken many pictures of flashes in close proximity but has only obtained pictures of stepped leaders on very few occasions. It will be interesting to hear from professor Berger whether the absence of stepped leaders on so many of his photographs bears any relation to the intensity of rainfall while taking the photographs.

THE MECHANISM OF INTRA-CLOUD DISCHARGES.

It can be confidently concluded that intra-cloud discharges are not propagated by a stepped leader process because these discharges do not emit the radiation pulses which are characteristic of stepped leaders.

In regions near the base of the cloud where there are large water drops, the discharge can be propagated by the process of filament formation when the field reaches 10 kV/cm, provided that the diameters of the drops exceed 2 mm. At high altitudes in the cloud where its content

may /.....

may consist of ice particles and droplets smaller than 2 mm., or of ice particles alone, this process can no longer take part in propagating the discharge. The following is a tentative explanation of the mechanism of the discharge process at high levels.

The droplets and also ice particles, as Chalmers (1947) has shown, will become polarized in the electric field. When the field between a neighbouring pair of droplets or ice particles reaches a value of about 30 kV/cm (the exact value depending on the pressure), electrical breakdown occurs. The discharge is subsequently carried forward from particle to particle, probably in a channel of large cross-section.

The presence of discrete pockets of high charge density in fairly close proximity to each other will cause the tip field to increase rapidly with the advance of the streamer so that it is not arrested as in the case of the stepped leader to ground. Furthermore, if this is the case it may not be necessary for the tip field to build up to 60 kV/cm which, according to Schonland, is the field required to produce the thermal ionization required for the progress of a stepped leader.

PROCESSES CONTRIBUTING TO INTERSTROKE FIELD CHANGES.

There are several factors which can contribute to the change of electric field as observed at ground level during the intervals between the strokes of a flash to ground.

Effect /.....

Effect of space charge below the cloud.

A re-arrangement of space charge between the base of the cloud and the ground will influence the field in close proximity to the flash. However, since the conductivity of the air near ground level is small the relaxation time is long which makes it unlikely that this effect will contribute noticeably to the field changes observed during the short time intervals between the successive strokes of a flash.

Effect of transient changes in the charging process.

The separation of charge in the cloud under the influence of gravity is also relatively slow. It is bound to be profoundly affected during the development of the discharge, but to what extent is difficult to judge owing to the lack of experimental data. Moore, Vonnegut et al. (1962) found by Radar observations that the large drops responsible for gushes of rain following after lightning flashes were not present prior to the electrical discharge. They suggest that after a return stroke the droplets in the streamer channels and the surrounding droplets are oppositely charged so that coalescence takes place by electrostatic attraction. This observation will have to be taken into account when formulating a theory relating to the transient effect of a lightning flash on the normal separation of charge in a cloud.

The J process.

The interstroke J process is considered to be a positive streamer discharge progressing mainly upwards from

the /.....

the upper regions of the previous return stroke channel. It was found that at distances nearer than 5 km interstroke field changes were nearly always negative in sign, whereas at distances between 12 and 20 km there were very few negative field changes, about 2/3 of them being positive and 1/3 zero.

In the intermediate range between 5 and 12 kms distance the tendency was for the initial interstroke field changes of a flash to be positive changing to negative between the later strokes.

The above distribution of sign of interstroke field changes at short range are in support of the suggested mechanism of the J process.

Effect of continuous discharge to ground.

A continuous discharge to ground during the intervals between the intermittent strokes of a flash brings negative charge to earth and will thus contribute a positive component to the interstroke field change at all distances.

Brook, Kitagawa and Workman (1962) have carried out a detailed study of continuing currents by simultaneous electrical and photographic observations in New Mexico. They find that a continuing current flows to ground in about 25% of interstroke intervals.

THE INTERSTROKE FIELD CHANGES DUE TO DISTANT FLASHES.

At distances beyond 20 km, J field changes although small should be positive so that it would have been expected that most of the interstroke field changes in this range

would /.....

would be positive. Such is not the case, however.

In England, Pierce (1955) found that only 25% of such interstroke intervals showed positive field changes whilst in the remainder no field changes could be detected. The above percentage of positive field changes agrees with the frequency of occurrence of continuing currents in New Mexico, so that it may be assumed that large positive interstroke field changes observed at great distances are mainly caused by continuing currents in the channel to ground. The contribution by the J process may be so small as to be undetectable.

At Johannesburg the distribution of sign is somewhat different. At distances between 25 and 100 km, 19% of interstroke field changes are positive. Here too, these field changes may be ascribed to continuing currents. Of the remaining field changes, however, 37% are zero and 44% negative. Fig. 1 shows three examples of field changes of flashes in the 50 km range. In (A) a positive interstroke field change is followed by 4 negative interstroke field changes. All the field changes are relatively small compared with those due to the preceding return strokes. The sequence of sign in this type of flash is not random but follows in the order positive, zero, negative, except for the occasional random occurrence of an exceptionally large positive field change which is obviously due to continuing current.

Of far less common occurrence are the field changes shown in (B) and (C) where negative interstroke field changes are comparable in amplitude with, and may even surpass, the preceding return stroke field changes. The occurrence at

large /.....

large distances of negative interstroke field changes at Johannesburg and not in England is possibly connected with the large vertical extent of thunderclouds at the former locality which is situated on an extensive plateau 1800 metres above MSL.

As outlined above, the basic data on which to base a theory for explaining the negative field changes are scanty but it appears that the effect can be explained in terms of a readjustment of space charge above the top of the cloud. A possible theory will now be briefly outlined.

THEORETICAL STUDY OF SPACE CHARGE EFFECTS.

Consider unit volume of air above a thundercloud at an altitude z above the ground.

Let the conduction current be $\dot{j}$, the potential φ, field E, conductivity σ and density of charge ρ.

If the field is not too high

$$\dot{j} = \sigma E \qquad \text{.................} \ (1)$$

since

$$\nabla^2 \varphi = -4\pi\rho$$

and

$$E = -\operatorname{grad} \varphi$$

it follows that

$$\nabla^2 \varphi = -\operatorname{div}(j/\sigma)$$

giving

$$4\pi\rho = (1/\sigma)\operatorname{div} j + (\operatorname{grad} 1/\sigma).(j)$$

for steady state conditions, div $\dot{j} = 0$ so that

/.....

$$4\pi\rho = (\mathrm{grad}\ 1/\sigma).(\sigma E)$$

since the conductivity is constant in the horizontal plane, we get

$$\rho = \frac{\sigma}{4\pi}\left[\partial/\partial z\,(1/\sigma)\right] E_z \qquad \text{............ (2)}$$

Gish (1944) has shown experimentally that in fair weather $1/\sigma$ can be empirically expressed as the sum of three exponential terms. Two of these can be neglected at high altitudes, so that for the region above the cloud his equation may be written

$$1/\sigma = 0{\cdot}37\,e^{-0{\cdot}12z} \times 10^{15} \qquad \text{ohm. cm, } z \text{ being in km.}$$

If it is assumed that the thundercloud does not alter the conductivity of the air above it (Gish and Wait 1950), equation (2) becomes

$$\rho = -\frac{0{\cdot}12}{4\pi} E_z \qquad \text{.............. (3)}$$

A similar expression was derived in a rather more lengthy way by Holzer and Saxon (1952)

It follows then that the space charge density at a point in the air above the cloud is proportional to the electric field at that point.

Using equation (3) it is possible to obtain an approximate estimate of the distribution of space charge in

a /.....

a vertical column above the cloud and to calculate the field change produced at a point on the ground by the relaxation of space charge after the occurrence of a stroke to ground.

Tamura (1954) expanded the theory of Holzer and Saxon to prove that the difference in the recovery curves after an intra-cloud discharge for near and distant flashes could be explained by taking into account the readjustment of space charge above the cloud after the occurrence of a flash. Tamura's expressions for the field component of the space charge will also be used in what follows.

The interstroke field change due to the space charge effect will be called the U field change. A stroke to ground removes negative charge from the cloud so that E_3 of equation (3) becomes more positive and the U field change will consequently be negative at all distances.

To circumvent the uncertainty in estimating the magnitudes of the charges involved in the discharge processes, the ratio U/J of the respective field changes was calculated assuming arbitrary values for the charges. Furthermore, it was assumed that the ratio U/J is unity at a distance of 20 km. Justification for this assumption depends on the experimental observation that at distances up to about 20 km the interstroke field changes correspond in sign with the expected J field changes whereas at larger distances this is no longer the case.

The variations of the ratio U/J with distance, starting from 20 km, are shown in figs. 2 and 3.

In fig. 2 the J process advances from 4 to 5 km. altitude and in fig. 3 from 7 to 8 km. The former thus represents conditions at the commencement and the latter those at the end of a flash with several strokes.

Curves /.....

Curves A have been calculated on the simple assumption that the U charge disappears from the top of the cloud at 12 km altitude as first tentatively suggested by Malan and Schonland (1951). Since these curves are approximately parallel to the abscissae they show that removal of charge from such a low altitude does not account for negative interstroke field changes.

Curves B were calculated by the simplified method outlined above and represent the effect of the adjustment of space charge in a column reaching from 20 to 30 km altitude and taking place after a stroke.

Curve C was calculated from Tamura's equations which assume that the space charge is distributed from the top of the cloud to infinite height.

The difference between curves B and C is not significant except in the range 20 to 30 km where curve B seems to fit the experimental observations somewhat better.

Both curves show that at large distances the negative U field change can be much larger than the positive J field change.

E_z of equation (3) increases in a steplike fashion after each partial discharge with the result that the U field change also increases. This can account for the observation that the interstroke field change is often positive or zero after the initial strokes and becomes negative after the later strokes of a flash.

As Brook, Kitagawa and Workman have pointed out the J field changes become very small at a distance of 50 km

from /....

from which it follows that the curves of figs. 2 and 3 do not account quantitatively for the relatively large negative field changes shown in fig. 1 (B) and (C).

It is possible that the field above the cloud occasionally becomes so large that equation (1) is not valid and the outlined theory breaks down. This may conceivably happen in a cloud of large vertical extent where the main positive and negative centres are widely separated so that flashes to ground are more frequent than intra-cloud flashes. When the records shown in fig.1 B and C were obtained, flashes to ground were 2 to 3 times more frequent than cloud flashes.

In the extreme case, the field above the cloud may become high enough to initiate a glow discharge between the space charge and the ionosphere (Malan 1937). In this case the conductivity of the air above the cloud will increase and cause a decrease in the relaxation time thus giving large and rapid U field changes.

It will be interesting to determine whether the rare large negative field changes have any connection with solar flares which cause increased ionization in the D layer of the ionosphere.

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The lightning stroke II
(Typed memorandum. Has it already been published ?)

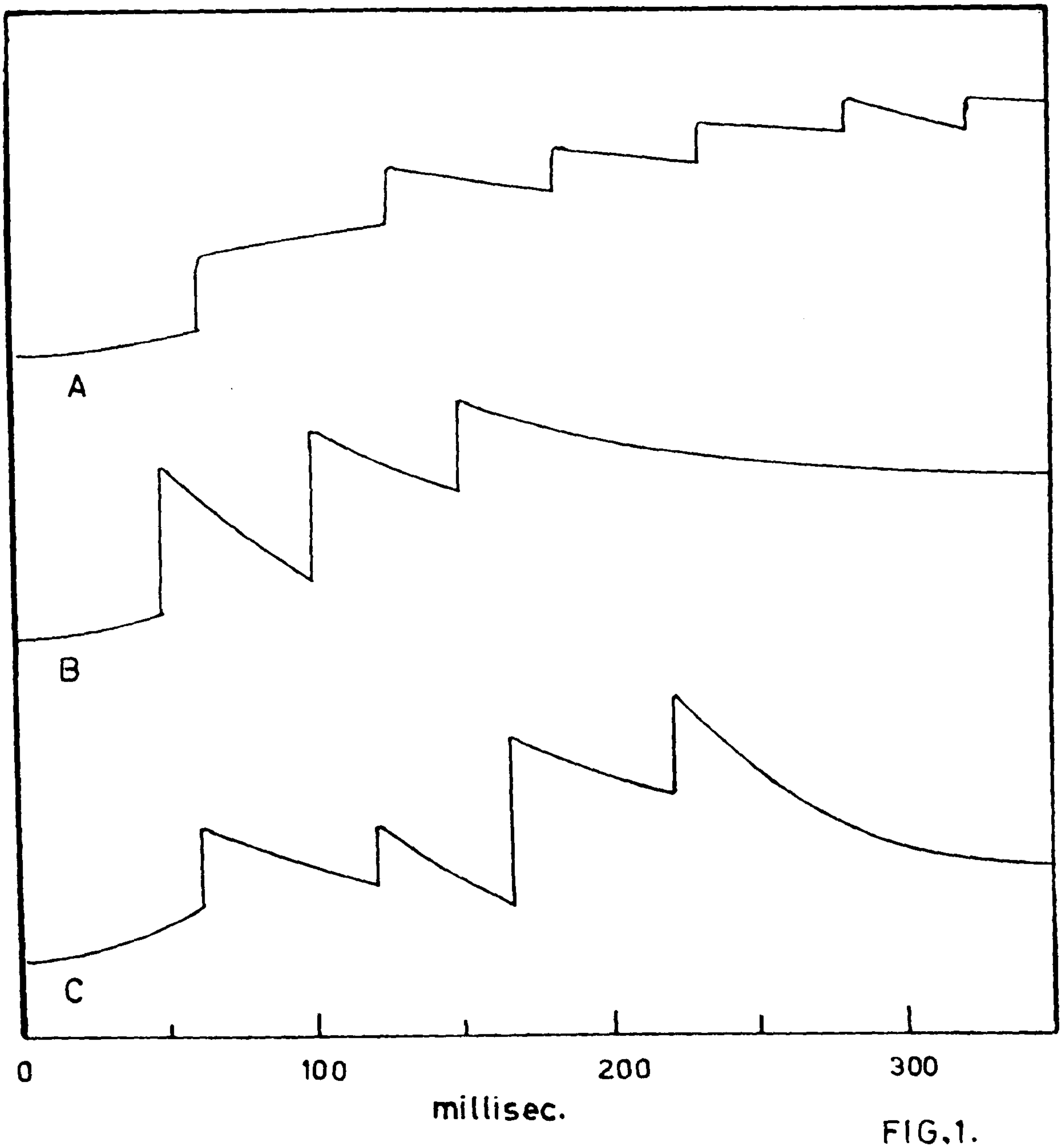

FIG.1.

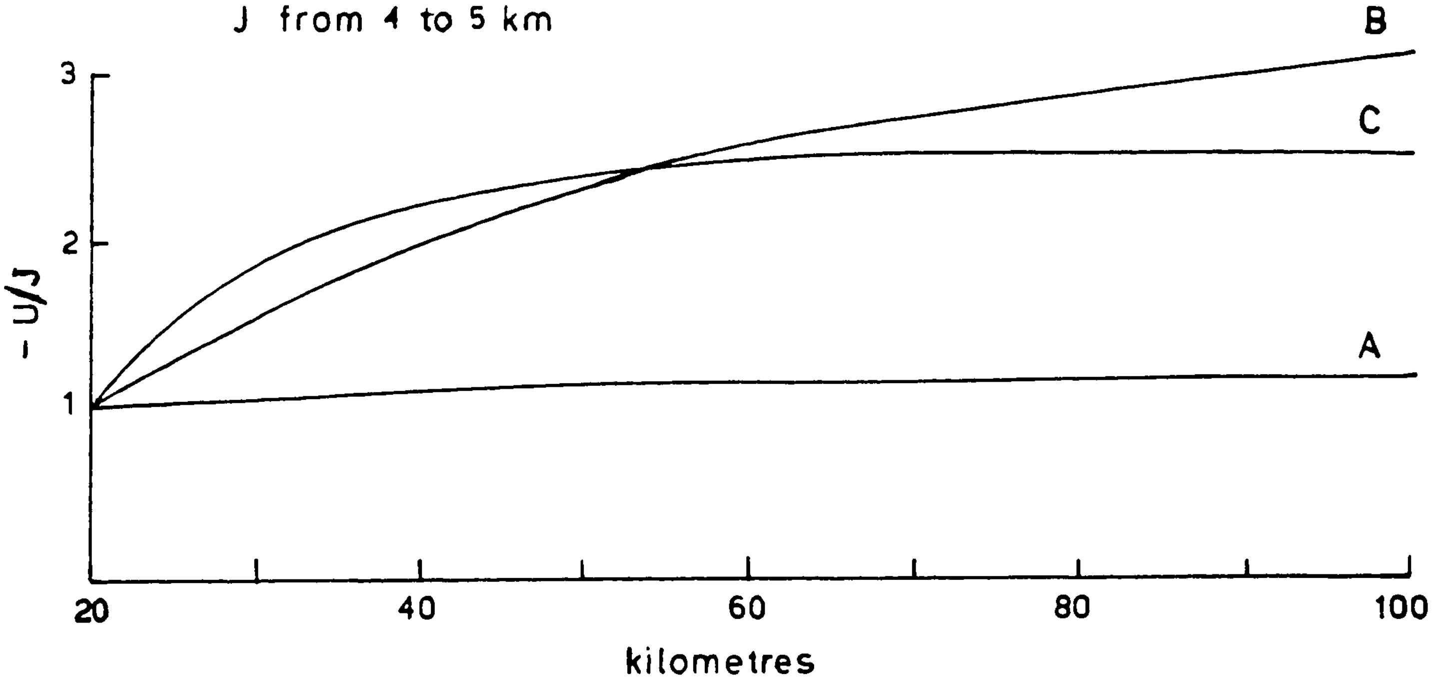

FIG. 2.

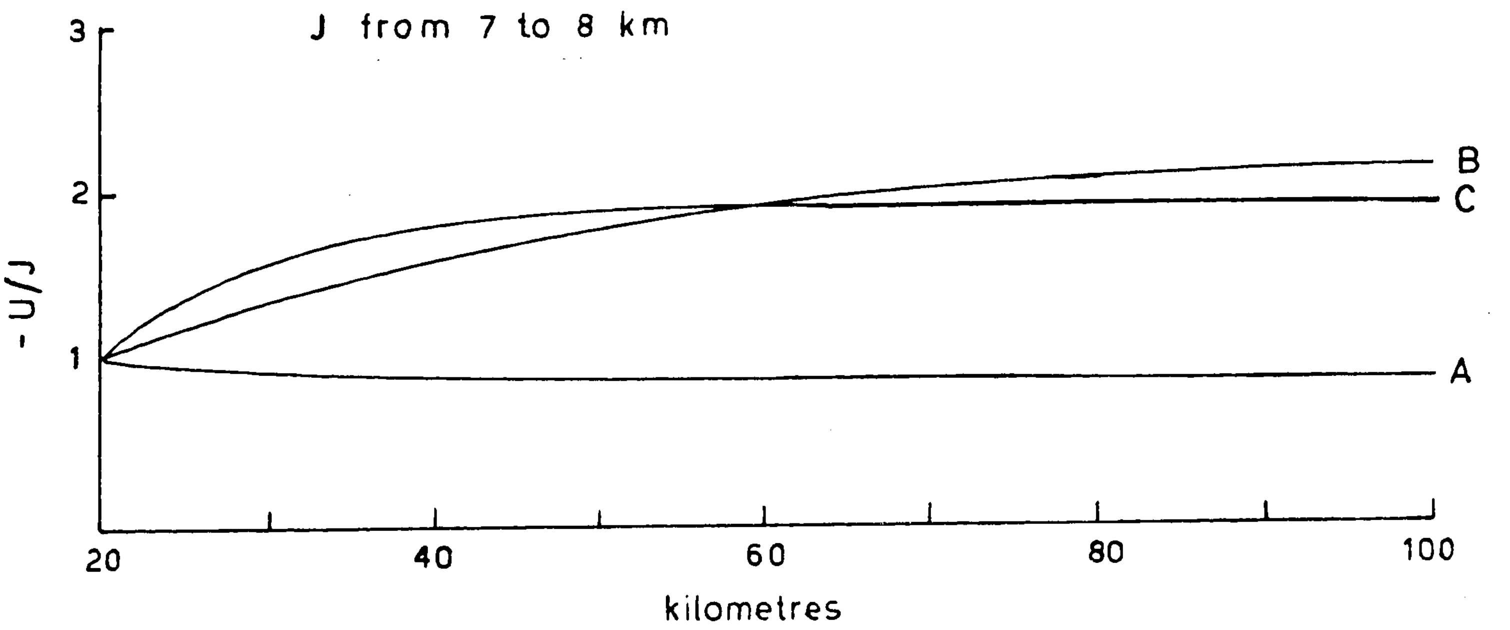

FIG. 3

SESSION 7.2

Types of Lightning

N. Kitagawa

Introduction

The mechanism of lightning discharge can best be studied by the simultaneous measurement using photographic and electric-field recording technique. Lately in New Mexico lightning measurements on this line with improved technique have been done extensively. The result thus obtained have revealed new aspects of lightning discharges as well as the detailed structure of the discharge mechanism. (Kitagawa, Brook and Workman, 1962; Brook, Kitagawa and Workman, 1962)

Based mainly upon these results, the author will try to depict the picture of the lightning, pointing the accompanying unsolved problems at the same time.

Terminology

The author adopts the terminology of Schonland (1956) in describing the various processes in the lightning discharge. **A flash** is a lightning discharge in its totality. **A stroke** is a partial dischange consisting of downward-moving return streamer. A flash may consist of a single stroke or a series of strokes in the same or an adjacent channel. A M component is a sudden enhancement of the continuing luminosity which occasionally follows a stroke in the channel (Malan and Shonland, 1947). The M components are not preceded by leaders.

Long-continuing luminosity is arbitrarily defined as luminosity which persists in the channel for a time longer than 40 msec i.e., luminosity which lasts as long as or longer than the usual stroke interval. A stroke followed by such luminosity will be called a long-continuing stroke. Occasionally a stroke is followed by continuing luminosity which lasts less than 40 msec; such a stroke will be called a short continuing stroke. A stroke whose luminosity decays abruptly will be called a discrete stroke. A K change is a small, rapid electric field change which occurs in the intervals between and after the strokes of a multiple stroke flash (Kitagawa, 1957; Kitagawa and Brook, 1960). The K changes are generally associated with streamer activity within the cloud. There is a slow electric field change which occurs during the interval of continuing luminosity, this will be referred to as a continuing or C change to distinguish it from the junction or J change which occurs without the accompanying channel luminosity between or after the strokes.

In analogy with the difinitions given by Malan (1954), a lighting flash which involves one or more continuing strokes is called a hybrid flash. A flash which involves discrete strokes or short continuing strokes is called a discrete flash. Cloud-to-Ground, in-cloud and cloud-to-cloud discharges will be referred to by the symbols, C-G, I-C and C-C discharges respectively. A cloud-to-clearair flash is called a air discharge.

General nature of C-G discharges

As a result of New Mexico lightning measurements it has been found that hybrid flashes i.e. flashes involving one or more long continuing strokes are found to be observed very commonly in C-G discharges.

In multiple flashes which constitute 86 per cent of all C-G discharges, the occurrence rate of discrete and hybrid flashes is about fifty to fifty. The percentage of single flashes with long continuing luminosity is exceptionally low (only 2 of 193). The long continuing strokes does not either occur as the initial stroke of a multiple flash. Figure 1 is a comparison of the luminous events of a discrete and a hybrid flash as recorded by the moving-film camera and by the electric field and electric field-change records. In the schematic representation of the luminous events, a straight, vertically oriented channel is assumed. The electric field record represents the actual variation of electric field, whereas the electric field-change record emphasizes the rapid components through the use of an antenna with a short time constant and a high amplification. Both of the flashes are about 20 km distant from the recording station. It can be noted in Figure 1 that the magnitude of slow electric field changes (J changes) is very small or practically zero during the intervals of non-luminosity between strokes of both discrete and hybrid flashes. On the contrary, it has been found that a large positive, slow electric field change (C change) is always associated with a continuing luminosity on the photographic record. The average number or strokes per flash in both discrete and hybrid flashes is 7. If we include the single flashes, the average number of stroke per flash is 6. Thus the number of strokes per flash has found to be appreciably larger than the statistics by Schonland (1956) based upon electric field-change records. It is not uncommon to find several strokes which produce field-changes of 1/10 to 1/20 of the field change caused by the largest stroke. Without the positive identification of the leader-return combinations on the high speed photographs, it is highly probable that R changes of such small magnitude might have been interpreted as K changes or overlooked.

Malan (1954) found that the large slow field change of the same nature as defined C change here, often occurs as a final stage of a multiple flash which involves fewer stroke elements. In New Mexico measurements such a hybrid flash found to be observed more frequently that its earlier stage is very sim~~m~~illar to that described by Malan but involves one or more stroke elements of very small R changes in its very late stage.

In England Pierce (1955 a) sometimes recorded S(β) field change. The field change of this type can reasonably interpreted as a continuing current field change in which the stroke field change initiating the C change is barely discernible on the electric field record. It is because of the occurrence of such small stroke field changes that the number of strokes per flash appears to be less when counted on the electric field records than when measured on the high speed photographs.

While the duration of long continuing luminosity varies widely as shown in Figure 3, the duration of the no-luminous interval i.e., the interval from the end of the luminosity of the preceding stroke to the following stroke tends to fall in certain limited range around 80 msec (from 50 to 200 msec). Though the duration of a no-luminous interval appears to be longer than a usual stroke interval, the value still lies within the range of discrete or short stroke intervals (5 to 180 msec).

The methods and assumptions used in calculating value for the charge which is brought to earth by individual discharge elements of a flash are described and discussed in detail by Brook, Kitagawa and Workman (1962). Here the method will be outlined. The electric field change due to a lightning stroke measured at the surface of the earth is given by

$$\Delta E = 90 \frac{2 Q_R H_R}{(D^2 + H_R^2)^{3/2}}$$

where ΔE is in volts/cm, Q_R is in coulombs and H_R and D are in km. D is the horizontal distance from the field meter to the flash and H_R is the vertical height to the assumed center of charge Q_R.

The hight H_R is determined by

$$H_R = h\, t_e / t_p$$

Where h is cloud base hight, t_e is the total duration of the dart leader measured on electric field change records and t_p is the time for the dart leader to travel from the cloud base to ground determined by photographic records. From the first equation, with the measured value of H_R, D and ΔE, the charge Q_R can be written

$$Q_R = \frac{\Delta E\,[D^2 + (h\, t_e/t_p)^2]^{3/2}}{180\, h\, t_e/t_p}$$

The above emthod is also applicable to the continuing current intervals. Let H_1 and H_2 be the heights determined for two successive strokes between which a continuing current to ground was evidenced on both the electric field records and the photographs. The charge Q_C is assumed to be centered at H_c , a distance midway between the tops of the two return stroke channels; i.e.,

$$H_c = \frac{1}{2}(H_1 + H_2)$$

The corresponding slow electric field change ΔE is then measured, and the charge Q_c is calculated.

The negative charge (no strokes carrying positive charge to earth were observed) lowered by individual stroke is shown in Figure 2(a) and 2(b) in two histograms showing the number of occurrences of strokes in which charge was (a) lowered by strokes which were preceded by stepped leaders and (b) lowered by strokes preceded by dart leaders. A striking contrast is seen to exist between the two types of strokes. The minimum charge lowered by the strokes associated with stepped leaders is 3.0 coul; for the others a minimum value is 0.21 coul. Both of the histograms exhibit a sharp cut-off at their minimum end. The most frequent value of charge brought down by first strokes lies between 3 and 4 coul; for subsequent strokes the most frequent value lies between 0.5 and 1 coul. For single flashes the average value of the charge lowered was calculated to be 4.6 coul. The charge lowered by the continuing current is shown in Figure 3 as a plot vs. its duration. The maximum duration of a continuing current interval was found to be 300 msec. The greatest amount of charge lowered during one of these long intervals was 31.2 coul. Though both the amount of charge and the duration vary widely, the plot shows that the average current i.e., the charge devided by the duration tends to be far less variable from current to current. It ranges from 38.4

to 130 amp around the mean value of 79.2 amp. Thus the continuing current turns out to be very efficient agent for carrying the cloud charge to earth. Because of this agent the total charge lowered by a hybrid flash is remarkably larger than that lowered by a discrete flash. The calculation shows that the average values for a discrete and a hybrid flashes are 20 and 34 coul respectively.

The result of the calculation of the charge center hight for each stroke element is shown in Figure 4 as a plot vs. the stroke order. The figure shows the definite tendency that the hight of charge center, exactly speaking, the length of the stroke channel increases from stroke to stroke. The most frequent height difference for the discrete flash is 0.3 km. The value for the discrete intervals of the hybrid flash is also 0.3 km. The continuing-current intervals are most frequently associated with a value of 0.9 to 1.6 km. Figure 4 suggests that hybrid flashes usually involve greater cloud volumes than do discrete flashes.

Continuing currents and the junction Process

With the realization that the continuing currents to earth often occupy the intervals between strokes previously assigned to in-cloud processes alone (i.e. J changes), it is desirable that we reexamine the interpretation of the inter-stroke field changes, as discussed by Malan and Schonland (1951 b), Malan (1955) and Pierce (1955 a,b)

Table 1 shows the electric moment change 2HQ associated with a flash, a stroke, a long continuing current and a J process, obtained in the present measurement. J change, identified by the absence of

Table 1 Electric Moment Change Associated with a Flash, a Long Continuing Current and a J process

Discharge	Electric Moment Change 2HQ (coul km)	
Flash	248	(average)
Stroke	22	(average)
Long Continuing Current	135	(average)
Junction Process	1.62	(maximum observed value)

a continuing channel luminosity on the photographs turns out to be remarkably small. As shown in Table 1 the maximum change was found to be 1.62 coul km. Large slow field changes do~~es~~ occur, but invariably the photographs show these to be associated with continuing current to ground. When we consider the average change in moment associated with the flashes in this study is 248 coul km (Table 1), it is not surprising to find that the J-change moment, having values much less than 1.6 coul km, are not detectable. Taking the maximum value as 2 coul km, we see that the J process produces a change in moment which is about 10 per cent of the average change in moment for strokes (22 coul km), and about 1 per cent of the average change in moment for continuing currents (135 coul km). It is now clear that the value 2HQ = 50 coul km used by Pierce (1951 b) for the J change in moment is really to be associated with the C change.

We shall assume that the most favorable conditions of noise allow the measurement of slow field changes of magnitude 10^{-3} of the earth's fair weather field, i.e., of magnitude 10^{-3} volt/cm. Using the value 1.6 coul km for the upper limit of the J change in moment, we calculate that the maximum distance at which a J change will produce an electric field change of 10^{-3} volt/cm is 52 km. Since only a C field change is expected to be detected as a slow electric field change on the record beyond this distance, it is highly probable that most of the J changes reported by Pierce (1955 a) for distances between 50 and 90 km were produced by continuing currents to ground. He was able to measure slow field change in approximately 25 per cent of the intervals between strokes and for the remainder no variation in field could be detected. This figure of 25 per cent is reasonably consistent with our own statistics for the occurrence of continuing currents in lightning discharges. These statistics also reinforce the conclusions that C changes, and not J changes, are detectable for distances beyond 50 km. A new process involving a discharge from the cloud top to the high conducting layers was postulated by Malan and Schonland (1951 b) and Malan (1955) to explain the apparent absence of J changes in the measurements of Pierce (1955 a) and Malan (1955) for distant storms (20 to 150 km). Since we now see that the absence of J change is actually to be expected for distances beyond 50 km, the compensating process (a discharge to the upper air) is unnecessary. Also, it appears that it is not nesessary to postulate a difference between thunderclouds in England and in South Africa (Pierce and Wormell, 1953).

During the interval between successive strokes of a multiple flash, there found to be two different stages of channel conditions, a continuing luminosity stage and a non-luminosity stage. We have done some experimental approach to the luminous conditions, but the channel condition during no-luminous intervals remains entirely unknown. A number of problems concerning this channel condition should be the subjects of future studies. For instances, what is the amount of the dark current in the channel? How the J process is connected to the ground? How such a conductive condition is maintained in the channel that allows the dart leader of a subsequent stroke to follow the same channel.?

M components and K changes

During the continuing luminosity M components are found to be associated with field changes similar to K changes on electric field-change records as can be seen in Figure 1. Seperations of M components are very small and tend to increase very rapidly with elapsed time within the first 15 msec from the return stroke.
Later on this tendency desappears and M-component intervals exhibit no dependence on the elapsed time. Figure 5 (a) shows the frequency histogram of M-component intervals in this later stage of continuing

luminosity. For the comparison the frequency histograms for K changes in discrete intervals of G-C discharges (b) and for K changes in I-C discharges (c) are shown in the figure.

So far the luminosity continues in the channel, streamers connected to the channel keep developing within the cloud into the flash charged region. The M components is the presentation of the current surge in the luminous channel produced by the momentary increase of the cloud charge supply. Thus, the occasional appearance of M components in a continuing current is considered to be the reflection of the non-uniform distribution of charge in the cloud. The similarity in three histograms (a), (b) and (c) in Figure 5 also suggests that M-component intervals and K-change intervals both in discrete stroke intervals of C-G discharge and in later stages of I-C discharges are all controlled by the same conditions, by the conditions attributable to the cloud structure, not by the conditions of the discharge process. Ogawa (1962) calculated the average developing velocity for the streamers associated with the long continuing current to be 1.6 × 10^6 cm/sec. This value, combined with the most frequent M-component interval of 6 msec, gives the linear dimension of 100 M for the spacing of the densely charged regions in the cloud. This dimension can be compared reasonably well with that of the unit cell of the convection suggested by Reynolds (1954) i.e., the microstructure in the so-called cloud cell, evidenced by the radar echoes of the strom or by the visual observation of cumulus towers and striation in the rain sheet.

The K change is a rapid luminous small scale discharge within the cloud. Usually the duration is less than 1 msec and the moment change involved varies from a few hundredth to about 1 coul km. Ogawa's (1962) analysis based on New Mexico measurements shows that the main discharge process which constitutes the K change is the rapid flow of the cloud negative charge into an already existing channel. Comparing the discharge processes associated with M components with those produces K changes, there seem to be no essential difference in the way of the streamer develop~~p~~ment within the cloud. A junction or J process described by Malan and Schonland (1951 b) is now reasonably interpreted as a whole series of K-change discharges invol~~e~~ved in a stroke interval. The J change turns out to be the smoothed trace of the electric field record which actually consits of a number of very small K-change steps during the non-luminosity interval of a multiple C-G flashes.

Nature of I-C discharge

Figure 6 shows a typical example of electric field and electric field-change records of a I-C discharges. The records is usually d~~e~~ivided into two different portions; the earlier active portion and the later portion. The later portion of field and field-change records are very similar to those between strokes of a C-G discharge i.e., J or C field changes; K changes follow each other on the electric field-change record with the identical time intervals with those of K changes and M components in C-G discharges (Figure 5). During the earlier portion pulse activity is much higher; amplitudes of some of pulses are much larger and pulses are spaced so densely that quiescent intervals are seldom recorded. Occasionally an earlier active portion may be preceded by a less active portion, called an initial portion, which is characterized by pulsations of high repetition rate and of relatively small amplitude. The rate of the moment change estimated on electric field record is generally higher during active portions than during later portions.

The electric field and electric field-change records of a later portion obviously show that the discharge mechanism is essentially the same as that of discharge processes which take place in the cloud during the intervals of a multiple C-G discharge. Though there is no strict distinction between the discharge of the M-component type and of the K-change type in the case of a I-C discharge, the discharge mechanism is considered to be closer to that of the continuing current interval of a C-G discharge, because the moment change in this portion is generally larger than that in the discret stroke intervals (i.e. J field change). And it is highly probable that continuing channels of considarable length are usually established in a later stage of a cloud discharge as occasionally evidenced on moving camera records of C-C or Air discharges. Occasionally a moment variation in a K change is appreciably larger compared with that in C-G discharges.

A measurement by Ogawa (1962) shows that for the I-C discharge the average moment change associated with the K change is about 6 coul km and the charge involved is estimated to be 2 coul. The average current during the change is 2000 amp.

A very frequent occurrence of pulses in an active portion apparentry suggests that a number of different streamer channels develop~~e~~ in the cloud at the same time or with slightly different time phases. Sometimes the development of relatively small scale streamers is repeated for the duration of some 50 to 100 msec before the burst of larger streamers takes place (an initial portion). At present quantative informations about streamer processes in an initial or in an active period of the I-C discharge are not available. However, we can point out one aspect of the initial stage of the I-C discharges. Regardless the discharge starts with an initial portion or immediately with an active portion, the pulse activity is much more irregular than that recorded in the very beginning stage of the leader field change of C-G discharge, both length of pulse intervals and pulse amplitude tend to be larger and more variable in the first several milliseconds ~~msec~~ compared with those in the later stage. Still the regularity in both period and amplitude well reflects the step-wise development of stepped leader streamers. In fact the pulse intervals during this stage lies in the range from 10 to 150 μsec. On the contrary for corresponding initial stage of the field change of a I-C discharge, pulse intervals spread over the extremely wide range from 10 μsec to several msec. Pulse intervals along with much irregular pulse shapes indicate that the mechanism of the associated discharge is entirely different. While the initial breakdown of a C-G discharge takes place in the water droplets region of a cloud, the initiation of a I-C discharge starts at much higher altitude where the cloud consists of ice particles and

A very frequent occurrence of pulses in an active portion apparentry suggests that a number of different streamer channels develop~~s~~ in the cloud at the same time or with slightly different time phases. Sometimes the development of relatively small scale streamers is repeated for the duration of some 50 to 100 msec before the burst of larger streamers takes place (an initial portion). At present quantative informations about streamer processes in an initial or in an active period of the I-C discharge are not available. However, we can point out one aspect of the initial stage of the I-C discharges. Regardless the discharge starts with an initial portion or immediately with an active portion, the pulse activity is much more irregular than that recorded in the very beginning stage of the leader field change of C-G discharge, both length of pulse intervals and pulse amplitude tend to be larger and more variable in the first several ~~msec~~ milliseconds compared with those in the later stage. Still the regularity in both period and amplitude well reflects the step-wise development of stepped leader streamers. In fact the pulse intervals during this stage lies in the range from 10 to 150 μsec. On the contrary for corresponding initial stage of the field change of a I-C discharge, pulse intervals spread over the extremely wide range from 10 μsec to several msec. Pulse intervals along with much irregular pulse shapes indicate that the mechanism of the associated discharge is entirely different. While the initial breakdown of a C-G discharge takes place in the water droplets region of a cloud, the initiation of a I-C discharge starts at much higher altitude where the cloud consists of ice particles and super-cooled droplets of very small size. The author suggested that the difference between the two initial breakdown processes is attributable to the difference in the breakdown impedance affected by the above two different enviromental conditions i.e., the difference in the relative populations of water drops and ice particles in the cloud (Kitagawa and Brook, 1960). In addition to the difference in the breakdown impedance, it is probable that the kind of breakdown streamers, positive streamers mostly, not negative streamers and the configuration of channels, extensively branched or separated into a number of channels will account for the different character of the initial ~~in the very early~~ breakdown process stage ~~of the field change~~ of I-C discharges.

We have tried to depict the nature of the I-C discharge in the comparison with the C-G discharge. As to discharge processes, however, which take place entirely in the cloud, we have very little quantative informations. For the further study of the lighting discharge, quantative measurements of these processes are desired, e.g. an initial breakdown streamer process, a streamer process in an active portion, a K-change process and a streamer process of continuing luminosity. One approach for these will be simultaneous measurements by field meters of high time-resolution at several stations on the surface.

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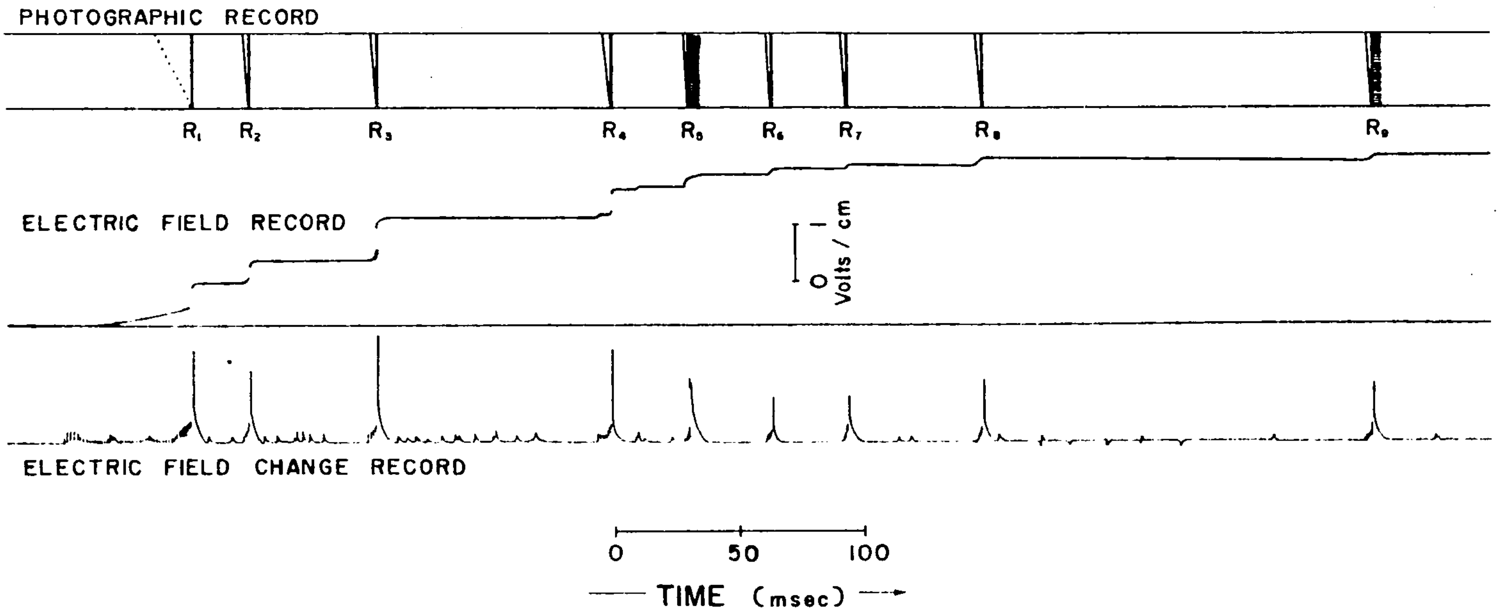
List of Figures

DISCRETE FLASH



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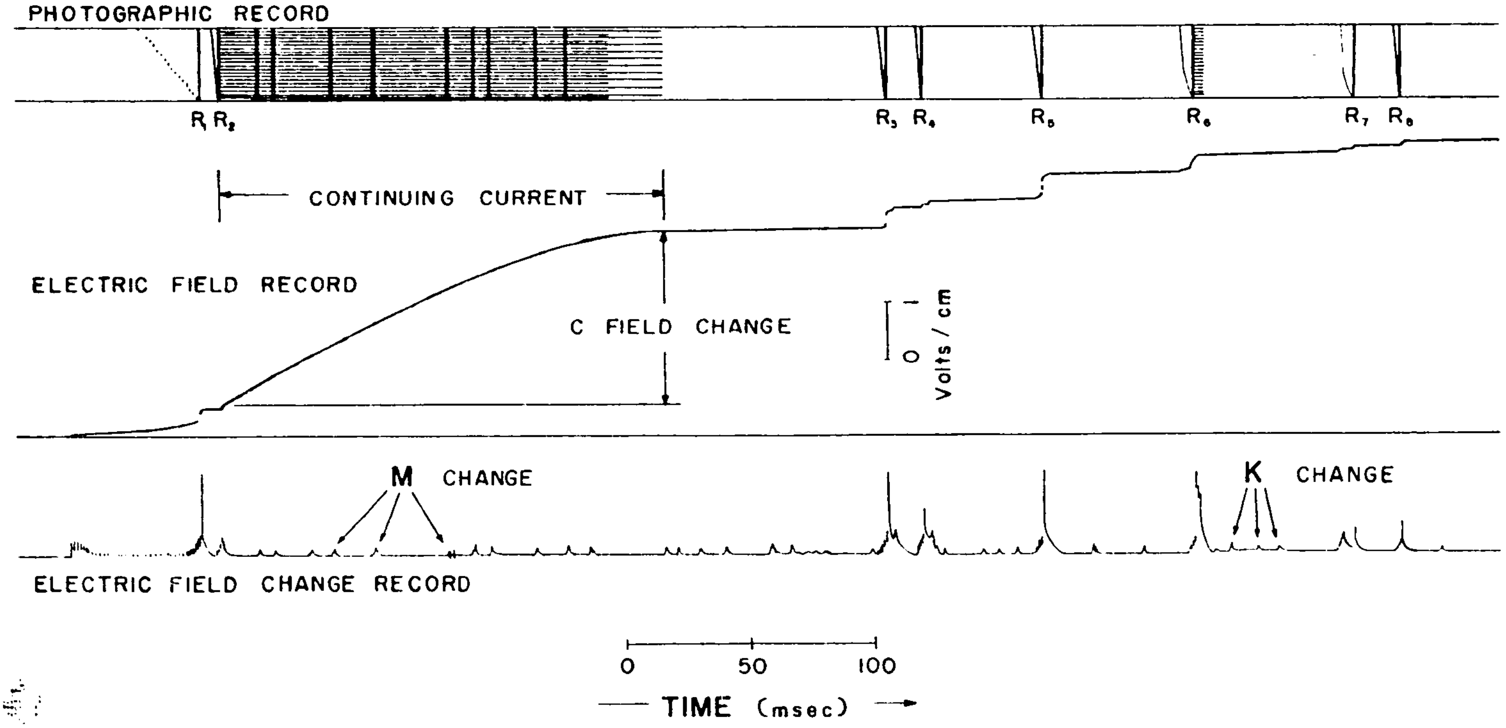

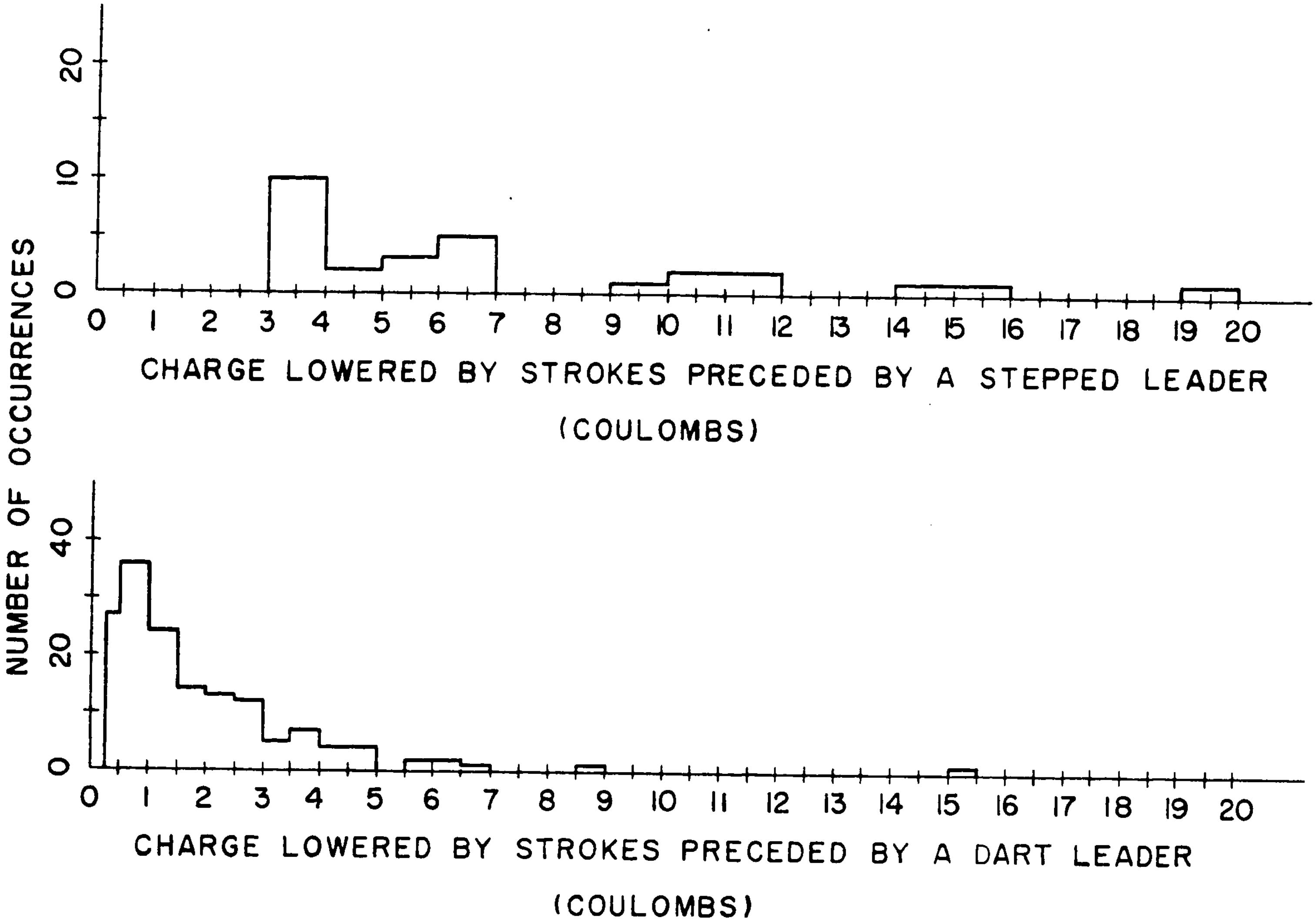
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CHARGE LOWERED BY STROKES PRECEDED BY A STEPPED LEADER
(COULOMBS)
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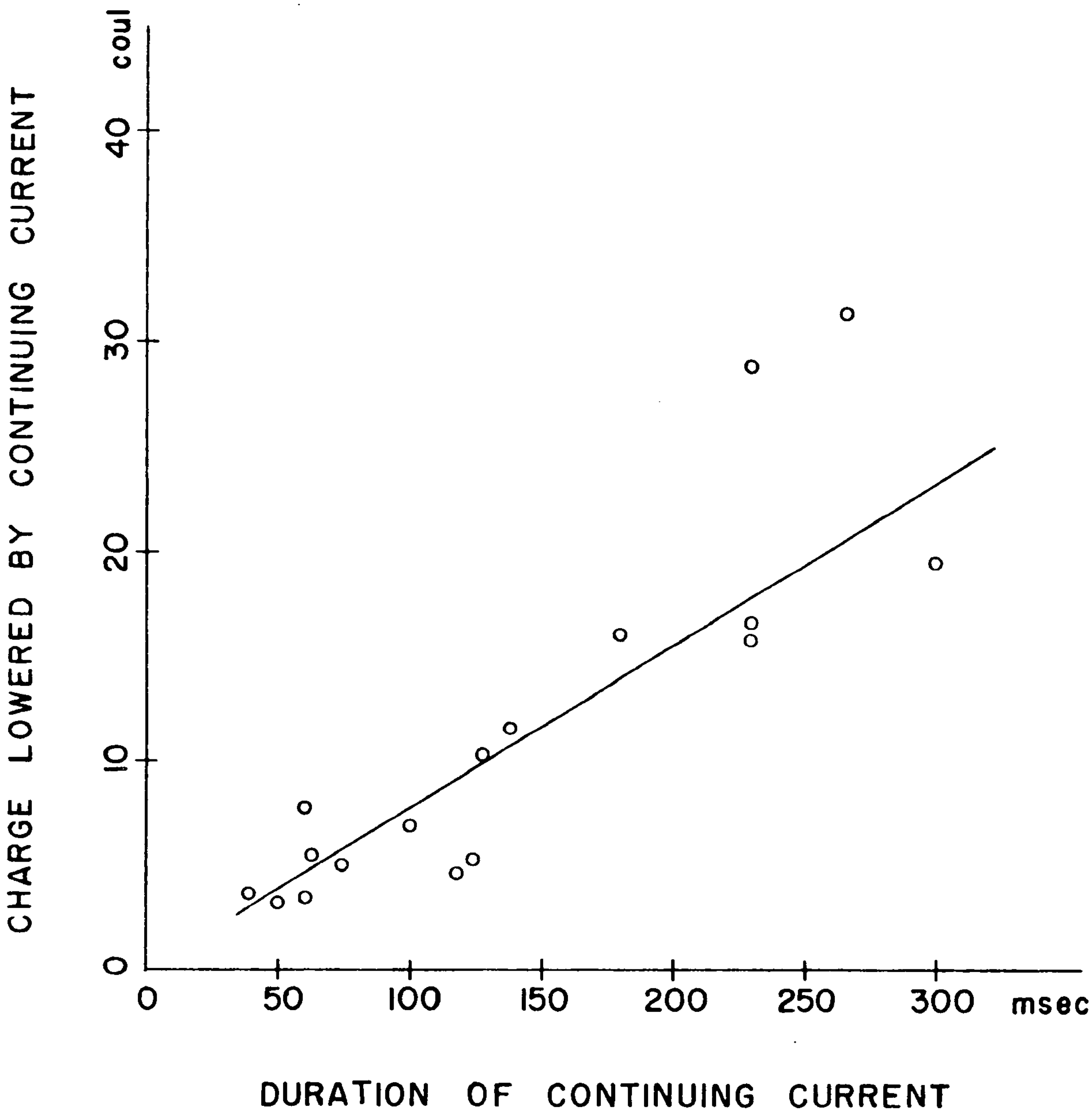
CHARGE LOWERED BY CONTINUING CURRENT
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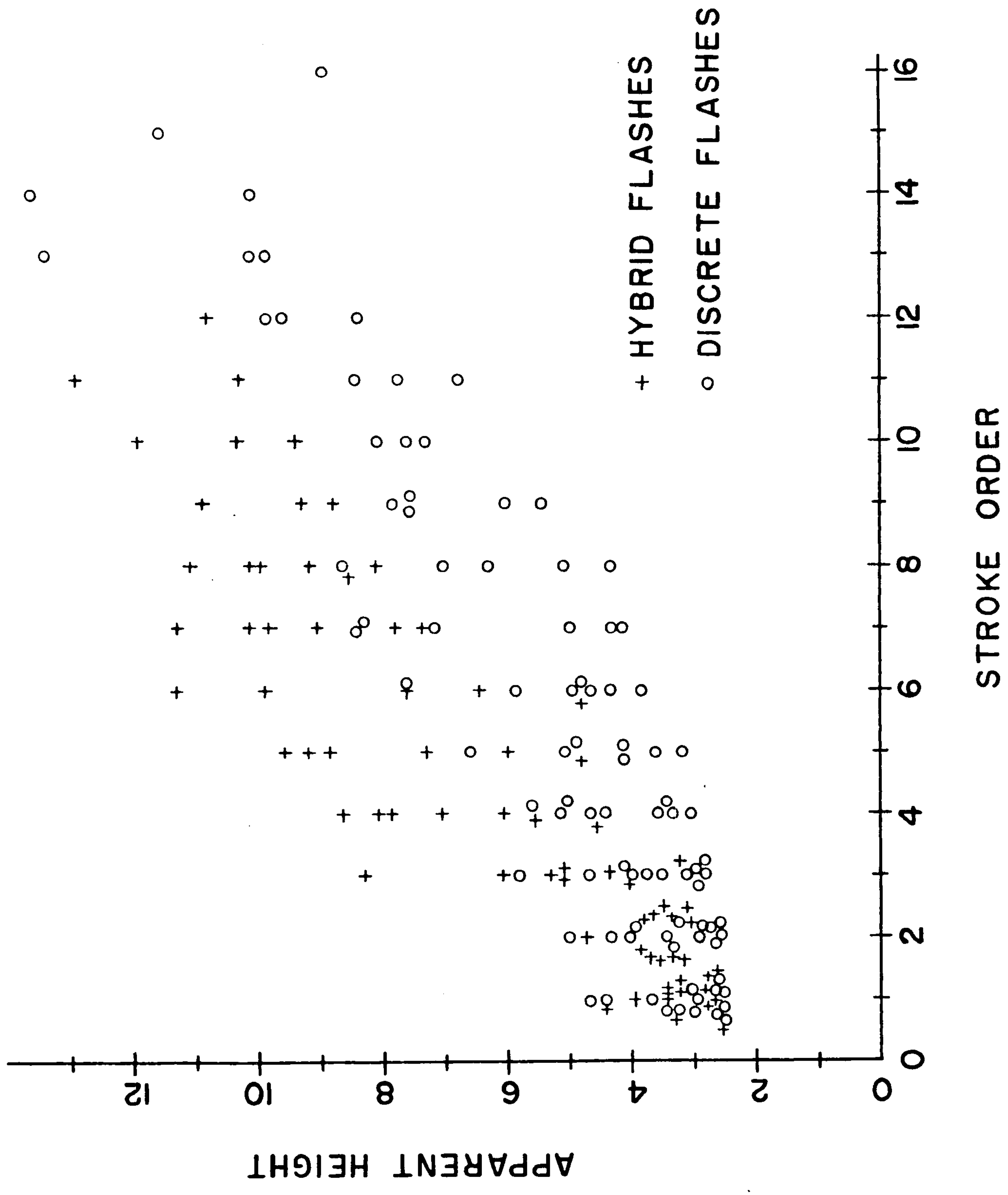
+ HYBRID FLASHES
○ DISCRETE FLASHES
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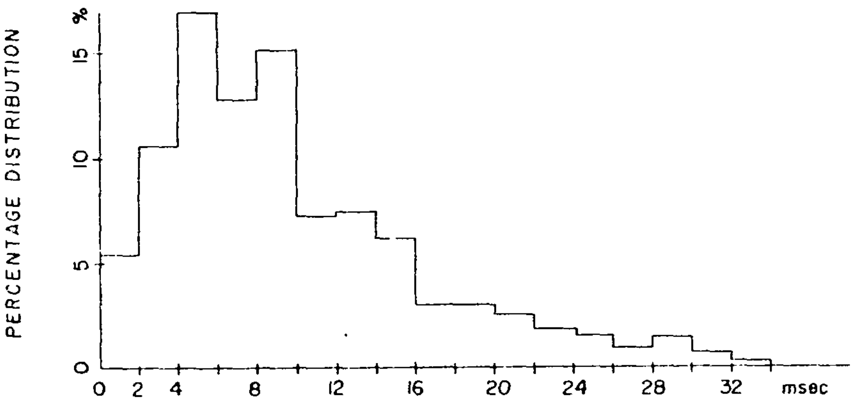
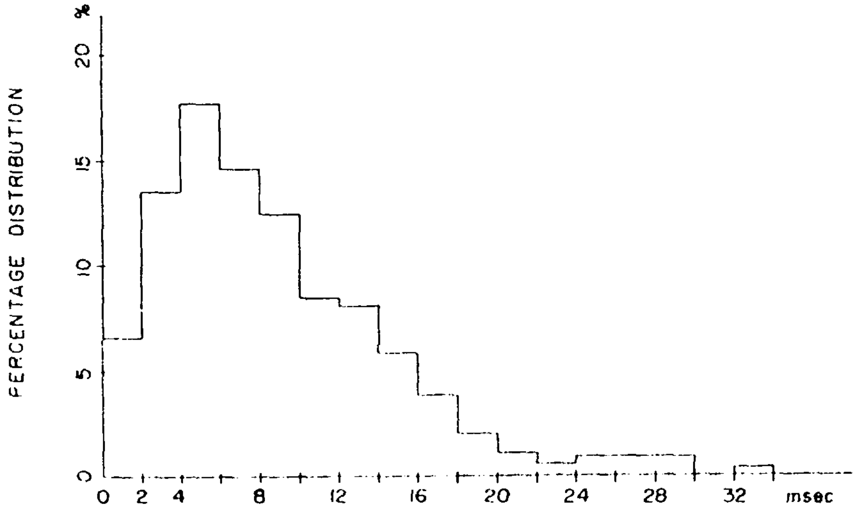
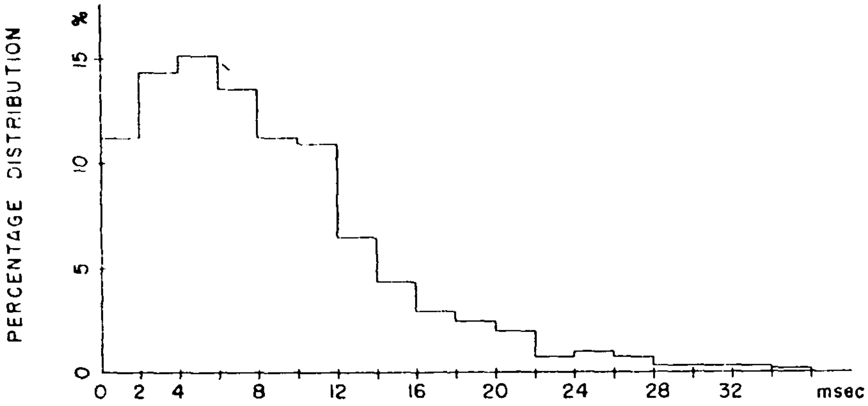


(a) M COMPONENT INTERVALS



(b) DISCRETE K-CHANGE INTERVALS—C-G DISCHARGES



(c) K-CHANGE INTERVALS—I-C DISCHARGES

SESSION 8.1

Lightning Protection

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Physical research on lightning and the practical application of its results are intimately related to each other. The demand for security against damage by lightning has greatly stimulated research. Lightning discharges affect buildings, power lines, machines and equipment, and telecommunications systems. They can cause damage to aircraft and during tunnel blasting deep down in a mountain. They kill and injure living creatures and cause fires and accidents. All this has given rise to innumerable investigations and publications in the majority of civilized countries in which lightning is a problem. Summaries on lightning protection matters have often been published. An early work by Goodlet (1) deals with questions such as the shattering of poor conductors, damage to buildings, oil-tank fires, damage to aircraft and effects on living creatures. A more recent work by McEachron (2) gives, in the first , place, an account of protective measures for communications and power--supply systems. The present report can only give a limited survey of such protection questions as have still not been completely elucidated; they relate, on the one hand, to physical phenomena and, on the other, to statistical and probability investigations, which are often connected with financial problems.

The publications from the Golden Age of lightning research - from about 1750 to 1780 - often show acute observation of nature in connection with protective measures. As an example, I quote two observations by Benjamin Franklin which touch on quite topical questions. The first shows his view of the limited protective range of an elevation rod - a question which is always being discussed. In "Poor Richard's Almanac" for 1753 Franklin writes:

> Provide a small Iron Rod (it may be made of the Rod-iron used by the Nailers) but of such a Length, that one End being three or four Feet in the moist Ground, the other may be six or eight Feet above the highest Part of the Building. ... If the House or Barn be long, there may be a Rod and Point at each End, and a middling Wire along the Ridge from one to the other. ...

The instruction is later repeated in Franklin's 24th letter (3).

The second observation makes clear the protective effect of a thin wire, in a case which is topical today, as regards finance. The church at Newsbury in New England had been badly damaged by lightning in the summer of 1754. Franklin gives a detailed account of the destruction. I reproduce extracts from his letter to Dalibard (3):

> The spire (of wood, reaching 70 feet higher than the 70 feet high steeple) was split all to pieces by the lightning, and the parts flung in all directions over the square in which the church stood, so that nothing remains above the bell. ... From the end of the pendulum, down quite to the ground, the building was exceedingly rent and damaged, and some stones in the foundation wall torn out and thrown to the distance of twenty or thirty feet. ...

The central portion was not damaged. The lightning current had destroyed a thin wire which connected the clapper of the bell to the clock mechanism 20 feet away. The flash was conducted to the pendulum wire, which had the thickness of a goose quill. Franklin draws the following conclusions:

> 1. That lightning, in its passage through a building, will leave wood to pass as far as it can in metal, and not enter the wood again till the conductor of metal ceases. And the same I have observed in other instances, as to walls of brick or stone.
>
> 2. The quantity of lightning that passed through this steeple must have been very great, by its effects on the lofty spire above the bell, and on the square tower all below the end of the clock pendulum.
>
> 3. Great as this quantity was, it was conducted by a small wire and a clock pendulum, without the least damage to the building so far as they extended.
>
> 4. The pendulum rod, being of a sufficient thickness, conducted the lightning without damage to itself; but the small wire was utterly destroyed.
>
> 5. Though the small wire was itself destroyed, yet it had conducted the lightning with safety to the building.
>
> 6. And from the whole it seems probable that, if even such a small wire had been extended from the spindle of the vane to the earth, before the storm, no damage would have been done to the steeple by that stroke of lightning though the wire itself had been destroyed.

Before concluding this short historical survey, I show (Fig. 1) one of the earliest lightning-conductor **drawings** ever published - a lightning conductor designed by Torbern Bergman for a building in Uppsala, Sweden, in 1765. Even at that period the special instruction is given that large metal parts in the building should be connected to the lightning conductor (4).

The Lightning Path near the Ground

Space charges between cloud and earth greatly affect the lightning path. A visible proof of this is the "Type β leader" according to Schonland (5, 6), which has a high velocity (more than 6 x 10^7 cm/sec = = 600 m/ms) between the base of the cloud and the space-charge layer (first stage) and a low velocity (about 1 x 10^7 = 100 m/ms) and often a pronounced fork in its further career to the ground (second stage). About 30% of the leaders in South Africa showed this phenomenon (7). The charges in the water-vapour cloud are transported to and distributed over the space-charge cloud. These charges consequently become "over-neutralized". The leader's space-charge channel receives additional charge and thereby has a greater volume than it would have had if the space-charge layer had not existed. On the return stroke the lightning channel accordingly receives a substantial additional charge. The current strength is increased. The course of the lightning current, according to Berger (8), who recorded it on the summit of Monte San Salvatore, shows that a current maximum is reached after 5-10 μs. The vertical length of the lightning channel after 5-10 μs is approximately 400-1200 m (5). The order of magnitude of the distance between the space-charge cloud and the ground agrees with the length of the leader's "second stage" measured by Schonland et al. At Monte San Salvatore the space charges may be particularly heavy. The two 70-metre-high towers on the 600-metre-high mountain both generate glow discharges in the static electric field. The charges - approximately 1 Coul in 10 minutes - may affect the lightning path. The statistics of lightning strokes to ground show this clearly (9). The annual number of lightning strokes to these towers is 29. If this is converted to 10 lightning days (corresponding to an isoceramic level of 47 lightning days) we obtain 6,2 strokes per year, the same order of magnitude as on the Empire State Building in New York and approximately 25-75 times greater than on a 70-metre-high tower on level ground (10).

How a leader develops near the ground is not known in detail. To calculate the field strength on the ground near the leader certain assumptions have to be made as to the charge distribution in the leader channel. Schonland assumed that the charges are evenly distributed over the length of the leader (5). Bruce and Golde (11), on the other hand, assumed that the charges decrease exponentially with height, corresponding to e^{-h/h_0}. The constant h_0 is between 54 m and 1430 m. Pierce (12) points out that the line density of charge along the channel cannot be uniform. It is probably greatest towards the middle portions. In the immediate vicinity of the cloud the charges are slight, as the potential difference is comparatively small. At the ground end the potential difference is great, but the time is not sufficient for the extensive production of charge. Griscom (13) evolved a theory according to which the space charges at the end of the leader are concentrated in a ball with a relatively large diameter. The reason for his discussions was an unexpectedly large number of flashovers in a high-tension network. Fig. 2 shows the charge distribution according to these different assumptions. In calculating the attraction distance between the leader and an object on the ground, the charge distribution in Fig. 2 plays an essential part. Thus Golde (14) calculates the distance between the leader, according to Fig. 2b, and the ground with different intensity values of the space charge for one field strength on the ground. A leader charge of 1 Coul, according to Golde, corresponds to a lightning current of 20 kA. Distributed exponentially, with h_0 = 1000 m, this charge at a distance of 17 m from the ground generates a field strength of 10 kV/cm. With a lateral distance of 45 m, calculated in the same way, the field strength is 3 kV/cm and consequently sufficient to start a capture discharge from an object about 20 m high to the leader. The attraction distance is thus $\sqrt{17^2 + 45^2} = 48.1$ m. This method of calculation of the attraction distance for smaller space charges and consequently smaller current strengths receives support from many observed lightning strokes on lower objects adjacent to high objects or horizontally to low objects. Fig. 3 shows an example (15), a stroke horizontally on a farmhouse roof to the lightning-conductor cable, which was located the width of two bricks from the edge of the roof. The damage was comparatively slight, a fact which is often observed in connection with such phenomena, for example, in the first "classical" lightning stroke at Purfleet, England, in 1777 (16) on the Meeting House of the Artillery College, which was furnished with a lightning arrester. The lightning did not strike the rod but struck an iron corner clamp above the cutlers. The tip of the rod formed a protective angle of 31° and was 14 m from the point struck. Here also the damage was insignificant, but the fact that a lightning conductor with a protective angle of 31° could not prevent it caused a great sensation at the time, without it being possible to give any explanation.

The protection of high-tension lines against direct lightning strokes with the aid of earth wires is an important technical problem which has given rise to many investigations, both theoretical and experimental. Davis (17) took up afresh the problem of calculating the protective value of these earth wires and consequently the frequency of lightning strokes to high-tension lines. He calculated the flashover voltage between the end of the leader and the ground with the aid of an impulse flashover gradient based on extrapolated experimental values. He determined by geometrical calculations the effectiveness of the ground wires' shielding angle in relation to the high-tension line. The shielding angles ranged from 45° to 15°. With a shielding angle of 45° in an earth wire at a height of 20 m, flashes with a current strength of over 37 kA would be intercepted by the earth wire. With a shielding angle of 20° the corresponding current strength is 20 kA. It can be deduced from the statistical distribution of lightning currents that the number of lightning strokes to the transmission line would be reduced from about 40% to 17% (10 to 4.25). This does not tally with practical experience. The quantitative calculation is dependent on very approximate assumptions as to the distribution of the charges in the leader. The geometrical method cannot take into account metre-long corona discharges which are generated from the cables and alter the geometrical picture.

Grindley (18) calculated the magnitude of the charges bound on earth wire and on phase conductor by the leader in some distant part of the wires. Equality of charges is taken as a condition in which both wires are equally likely to be struck. The charges are calculated from the field due to the leader and it is shown that equality of charges corresponds to both wires being at the same equipotential of the leader. Calculation suggests that shielding is normally adequate for conductors in a wedge, of which the apex line is the earth and of semi-vertical angle 45°. At a shielding angle of 45° an earth wire would consequently offer perfect protection. Fig. 4 shows that this does not agree with experience. This figure is a collocation of lightning faults in high-tension lines operating at 275-400 kV and a few lines below 275 kV with a low earth resistance in the pylons. The majority of these faults arose from lightning strokes to the line. The values are derived from a tabulation by Kastenko (19) and have been converted to a line length of 100 km, 100 lightning days and a line height of 30 m. According to this tabulation, the faults are reduced from about 10 to 0.25 when the shielding angle is reduced from 45° to 20°. In addition to Kastenko's values for protective lines about 30 m high, the values published by Burgsdorf (20) for 220 kV, 150 kV and 110 kV lines in the USSR are also reproduced (Fig. 4). These lines have an average height of 15 m. The original values have been converted from 30 lightning hours (= 20 lightning days) to 100 lightning days. The number of lightning strokes to the phase conductor increases very substantially with increasing shielding angle. The risk of a stroke increases approximately quadratically with the height of the object (10). If these values, which were established for lines 15 m high, are converted to a height of 30 m by a factor of 4, the agreement is then satisfactory.

T. Horváth (21) has attempted to avoid the disadvantages of a geometrical calculation by means of an experimental model investigation. He determined the probability distribution of the critical distance between the leader and the grounded object with the guidance of Golde's calculations and of the statistical distribution of lightning currents. By model experiments on a scale of 1:30 to 1:100 he determined the probability of a lightning stroke on the conductor, which was protected by an earth line with shielding angles of 20° and 30°. By reducing the shielding angle from 30° to 20°, the number of lightning strokes was reduced in the ratio of 10:1 in these model experiments on a scale of 1:50. This agrees with experience, as shown in Fig. 4. But the problem is not thereby solved, as the experiments are based on uncertain assumptions as to the critical distance. The relative amplitude of the pre-discharges in these model experiments is not in accord with reality. These model experiments do not reproduce correctly the influence of the height of the line on the frequency of lightning strokes. An alteration in the scale of the model and thereby the height of the line in the ratio of 2:1 results in a change in the stroke frequency in the ratio of 30:1 with a shielding angle of 20° and of 10:1 with a shielding angle of 30° and therefore not in agreement with observed values.

The question of the influence on the lightning path of corona discharges from lightning-conductor points is as old as lightning research. This complex of questions includes Dauzère's inquiries concerning an accumulation of lightning strokes on a boundary line between two different geological formations. According to Dauzère, the emanation of radium from geological discontinuities influences the lightning path through the ionization of the air. About ten investigations ensued. Some showed a tendency to strive after clap-trap. The question would long ago have been laid ad acta if substantial ~~financial~~ commercial interests had not been involved in protecting buildings centrally by a single radio-active point. The γ-radiation generated by these radio-active lightning conductors can be demonstrated by sensitive instruments at a distance of several hundred metres. But the ionization of the air should be 10^6 to 10^8 times more powerful than the ionization that can be produced by a radio-active point, to have any possible effect on the lightning path (23). Uncertainty in judging electrical effects in the atmosphere is often a result of incorrect measurements. Unfortunately, many investigations made before 1942 are valueless on account of fundamental errors in measurement, particularly as regards the electrostatic field in thunderstorms. In low-lying land with plants, trees and grass the field is limited to values which seldom exceed 10 kV/m. Incorrect measurements at a height of 600 m above sea-level at the High Knob station in , for example, resulted in field strengths with an average value of 200 kV/m. Ten per cent of the measured values showed a field strength of more than 260 kV/m (24). Even with a field of 6-10 kV/m all plants produce such intense space charges that the electrostatic field seldom exceeds 10 kV/m. With a field of 70 kV/m, discharges on a man's fingers are visible. Only in areas without these "points", for example, at sea, can such powerful electric fields arise that St. Elmo's fire can be formed on a ship. There is consequently a conceivable risk of lightning strokes on ships, but with the steel ships of today this is no longer of current interest.

The Lightning Path on the Ground

The statistical frequency of lightning currents and charges is fairly well known through many investigations (25). Their probability distribution is represented within certain limits by a normal logarithmic distribution. If the percentual number of the magnitude x (current or charge) within the limits Δx is denoted by Δz, the distribution is expressed by

$$\frac{\Delta z}{\Delta x} = \frac{1}{\sqrt{2\pi}} \cdot \frac{1}{Msx_0} \cdot \frac{(x_0)}{x} e^{-(\log (x/x_0))^2/2s^2}, \tag{1}$$

where x_0 is the ~~average~~ median value, M the base of the natural logarithm (2.306) and s the standard deviation. The mode of distribution x_{mod} is

$$x_{mod} = x_0 e^{-(Ms)^2} \tag{2}$$

and the arithmetical average value x_{arith}

$$x_{arith} = x_0 e^{+(Ms)^2/2}. \tag{3}$$

The probability of the magnitude x is calculated by the Gaussian distribution

$$P = \frac{1}{\sqrt{2\pi}} \int_{\infty}^{t} e^{-t^2/2} dt \tag{4}$$

where

$$t = \frac{1}{s} \log (x/x_0). \tag{4a}$$

Table 1

Some typical values are given in Table 1. Column 1 reproduces the values ~~values~~ recommended by the AIEE for lightning currents above 5 kA (26). According to this tabulation, with 18 kA as ~~average~~ median value, the current strength which occurs most frequently is 10 kA. The arithmetical mean is calculated as 23.7 kA. Column 2 shows the average values in investigations by both Berger and Stekolnikov and measurements in Sweden (25) which take into account current strengths below 5 kA. The current strength which occurs most frequently is 4.25 kA. The arithmetical mean is 22.8 kA. The charges in column 3 are values for a single lightning stroke. Column 4 gives charges for a complete lightning discharge consisting of multiple discharges and prolonged discharges (25).

Extrapolation for a cumulative value less than 2% would give values too large for the current strength. If the percentage of lightning currents greater than 50 kA is drawn on log-lin paper, P_J for J(A) lightning currents, according to columns 1 and 2 in Table 1, is represented by the following expressions:

$$P_{J_1} = e^{-0.384 \times 10^{-4}(2 \times 10^4 + J)}, \tag{5a}$$

$$P_{J_2} = e^{-0.288 \times 10^4(3 \times 10^4 + J)}. \tag{5b}$$

with J the current in A.

If the current strength is calculated for a probability $P = 0.1$ and less, according to (5a) and (5b), the values given in Table 2 are obtained. Powerful strokes with current strengths exceeding 200,000 A occur very seldom.

Table 2

The ~~specific~~ current-heat impulse $\int i^2 dt$ has not been systematically investigated. Practical experience is available from investigations with a power transmission line from Boulder to Los Angeles (27) carrying 287 kV in an area with about 30 lightning days a year. Three stations are shielded against lightning strokes by capture towers 50 m high, carrying earth wires. These towers and some pylons, 80 towers in all, are furnished with elevation points, magnetic links for current measurement and six copper wires connected in series (see Table 3). The current-heat impulse values given have been calculated from experimental investigations by Foitzik (28).

Table 3

Experience over 20 years shows that, in lightning strokes on these towers, 1, 2 or 3 wires are destroyed, never 4. One example mentioned is a current strength of 43 kA, which destroyed wires nos. 1-3. On another occasion 36 kA were measured without wire no. 1 being destroyed. Bellaschi (29) determined experimentally the connection between the current impulse (decreasing exponentially) and the half-value period T_H required for fusing copper wire:

$$I = 3{,}2 \times 10^5 \times \frac{A}{\sqrt{T_H}}. \tag{6}$$

where A is the cross-section in mm^2 and T_H the half-value period in μs.

With a 36 A peak current which does not fuse 0.81 mm wire, the half-value period, according to (6), is less than 40 μs. The probability of these towers being struck would seem to be at least 0.15 per year. With 80 towers and 20 years' experience the probability of the current-heat impulse being sufficient to destroy a 2.09 mm^2 copper wire is thus less than 0.4%.

After 16 years of measurements at San Salvatore, Berger (9) confirms that the current-heat impulse was greater than 1.5×10^6 A^{2}sec on five

Table 4

occasions and greater than 6.4×10^6 A^2 s on one occasion. The corresponding probabilities are about 0.75% and about 0.15% respectively. These results are collated in Table 4.

The maximal velocity at which the lightning current increases in strokes to the ground (di/dt) has not been so comprehensively investigated as to enable the observational material to be treated statistically. Direct measurements on tall chimneys, carried out by Hyltén-Cavallius and Strandberg (30), showed on several occasions di/dt values greater than 30 kA/μs and once a value of about 100 kA/μs. At 30 kA/μs the inductive voltage drop in a ~~cable~~ line with an inductance of 1.67μH/m is 50 kV/m. Oscillographic measurements of the lightning current make an analysis possible. Berger (8) was able to show a current rising to the maximum value after 5-10 μs as a consequence of a first downward-progress leader from a negative cloud and of an upward midgap streamer from the air (Fig. 5a). Ten per cent of the measured course shows a steepness greater than 25 kA/μs. Partial strokes from negative clouds, which follow either the first discharge, in accordance with Fig. 5a or the prolonged discharge typical of San Salvatore of a few tens or hundreds of ampères, have a front period of only one or a few microseconds (Fig. 5b). The specific steepness is thus substantially greater) (than with a current course in accordance with Fig. 5a. The method of measuring the current course with the aid of a delay cable has been used since 1960. The results are consequently not yet, so numerous as to) (enable a statistical analysis to be carried out.

The multiplicity of courses which lightning current can take on and in the ground results in numerous and varying phenomena connected with questions of protection. Extreme and uncommon phenomena attract particular attention in this connection and are naturally more conspicuous than the more common cases. The following phenomena are mentioned briefly and are illustrated in individual cases by examples.

1. Power phenomena, for example, in a lightning-conductor ~~cable~~ line. The power increases as the square of the current strength. With a

lightning current of 100 kA there comes into existence a power of 500 kp in a ~~cable~~ line which follows a very pronounced cornice on a building. In addition breaking forces arise in straight lengths.

2. The following are some of the manifold voltage phenomena at the place of striking, and starting from the point of striking:

(a) Voltages of up to several million volts as a result of the resistance in transit to earth.

(b) Sliding discharges from the point of striking to the surroundings up to a distance of 50 m, arising in very poorly conducting bedrock, for example, granite.

(c) Voltage differences in a cable as a result of rapid change in the lightning current. The voltage difference may be 100 kV per metre of ~~cable~~ line at 60 kA/μs.

(d) "Displacement" of voltages to distances of many hundreds of metres through fissures in rock (tunnel building), wire fences, power lines or underground cables.

3. Heat phenomena.

(a) When the striking place consists of metal, power is supplied to the surface of the metal equivalent to the strength of the lightning current times the anode voltage drop. At 100 kA a power of about 1000 kW is supplied. The power density in copper is about 800 kW/cm^2 and in aluminium 350 kW/cm^2 in the first 10 μs and then decreases owing to the reduction of the current density.

(b) In the interior of the metal current heat arises, which is inversely proportional to the fourth power of the linear dimensions of the conductor, for example, the wire diameter or the plate thickness.

(c) Transmission of heat from the lightning channel to the surroundings, thereby causing fire. With a lightning stroke in sand fulmurites may be formed. At 100 kA the power is approximately 150,000 MW/m in sand.

4. Pressure phenomena.

(a) In the rapid expansion of the lightning path as a result of a rapid growth in the lightning current, a pressure wave arises which is released from the lightning channel at supersonic speed. The [redacted] pressure and the wave impulse may produce considerable damage.

(b) The same phenomenon may arise in the vaporization of metal wires.

(c) Turbulent forces [redacted] arise in the evaporation of water in a cleft. Trees split in most cases. At 100 kA blocks of stone weighing 5 tons may be torn off and rocks weighing 100 kg thrown 20 m.

This short tabulation will be illustrated by a few examples.

1. On June 15, 1956, lightning struck the church at Rudolzhofen (Bayern, Germany) and did extensive damage to the lightning-conductor installation and to the church (31). Fig. 6 shows a semi-diagrammatic picture. From the top of the tower two copper conductors ran to earth, one (4 x 3 = 12 wires, 30.6 mm^2) directly and the other (7 wires, 24.2 mm^2) over the body of the church. The cables were torn to pieces in at least seven places, denoted in Fig. 6 by the figures 1 to 7. (The conductor with lightning faults 1 and 2 ran down the other side of the tower. The power input similarly took place on the other side. Fig. 6 was drawn with this down lead on the front side for the sake of a more perspicuous survey.) At 1 the slate roof was damaged. At the grounding point 8 a hole appeared in the concrete pipe which had been used as a mechanical protection. The rainpipe was damaged at I and II. A flashover had occurred from the down lead to the rainpipe at a distance of about 30 cm and from the rainpipe to the power cable, similarly at a distance of 30 cm. The cable in the church (4 x 1.5 = 6 mm^2) was vaporized for a length of 10 m, equal to 0.5 kg of copper. Considerable pressure damage was done to the organ and the electrical installation. Examination of the material showed that the temperature of the cable had been about 700°C. To heat copper cables of 54.8 mm^2 to red heat, a current-heat impulse of 1000 x 10^6 A^2 s is required and to vaporize 6 mm^2 copper, 37 x 10^6 A^2 s. From these power and heat phenomena the strength of the

lightning current can be estimated as 300,000 kA, which, with an effective duration of at least 11 ms, meant a cloud charge of over 330 Coul. Such phenomena occur with a probability of less than 1:100,000 (see Table 2).

2. Fig. 7 shows the situation in a lightning stroke which caused considerable damage to a house without the lightning conductor being able to prevent it (32). The flash had struck a birch tree about 20 m high at a distance of 35 m from the house. The tree stood on granite covered with a thin layer of soil. The area was strewn with large and small stones. Several traces led from the tree, which was totally splintered. One trace, more than 35 m long, led to the house. Several cubic metres of earth and stones had been thrown up, six windows had been smashed and 40 or 50 litres of earth and stones had been flung into the upper floor of the house. Via the cellar the flash had struck a wall socket for the electric cable in the kitchen, about 1.5 m above ground level. The cable (2 x 1.5 mm^2) was vaporized. The trace then disappeared into a 4 mm^2 cable and thence to a water-pipe with a flashover approximately 10 cm in length. Four persons who on this occasion were sitting only 2 m away from the vaporized cable were uninjured. This phenomena – that a house may be struck and damaged from under ground – is not particularly uncommon in Scandinavia when granite is the bedrock (33). Experimental investigations of peak currents in clefts permit an extrapolation to a current strength of 100 kA with a half-value period of 200 μs. In damp sand the amount of energy developed in such cases is approximately 1000 kWs per metre of the lightning path. This is equivalent to the energy developed in the detonation of 215 g of dynamite or 350 g of gunpowder per metre.

"Displacement" of the voltage plays an important technical part. In tunnel construction in high mountains, primers prepared for blasting have been exploded too soon and accidents have been caused. As a safety measure the cables are provided with a metallic sheath (34) and special primers are used which require substantially greater power for firing than the ordinary primers, which ignite even with a power of 1 mWs (35). ~~The~~ Cables in the ground may be exposed to a direct lightning stroke at a distance of several tens of metres from the place of striking. Telephone cables connected with overhead lines are exposed to indirect and direct lightning action. Copious specialist literature shows the importance of safety measures (36-40, a limited selection).

3. In a lightning stroke on a lightning conductor, high voltages may arise in the ~~cable~~ line, with the result that a flashover may occur indoors to electric cables or telephone wires 40 or 50 cm away. Many fires have been caused in this way. These high voltages are then transferred via power or telephone lines to adjacent houses. It is, however, often possible to establish that the damage at a distance of about [illegible] 10 m from the point of striking is fairly slight. McCarthy et al. (41) analyse a lightning stroke on a church in north-western Pennsylvania with the aid of installed oscillographs and magnetic links. The lightning stroke shattered a 4" by 6" by 18' wooden rafter, left the steeple and terminated on the wiring above the ceiling. The church had no lightning conductor - the electrical installation was the lightning conductor. Some fuses were blown and some lamps vaporized, but neither the watt-hour meter nor the 7.2 kV transformer 60 metres away was damaged or affected by the flash. The lightning current was established as having been 31.7 kA. Of this, 4.6 kA went to earth in the transformer, 19.5 kA to the high-voltage-grounded conductor and 6.7 kA to the high-voltage phase conductor via the transformer. The duration of this partial current was determined oscillographically as longer than 2000 μs. Similarly the damage to the electrical system in the case of the powerful flash at Rudolzhofen (Fig. 6) was very slight. Fig. 8 shows the damage in the general plan, denoted by figures 1-8; fuses blown, lamps vaporized and flashovers in junction boxes. No meter was damaged, in spite of the fact that the distance to some installations was less than 30 m from the place of striking.

4. Very high voltages may arise in lightning strokes on a thick bed of sand, the foundation of which consists of a better conductor, for example, clay. The lightning channel goes almost perpendicularly down. The voltage gradient is about 100-150 kV/m. After about 100 μs of contact with the lightning channel pressed into the sand, fulgurites arise. The temperature of the lightning channel, according to spectroscopic

measurements by Mandelstam (42), is 16,000-25,000°C. Fulgurites arise at 1800°C. Their generation can only be established in a chance direct observation of a lightning stroke in sand (43). In the atmosphere the pressure is propagated as a detonation wave, which can shatter window panes at a distance of about 10 m. Fig. 9a shows a remarkable case of damage caused by pressure to a window pane. An almost circular disc (160/170 mm in diameter, glass thickness 2.5 mm) with sharp edges had been cut out of the pane. The window was an external one, separated from the undamaged inner one by a space of about 50 mm. The round disc had fallen down between the two windows. (The window is in the Institute's archives, initiated by Professor H. Norinder.) Böckmann (44) describes similar damage (Fig. 9b) in June 1754 to a hothouse in Karlsruhe. The window was torn out of the frames in which it was nailed and thrown out into the garden - a result of the negative pressure. The explanation of the damage may be that the stress on the glass through the pressure wave and ~~negative pressure~~ depression wave of the lightning channel was reinforced to breaking point through the wave's being propagated in the glass and reflected at the edge of the glass.

Lightning Protection in the Light of Standard Codes

The knowledge and practice of that time was summarized by the Lightning Rod Conference in London in 1878 (45). About 25 years later individual countries - England, the USA and Germany - began to draw up instructions and guiding principles dealing with the protection of different kinds of buildings, towers, chimneys, ships and last but not least structures containing inflammable liquids, gases and explosives. A tabulation of the codes available to me is given as ref. (46). On the whole, the instructions are much the same but on closer scrutiny show divergent views which are not due to the individual character of particular countries.

The question of the zone of protection is not dealt with in a uniform manner. In the USA (16, m) a shielding angle of 45° in important cases and 63° in less important cases is considered sufficient (Fig. 10).

In England (46, 1) a shielding angle of 45° is given, but not, however, for particularly important buildings, such as explosives factories, oil and petrol tanks, etc. In the USSR (46, n) the shielding angle is subdivided. In a chimney 52 m high the shielding angle for the upper part is very limited (Fig. 11). For the lower part a protective radius of 40 m is stated on the basis of model experiments.

Contrary views on elevation rods are made clear by Figs. 12 and 13. In the USA several elevation rods are recommended, for example, 15 on "the typical installation on a barn group". In Germany special rods are not recommended on the roof of a farmhouse. The roof conductors act as an air terminal. Some awe-inspiring objects (Fig. 14) included in the Code for Protection against Lightning (1959) in the USA are probably of most use on the psychological plane. According to British Standard (46,l) , an air termination need not have more than one point and should be at least 1 foot above the salient point on which it is fixed. We accordingly see that the dimensions of the elevator rod, which was formerly 10 feet high or more, are now only rudimentary (Fig. 15).

In all the instructions the question of reliable grounding plays an important part. In England a maximum value of 10 ohms is prescribed (45, 1, 308c). In Austria this is not possible at ~~financially~~ economically justifiable expense in certain provinces. The Austrian instructions (46, a, 10, 3) therefore allow higher ~~transition~~ resistance values than 10 ohms for a specific earth resistance of more than 250 ohms/m. For this, exact instructions with various examples are given. In the USA (46, m, 317h) it is laid down that low resistance is, of course, desirable but not essential. By a building resting on a base of solid rock it would be impossible to make a ground connection in the ordinary sense of the term. The most effective means would be an extensive wire network laid on the surface of the rock surrounding the building, after the manner of a counterpoise to a radio antenna. Here we approach the standpoint of James Clerk Maxwell (47) that "earth" does not exist in the protection of buildings against lightning. The essential thing is to prevent potential differences. Maxwell in 1876 suggested making a construction like a cage with 6 mm^2 copper wires. In modern houses with heating systems, water-pipes and electric cables, not many wires would be needed to complete the whole arrangement according to Maxwell's suggestion (Fig. 16).

The cross-section of the conductor necessary for the discharge has for many decades been fixed more on the basis of the craftsman's experience of mechanical strength and of practical knowledge of very powerful lightning strokes than on the basis of physical investigations and calculations of probabilities. For the protection of aircraft, however, it was necessary to determine the cross-section of the conductor for bonding purposes. The current-carrying capacity of the bonding system has to be such that a lightning discharge current can be carried between any two extremities of the airplane without risk of damaging flight controls and external surfaces or of producing excessive voltages within the aircraft. The investigations were carried out with peak currents up to 100 kA, reaching the crest value at 10 μs and dropping to 50 kA at 20 μs. For this a copper cable with a cross-section of 3.3 mm^2 or an aluminium cable with a cross-section of 5.1 mm^2 was necessary (48). With a few exceptions the cross-section prescribed in the standards of different countries is a result of experience in building technique and is much bigger.

Lightning protective systems can be divided into three groups: (1) super-installations, in which relatively large sums of money have to be spent to obtain perfect protection; (2) standard installations, which are designed, in the first place, for valuable buildings (public buildings) and buildings in which financial considerations play a small part; (3) "do-it-yourself" installations, in which the financial aspect of protection plays the main part and which are designed for the numerous small dwellings in the provinces, for which a standard installation would be too expensive.

An example of a super-installation is shown in Fig. 17, an explosives factory built on poorly conducting ground. The surroundings of the building are protected by banks of earth. On these banks stand wooden posts carrying a network of 50 mm^2 copper wires with a mesh width of about 8 m. This network is grounded through a ring conductor with outgoing earth wires at a relatively ~~short~~ great distance from the building.

This is constructed like a Faraday cage and grounded separately. All the metal parts in the building are carefully grounded in order to avoid the generation of small sparks by a lightning stroke. There is no permanent metallic connection between the building and its surroundings. If the supply of electricity is necessary, this is done by means of a cable, the last 10 m of which are arranged overhead and are separated from the building at this distance when lightning is forecast.

Standard installations are so thoroughly described in the instructions of the respective countries (46) that it is not necessary to give an account of them. Only one point may be mentioned: the practical difficulty of connecting large metal parts to the lightning protective system. A relatively large amount of lightning damage has been brought about by, amongst other things, television antennae. The difficulty is that in many cases the supports for the antennae, usually iron pipes affixed to the roof or a chimney, are not grounded at all. Obviously they are virtually ungrounded lightning rods with only the twin lead of small wires as a circuit to ground, either through a small arrester, probably poorly grounded, or through the TV set. The twin lead is easily vaporized and thereby produces an explosion (49).

In the majority of countries lightning protective systems are not economical for small houses: other considerations play the main part in their ~~production~~ installation. Insurance statistics show that lightning damage in the countryside seldom exceeds a value of 3,6 per insured small dwelling and year. As a rule, it is not possible to produce a standard lightning protector for an economical sum of 20 x 3 = $60. In Poland **Szpor** has suggested protecting small houses with 10 mm^2 iron wire (50). Several hundred thousand installations have yielded a surprisingly good result as regards lightning (16). More detailed investigations of current-heat impulses and their probability showed that 10 mm^2 copper wires are completely adequate (51). The installation is made cheaper not so much by reducing the cross-section of the conductor but by the fact that it is possible to use lighter fittings and brackets, which are available mass-produced. It is possible to stretch the wires over the building oneself, without having to depend on the experts who are required for erection work with the heavier standard wires. It is requisite, however, that owners of small dwellings who wish to build a lightning conductor themselves should receive the essential instructions. This system is permitted in Sweden (46, i, 9).

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Tables

Table 1. Normal log distribution.

Column	1	2	3	4
Magnitude	Current, kA		Charge, Coul	
~~Average~~Median	18	13	3.1	15
Deviation	0.32	0.46	0.40	0.51
Mode	10.4	4.25	1.33	3.8
Arithmetical mean	23.7	22.8	4.7	30

Table 2. Extreme current strengths.

Probability	Current 1, A	Current 2, A
1:10	42,000	50,000
1:100	100,000	130,000
1:1000	160,000	210,000
1:10 000	220,000	290,000

Table 3. Current heat impulse

No.	Wire diameter, mm	Wire cross section mm^2	Current heat impulse, 10^6 A^2sec
1	0.81	0.52	0.019
2	1.02	0.82	0.048
3	1.29	1.31	0.12
4	1.63	2.09	0.303
5	1.83	2.63	0.49
6	2.05	3.30	0.77

Table 4. Probability of current heat impulses.

Region	Probability %	Current heat impulse 10^6 A^2sec
Boulder	< 0.4	0.303
San Salvatore	0.75	1.5
	0.15	6.4

Figures

Fig. 1. Lightning conductor proposed by Torbern Bergman for a building. ~~in~~ Uppsala, ~~in~~ 1760.

Fig. 2. Diagrammatic survey of the charge distribution in a leader channel, according to various proposals.

Fig. 3. Marks left by a lightning stroke on a farmhouse. (a) General view. (b) Detail of point of striking.

Fig. 4. Lightning faults on high-tension cables protected by earth wires with various shielding angles.

Fig. 5. Course of lightning current, according to Berger. (a) First stroke from negatively charged cloud. (b) Subsequent partial discharge.

Fig. 6. Damage caused by a powerful flash of lightning striking the church at Rudolzhofen (Bayern, Germany).

Fig. 7. Traces of lightning over poorly conducting ground from a distance of 35 m to a house.

Fig. 8. Distribution of insignificant damage caused by lightning to the electrical installation near the powerful flash mentioned in Fig. 6.

Fig. 9. Holes in window panes as a result of lightning discharges. (a) Window in Stockholm in August 1944. (b) Window in Karlsruhe in June 1754.

Fig. 10. Shielded zone of a mast, according to NEPA № 78

Fig. 11. Shielded zone of a chimney, according to Russian model experiments.

Fig. 12. Typical installation o~~f~~n a group of barns, according to the Code of Protection against Lightning (1959). (NEPA № 78)

Fig. 13. Lightning-conductor installation on a farmhouse, according to German recommendations.

Fig. 14. Air terminals, according to NFPA No. 78.

Fig. 15. Modern air terminal.

Fig. 16. A modern house with oil-fired heating etc. and lightning protection.

Fig. 17. Installation of a protective network on wooden poles over a building used for the manufacture of explosives.

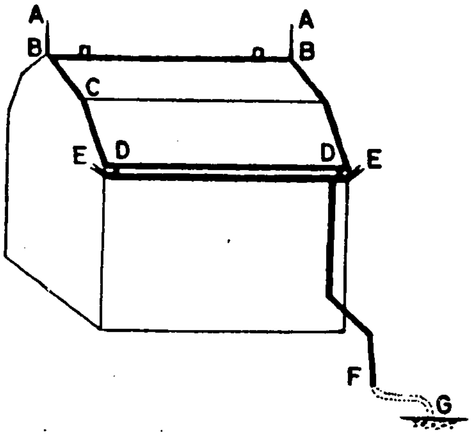

Fig.1. Lightning conductor proposed by Torbern Bergman for a building. Uppsala, 1764

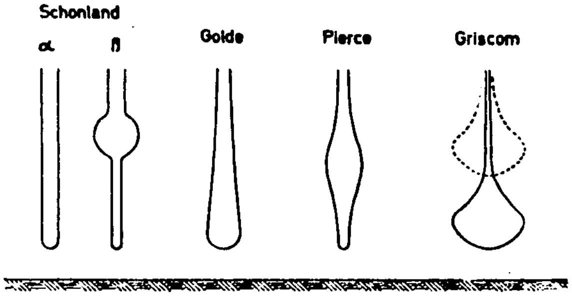

Fig.2. Diagrammatic survey of the charge distribution in a leader channel, according to various proposals.

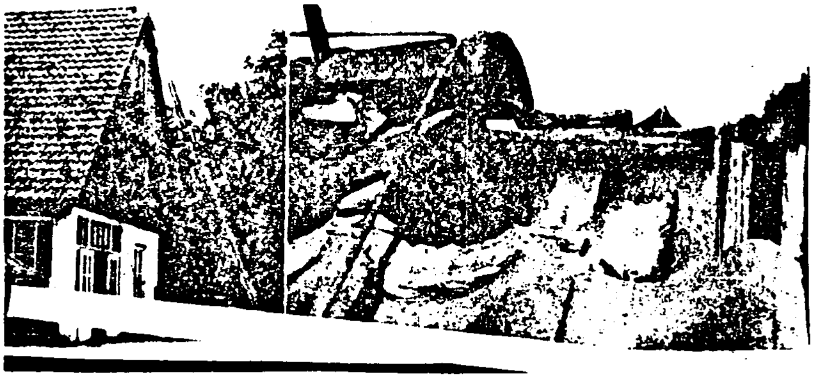

Fig.3. Marks left by a lightning stroke on a farmhouse
a) General view. b) Detail of point striking

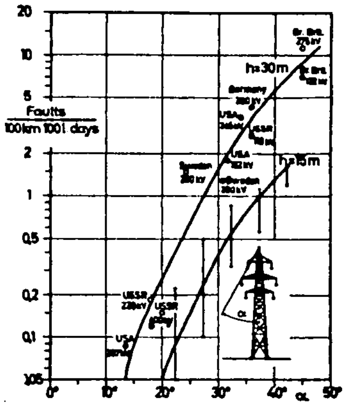

Fig.4. Lightning faults on high-tension lines protected by earth wires with various shielding angles.

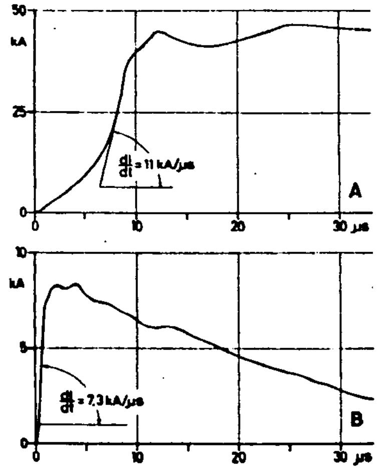

Fig.5. Course of lightning current, according to Berger
a) First stroke from negatively charged cloud.
b) Subsequent partial discharge.

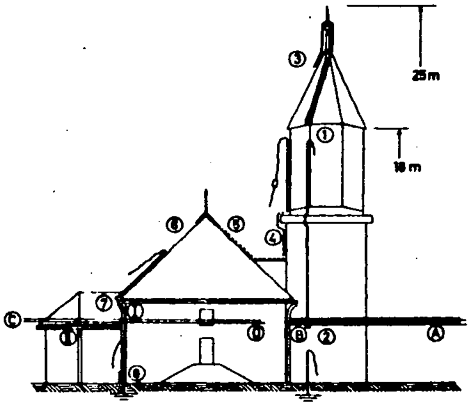

Fig.6. Damage caused by a powerful flash of lightning striking the church at Rudolzhofen (Bayern, Germany).

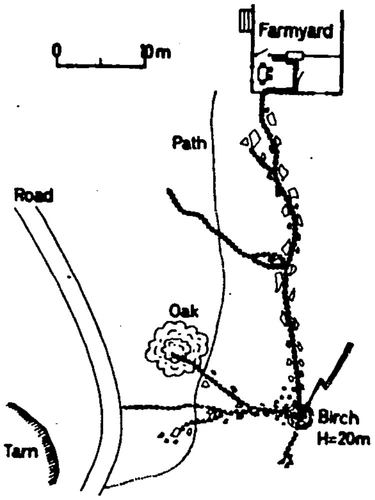

Fig.7. Traces of lightning over poorly conducting ground from a distance of 35 m to a house.

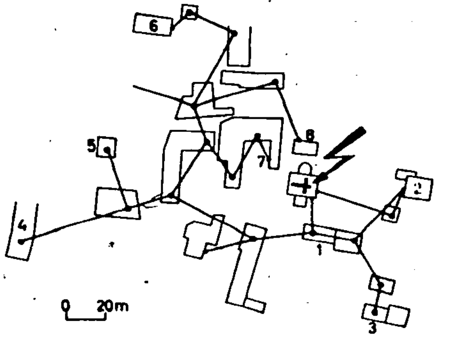

Fig.8. Distribution of insignificant damage caused by lightning to the electrical installation near the powerful flash mentioned in Fig.6.

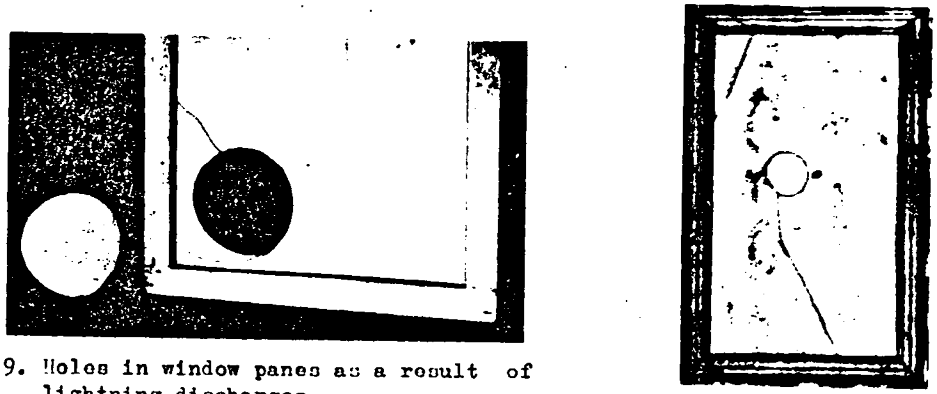

Fig.9. Holes in window panes as a result of lightning discharges.

a) Window in Stockholm in August 1944.

b) Window in Karlsruhe in June 1754.

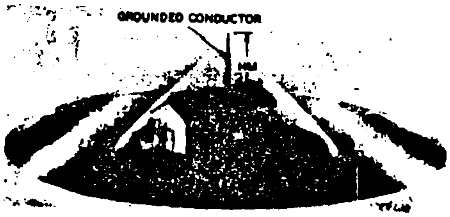

Fig.10 Shielded zone of a mast, according to NFPA No 78.

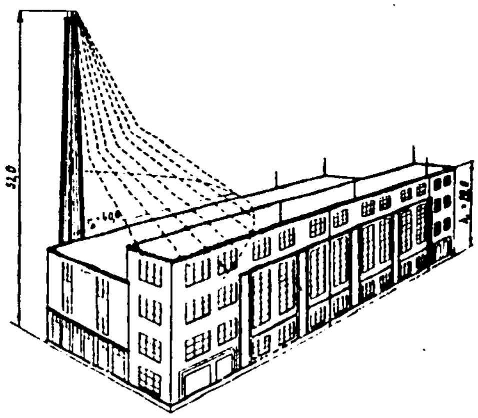

Fig.11. Shielded zone of a chimney, according to Russian model experiments.

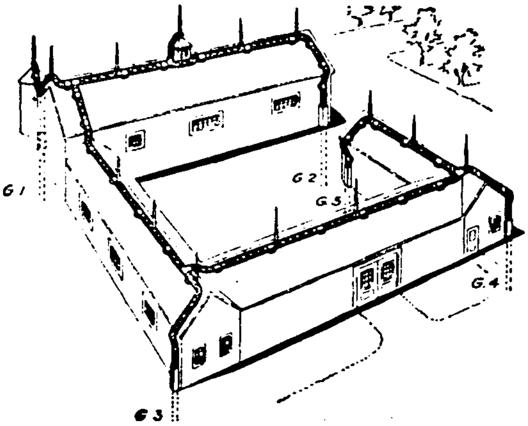

Fig.12. Typical installation on a group of barns, according to the Code of Protection against Lightning (1959). (NEPA No 78).

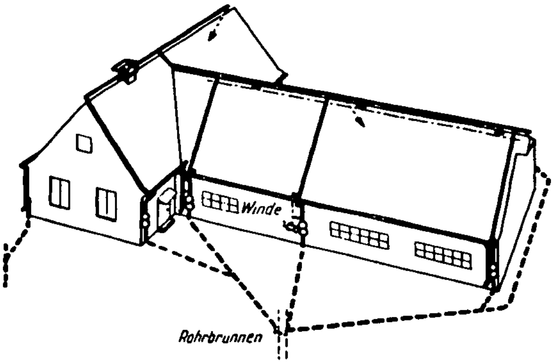

Fig.13. Lightning-conductor installation on a farmhouse, according to German recommendations.

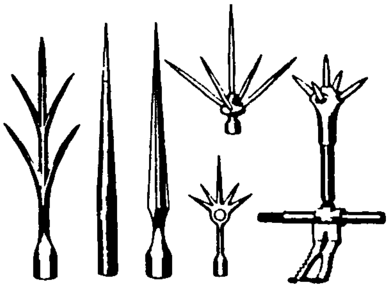

Fig.14. Air terminals, according to NEPA No 78.

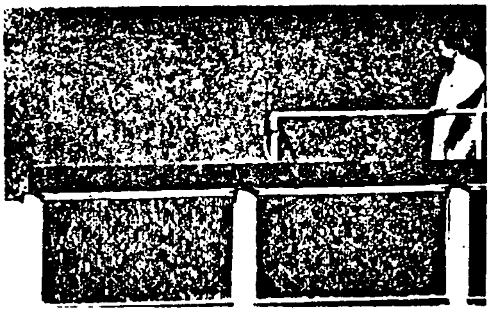

Fig.15 Modern air terminal.

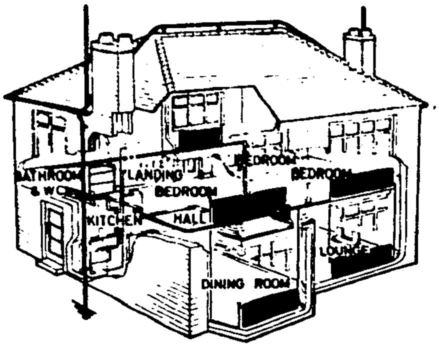

Fig.16. A modern house with oil-fired heating etc. and lightning protection.

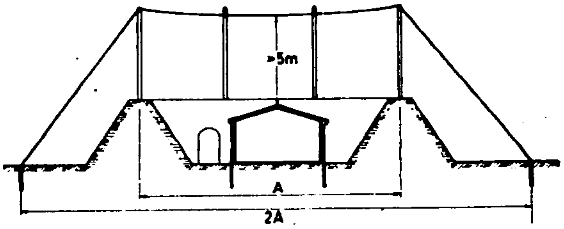

Fig.17. Installation of a protective network on wooden poles over a building used for the manufacture of explosives.

SESSION 9.1

Whistlers as a Phenomenon to Study Space Electricity.

by N.D. Clarence.

Part of the data used in this paper have been taken from the results of a joint project by the author and Dr. P.A. P'Brien now of the University of Khartoum. The results of this project are now in the course of preparation for publication elsewhere.

SUMMARY.

After a brief resumè of evidence supporting the contention that whistling atmospherics may be generated by lightning discharges to ground, and that the components of a multiple flash whistler arise from the separate strokes in the flash, an analysis of the measurement of dispersions of multiple flash whistlers is given. It is shown that there is an increase of about 3% in the dispersion of the second component as compared with that of the first. An explanation of this is tentatively given in terms of an upward electron jet originating from runaway electrons in the thundercloud. Further supporting evidence for such a jet is sought from a study of the records of electrostatic field changes during a lightning discharge to ground.

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Introduction.

During the International Geophysical Year whistling atmospherics were recorded in South Africa at Durban (geomagnetic co-ordinates $31^{\circ}34'$ S, $93^{\circ}04'$ E) by sampling incoming atmospherics for two minutes each hour during the day and night. All records were made on magnetic tape from which frequency-time curves of whistlers were made using a Kay Electric Sona-Graph. The records referred to below were all obtained during the period September 1957 to August 1959.

Multiple Whistlers.

Multiple whistlers, consisting of several components were frequently recorded and may be classified as either multiple path or multiple flash type (Helliwell and Morgan 1959). It is not possible to determine, merely by inspection of a spectrogram, the group to which any particular example belongs. It is known, however, from the Eckersley dispersion law that $t^2 = D^2/f$ where t is the time interval between the occurrence of the lightning stroke producing the whistler and the arrival at the observer of the component of radiated energy of frequency f. A plot of $f^{-\frac{1}{2}}$ v t gives a straight line the slope of which is the reciprocal of the dispersion, D, of the whistler~~s~~. Grouping may be carried out by drawing the Eckersley plot for each component and producing the straight line back to cut the time axis. In the case of the multiple path type the lines produce back to a single point indicating the same source for all components. For the multiple flash type the lines cut the time axis at points which are separated by from 10 ms. to several hundred milliseconds indicating a discrete source for each component. Typical examples are shown in fig. 1(a) and (b).

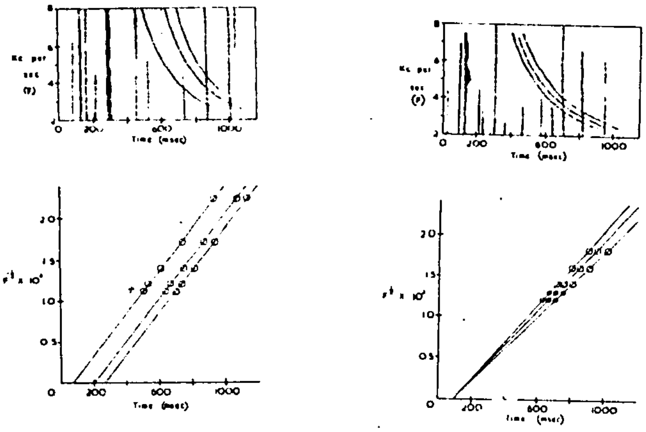

Fig.1. Eckersley plots for (a) multiple path whistlers and (b) multiple flash whistlers.

Of the Durban records of multiple whistlers selected for analysis, over 90% were of the multiple flash type. The ensuing remarks refer specifically to multiple flash whistlers.

The origin of whistlers.

Although sources other than lightning discharges cannot be excluded, there is a great deal of evidence supporting the contention that whistlers arise from lightning discharges.

The strong correlation found between thunderstorm activity in the region near the geomagnetic conjugate point of a recording station and short whistler activity at the station suggests that lightning discharges are the source of whistlers.

Helliwell, Taylor and Jeans (1958) found correlation between observed vertical discharges and long whistlers heard. The atmospheric waveforms recorded at the time were typical of those for flashes to ground.

By the simultaneous recording of long whistlers and the waveform of the related lightning discharges, and by direct comparison of the time intervals between whistler components and strokes in the lightning discharge, Norinder and Knudsen (1961) have shown clearly, for the records published, that the components of the whistlers arose from multiple discharges in the same lightning channel.

Although similar direct comparisons could not be made in Durban, as only short whistlers were recorded, the Durban results do provide further indirect evidence that lightning discharges are the source of whistlers. The distribution of the time intervals, Δt, between components of whistlers is shown in fig.2, together with the distribution of the time intervals between strokes of a lightning flash to ground.

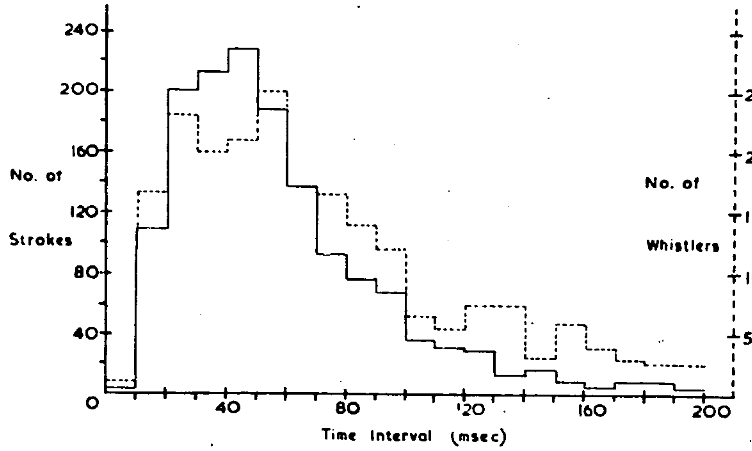

Fig.2. Distribution with time interval of
(a) lightning strokes to ground (full curve) and
(b) whistler components (dotted curve).

The modal value for Δt of between 20 and 60 ms. is in agreement with the value for the most probable time interval between strokes of lightning discharges to ground given by Bruce and Golde (1941) for records in Europe. Also the distribution may be compared with that for the time intervals between strokes to ground given by Schonland (1956) where the similarity of the two curves is again obvious.

It seems clear that where a multiple flash whistler has several components it is generated by a lightning flash to ground which consists of several separate strokes. For this reason it is felt that this type of multiple whistler could be more appropriately termed a "multiple stroke" whistler but for the sake of consistency with published literature the term "multiple flash" whistler is retained.

In the case of cloud flashes the modal value of the time intervals between rapid field changes is significantly less than the above value and of the order of 10 ms (Malan 1955; Kitagawa and Kabayashi, 1958). Furthermore, the radiation energy from cloud discharges in the 3-6 Kc/s range is at best only 1% of the corresponding energy for ground flashes (Malan 1958). It seems unlikely therefore that whistlers are generated by discharges within the cloud.

The Dispersion of Multiflash Whistlers.

The Ratio of the Dispersions of successive Components.

Whistlers with two components only.

For multiple whistlers with two components only, there was often a significant difference between the intensity of the components. The records could be divided approximately equally into three groups where the intensity of the second component was (a) greater than, (b) approximately equal to and (c) less than, the intensity of the first component. Also the dispersion of the second component was often slightly greater than that of the first.

In Table 1 the results of an analysis of the ratio of the dispersion of the second component to that of the first, D_2/D_1, are given. In the column giving the mean value of D_2/D_1, the standard error of the mean is also shown, and the final column gives the level of significance between the measured dispersion and a ratio of one.

This result proved particularly interesting in view of the fact that previous authors have stated that the dispersions of successive components are either identical or approximately equal. (Storey 1953; Iwai and Outsu 1956; Helliwell and Morgan 1959; Norinder and Knudsen 1961;). Because of the small difference between the measured values of D_2/D_1 and the value one, selected groups of records were analysed

Intensity Group	No. of records.	No. with D_2/D_1 1	Mean value of D_2/D_1	Significance level, P.
(a)	31	29	1.052 ± 0.011	0.001
(b)	41	28	1.026 ± 0.007	0.001
(c)	31	24	1.016 ± 0.006	0.01
All groups	103	81	1.031 ± 0.005	0.001

Table 1. Ratio of dispersions of components in a two component whistler.

by several different workers. All agreed with the main finding that $D_2/D_1 > 1$. Significance tests have also been carried out between the mean values of the dispersion ratio for the various intensity groups. Significance was calculated to be at the 0.04 level for groups (a) and (b) and at the 0.29 level for groups (b) and (c).

It is concluded, therefore, that the dispersion of the second component of a two component whistler is about 3% greater than that of the first and that there are significant differences between the dispersion ratios when two component whistlers are grouped accordingly to the relative intensity of the two components.

Whistlers with more than two components.

A similar analysis of the dispersion ratio for successive components in the case of whistlers with more than two components, leads to a similar conclusion. Results for records of whistlers with three, four and five components are shown in Table 2.

No. of records.	Mean value of Dispersion Ratio.	Significance level P.
52	$D_2/D_1 = 1.023 \pm 0.007$	0.005
52	$D_3/D_2 = 1.031 \pm 0.007$	0.001
20	$D_4/D_3 = 1.018 \pm 0.015$	0.30
7	$D_5/D_4 = 1.011 \pm 0.020$	0.70

Table 2. Ratio of dispersions of successive components for whistlers with more than two components.

Although the dispersion ratios D_4/D_3 and D_5/D_4 are both greater than one the number of available records is too small for any great reliance to be placed on these figures.

The Relationship between Dispersion and the Time Interval between Components.

An investigation was carried out to see whether the difference in dispersion between successive components was in any way related to the time interval between components. The analysis was made by plotting ΔD, the difference in dispersion between successive components, against Δt, the time interval between components. Time intervals of 20 ms were used and the results were obtained from all records of $D_2 - D_1$ and $D_3 - D_2$. In both cases it was found that there was an initial increase in ΔD, as Δt increased, followed by a decrease. The maximum value for ΔD occurred for a value of $\Delta t = 30$ ms.

The results for $D_2 - D_1$ are shown in figure 3, the numbers in brackets indicating the number of records, in the particular time interval, available for calculation.

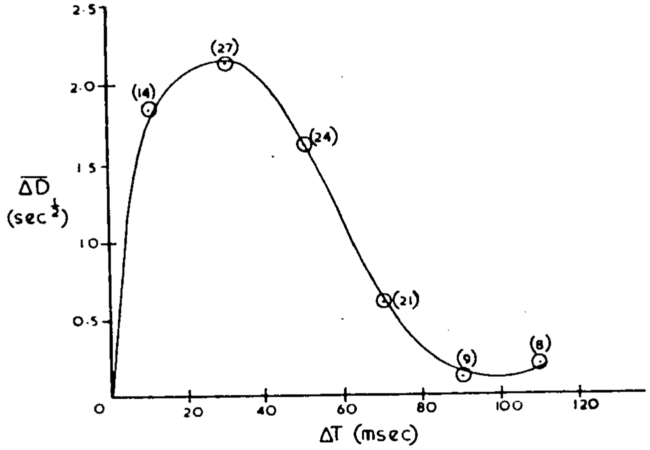

Fig. 3. Relationship between the difference in dispersion between the first two whistler components and the time interval between them.

Speculations on a Possible Explanation of these Results.

From the above it would appear reasonable to assume that (a) in the majority of cases the source of a whistling atmospheric is a lightning discharge between cloud and ground;

(b) in multiple flash whistlers the several components arise from the separate strokes of the lightning discharge,

(c) there is a small increase in dispersion between the successive components of a multiple flash whistler;

(d) the increase in dispersion between whistler components is related to the time interval between them.

Point (d) is of particular interest as it suggests that the dispersion measurements may be related to the physical processes occurring in the thundercloud during the interval between strokes. A possible explanation of the variation in D might be sought in terms of these processes.

Factors Influencing the Dispersion of a Whistler.

The dispersion D of a whistler is given by $D = \frac{1}{2c}\int \frac{f_o}{f_H}\, ds$. (Storey,1953), provided the frequency of the whistler is much less than either the gyrofrequency f_H or the plasma frequency f_o. ds is an element of path length and the integration is taken over the whole path. By substituting for f_o and f_H, $D = \left(\frac{e}{2}\right)^{\frac{1}{2}} \int \left(\frac{N}{H}\right)^{\frac{1}{2}} ds$. where e is the electronic charge in e.m.u., N the electron density per cc and H the magnetic field strength in oersted.

It is known that the ducting of whistlers, giving rise to the multiple path type, occurs very much more frequently in higher latitudes than it does at lower latitudes. It would seem reasonable, therefore, that the energy in each component of a multiple flash type has traversed the same path. In the short time interval between components the values of the magnetic field strength along the path will not change. Consequently, any change in dispersion between one component and another can only be due to a change in electron density along the path.

The fact that Δ D initially increases with Δ t, as shown in Fig.3, suggests that the change in dispersion is related in some way to the physical processes occurring in the thundercloud during the time interval between strokes. Could then the source of electrons, necessary to account for the increase in dispersion originate in the thundercloud?

Runaway electrons were postulated by C.T.R. Wilson (1925) who showed that in the presence of electric fields such as are found in thunderclouds, the energies of such electrons could be as high as 10^9 Mev. Evidence for such penetrating particles of high energy has been found by Schonland and Viljoen (1933), using geiger counters and by Halliday (1941) using an expansion chamber. In the former case there was a pronounced tendency for the counting rate to increase at the moment of the flash and in addition more impulses were registered during the few seconds before a flash than during a similar interval after the flash. The radar studies of Atlas (1958), Hewitt (1957) and Rumi(1957) have shown the existence of upward ionised jets during discharges of a thundercloud to ground. Such jets extend to heights well above the top of the thundercloud and are estimated by Rumi to have a velocity of approximately 2×10^7 cm/sec.

Using data given by Nelms (1956) for the range of electrons in various media it is estimated that for an electron to penetrate the remaining atmosphere from a height of 10 Km. it must have an energy of the order of several hundred Mev. It is possible therefore that runaway electrons, accelerated within the thundercloud, could provide an upward jet of electrons.

Assume, in the first place, that such a jet of electrons moves upwards during the time between one stroke and the next. The modal value of Δt between first and second strokes is 40 ms. and for this time interval $\Delta D = 2.0 \sec^{\frac{1}{2}}$. If the upward velocity of the jet is assumed to be 2×10^7 cm/sec., in 40 ms. an ionised column 8 Km long will be formed. The electromagnetic energy radiated from the second stroke would thus pass through this charged column in addition to traversing the whistler path traversed by the energy from the first stroke.

The question now arises as to whether this column of enhanced ionisation can satisfactorily account for the increase in dispersion of the second component over that of the first. Assuming a magnetic field strength of 0.12 oersted the value of the electron density in such a column, which could account for an increase in dispersion of $2.0 \sec^{\frac{1}{2}}$ is 9.7×10^7 electrons/cc. For such a medium the quasi-longitudinal approximation of the magneto-ionic theory, upon which the expression for D is based, is applicable and, assuming a colision frequency of 10^{10}/sec., the medium would have a refractive index of 22 for a 5 Kc/sec wave.

The above value for the electron density necessary to account for the measured dispersion is the effective density required in the assumed column. It could be used to estimate the current density in the jet and the total charge moving upwards from the thundercloud. In this case, however, values obtained would be minimum values for two reasons. Firstly the picture of the upward moving column has been greatly over simplified and no account has been taken of the effect of recombination. This would increase the value of the electron density by at least an order of magnitude From the intensity of radar reflections the electron density in upward jets has been estimated at 3×10^{11} per cc. as it leaves the cloud and 2.8×10^7 per cc. at a height of 60 Km. These figures are consistent with the known values for recombination coefficients at these heights which are of the order of 10^{-7}. The calculated value for the electron density necessary to account for increased dispersion falls satisfactorily within this experimental range of densities.

Secondly it has been assumed that the jet current flows for the whole of the time interval between strokes. From the work of Schonland and Viljoen (1933) this assumption appears to be justified, but it is likely that the intensity of the upward jet increases to a maximum at the time of the discharge.

The current density, J , in the jet is given by $J = Nev$. and using the calculated value of $N = 9.7 \times 10^{7}$ per cc. and $v = 2 \times 10^{7}$ cm./sec. is equal to 0.31 ma/cm^{2}.

The total charge carried upward by the jet is given by $Q = A.L.N\,e.$ when A and L are the area of cross section and length of the ionised column respectively. Substituting known values $Q = A.\frac{1.24}{10^{5}}$ coulombs with A in square centimetres. Estimates of the radius of upward jets vary over a wide range from a few centimetres to several kilometres depending on the assumed model of the thundercloud. With the uncertainty in the value of A it is difficult to make an estimate of Q. However, assuming a radius of 1 metre, approximately 0.7 coulombs of charge would be carried upward by the jet. Increasing the radius soon leads to enormous values for the charge carried upwards and unless the radius of an upward jet is of the order of 1 metre or less the assumptions made above become untenable bearing in mind that the charge brought to ground is approximately 4 coulombs.

The effect of upward jets on field change measurements.

If upward jets of electrons as postulated, do in fact exist some evidence for them might be expected from field change studies of lightning discharges. Malan and Schonland (1951 A) have considered the electrostatic field which would be produced by an upward moving charge and have shown that there is a reversal in the sign of the measured field change as the charge passes through a reversal height. Assuming that measurements are made at a distance D from a vertical discharge, the reversal height, H_r, is given by $H_r = D/\sqrt{2}$.

~~From~~ For upward moving positive charge, electrostatic field changes would be positive whilst the charge was below the reversal height and negative when above this height. In the case of upward moving electrons the signs of the field changes would be reversed.

Malan and Schonland esplain the observed results in terms of an upward moving positive junction streamer between strokes ~~and~~ having a velocity of approximately 3×10^{6} cm.sec. Final slow positive field changes observed for flashes at a considerable distance may also be due to positive streamers from the top of the thundercloud.

Consider the simultaneous existence of upward moving junction streamers of positive charge and upward jets of electrons. If both processes are below H_r the electrostatic field changes produced by them would be of opposite sign. Since both streamers originate in the thundercloud the faster moving electron jet would be the first to pass through the reversal height. When this happens the field changes due to each process would be positive and a sudden increase in the rate of change of the electrostatic field might be expected. Such field changes are occasionally observed in the final field changes of fairly distant discharges. A typical example of such a field change is shown in Fig. 4.

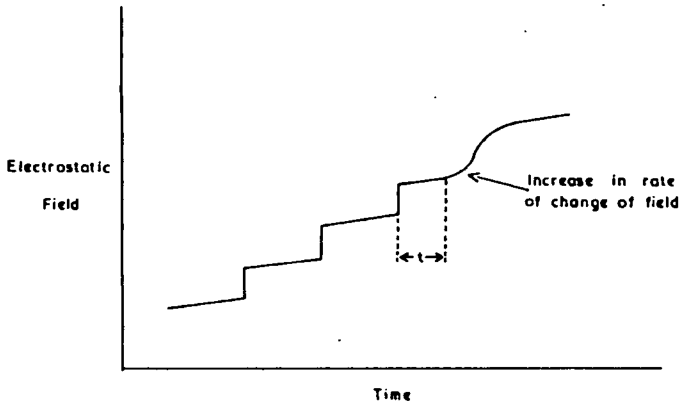

Fig.4. The electrostatic field of a fairly distant discharge showing a sudden increase in the rate of change of field during the final field change.

Suppose now that the following information is available: Distance of the discharge from the observer and hence H_r; the height of origin of the final stroke; the time interval, t, between the final stroke and the increased rate of change of the field. From these data it is simple to estimate the velocity of the upward electron jet, assuming that the increased rate of field change may be attributed to its passing through the reversal height.

The results of these calculations are shown in Table 2. for nine records generously provided by Dr. D.J. Malan, of the Bernard Price Institute, from data collected by him over many years. The stroke heights used in the calculations have been taken from Malan and Schonland (1951 B). In all cases the increased rate of field change occurred after the final stroke which originated below the reversal height.

Record No.	Distance (Km)	H_r (Km).	Field change increase after stroke No.	Assumed height of discharge (Km)	t (ms)	Velocity of electron jet. (cm/sec x 10^{-7}).
DA1,3	30	21.2	3	5.4	65	2.4
DAE3,1	20	14.1	2	5.1	14	6.4
DE2,3	16	11.3	3	5.4	20	2.9
DAH1,1	15	10.6	2	5.1	32	1.7
DAB5,9	15	10.6	3	5.4	60	0.9
DX4,6	10-20	10.6	9	8.9	28	0.6
DO3,5	13	9.2	2	5.1	16	2.6
DE4,6	12	8.5	2	5.1	46	0.7
DO2,3	10	7.1	1	3.7	.50	0.7

The calculated values of the electron jet velocity lie within the range $0.6 \times 10^7 - 6.4 \times 10^7$ cm/sec. Bearing in mind that there could be a considerable difference between the assumed and actual height of the final discharge, these estimated values of the velocity may be regarded as consistent with those obtained from radar studies.

The results of the above paragraphs appear to lend support to the assumptions made. In spite of this, the suggestion that the increased rate of field change is due to the processes outlined must be regarded as tentative for several reasons. The 9 records analysed were the only ones showing the effect out of a total of 285 records and a more frequent occurrence of the effect might be expected. Similar increases in the rate of field change between strokes earlier than the last might also be expected but there is little evidence for this. Finally, out of a total of 159 field change records of flashes which occurred at a distance of 8 km. or nearer there are three instances of an increase in the rate of field change occurring after the final stroke. These results cannot, however, be explained in a similar fashion as it is likely that all processes took place above the reversal height.

In spite of these difficulties it is felt that further radar studies, designed specifically to investigate the existence of ionised jets above thunderclouds during the intervals between strokes, would be justified.

ACKNOWLEDGEMENT.

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