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THE ELECTRIC FIELD OF A THUNDERCLOUD AND SOME OF ITS EFFECTS.

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ABSTRACT.

A thundercloud is an electric generator in which the separation of positive and negative charges occurs at a rate corresponding to a current which may amount to some amperes ; the potential difference between its poles may reach values of the order of a million kilovolts. Attention is drawn to three effects of the electric field of thunderclouds or shower clouds (all of which may occur even when there is no thunder). (1) The electric field of the cloud may cause ionization at great heights, the result being continuous or discontinuous discharge between the cloud and the upper atmosphere. (2) Discharge from pointed earthed conductors is likely to constitute an important part of the current between the ground and the base of a thundercloud, and the resulting ionization near the ground may be large. (3) By its accelerating action on particles the electric field of a thundercloud may produce extremely penetrating corpuscular radiation.

INTRODUCTION.

WE may regard a thundercloud as a great electric generator. I shall not attempt to discuss its probable mechanism, whether, for example, it resembles more closely that of a frictional or of an influence machine. The principal theories of its action are those of Simpson and of Elster and Geitel.

Observations on lightning discharges and on the changes in the electric field which are associated with them indicate that the rate of separation of positive and negative charges within a thundercloud frequently corresponds to a current of some amperes, and that potential differences of the order of one million kilovolts are developed.

The charges separated in the thundercloud may re-combine directly by a short-circuiting discharge within the cloud or by continuous or discontinuous discharges through external circuits, one such circuit including the earth and the upper atmosphere.

The changes produced in the electric field by lightning discharges at different distances are most easily interpreted if we suppose that the upper charge of a thundercloud may be either positive or negative, but that it is more frequently positive than negative.

The most conspicuous effect of the electric field of a thundercloud is the production of lightning discharges. I do not propose to discuss the phenomena of ordinary lightning discharges ; I shall confine myself to the consideration of three less obvious effects which may result from the electric field of a thundercloud. These effects are : (1) ionization in the upper atmosphere ; (2) ionization by point discharge from earth-connected conductors ; and (3) the production of penetrating radiation.

I. IONIZATION IN THE UPPER ATMOSPHERE BY THE ELECTRIC FIELD OF A THUNDERCLOUD.

Each of the charges (upper and lower) of the thundercloud forms with its image in the earth a system which has an electric moment $2\Sigma qh = 2QH$, where q is the charge at any height h, Q is the whole charge, and H its mean height above the

ground. The electric moment of the thundercloud is the difference between the electric moments of its upper and lower charges. (Where the electric moment of a charge, or of the whole cloud, is spoken of it is to be understood that the effect of the image is included.) At distant points on the earth's surface (not, however, so distant that the curvature of the surface has to be taken into account) the vertical electric force due to a thundercloud of moment M is M/r^3, where r is the horizontal distance of the point from the centre of the thundercloud. The sudden changes in the electric moment of the thundercloud which result when one or both charges are wholly or partially destroyed by lightning discharges may be found by observing the sudden changes in the vertical electric force at the ground at known distances. The mean value of such changes in the electric moment of thunderclouds, or, in other words, the mean value of the electric moment of a lightning discharge, is found to be of the order of 3×10^{16} e.s.u. cm. The average electric moment of a thundercloud on the point of discharge is likely to be greater.

The electric force due to a cloud of electric moment M, at a point vertically above it in the upper atmosphere, may be taken as approximately $2M/r^3$, where r is the height of the point above the ground. While the electric force due to the thundercloud falls off rapidly as r increases, the electric force required to cause sparking (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparking limit.

At a height of 60 km. the density of the air is about $1 \cdot 6 \times 10^{-4}$ of that near the ground, while the composition of the air is not very different, so that the critical value of the field may be taken as about $30{,}000 \times 1 \cdot 6 \times 10^{-4} = 4 \cdot 8$ volts per centimetre. To produce such a field at this height a thundercloud would require to have an electric moment of $1 \cdot 7 \times 10^{18}$ e.s.u. cm.; to produce a field of the critical value at greater heights a smaller electric moment would be sufficient, but the data as to composition and density become uncertain. If we assume the critical field to remain proportional to the pressure, a thundercloud with an electric moment of about 1/10 of the above value (i.e., only a few times the average electric moment of a lightning flash) would produce a field exceeding the critical value at a height of 80 km. Thus, if there were no already existing conducting layer there is little doubt that a thundercloud would itself cause ionisation in the upper atmosphere.

Let us assume that there is already a conducting layer with its lower boundary at, for example, 80 km. Ions are dragged out of this by the field of the cloud, positive if the upper pole of the cloud is negative, negative (probably as free electrons) if it is positive. If the field exceeds a critical value, considerably less for the negative than for the positive ions, the ions acquire sufficient energy to cause ionization by collision. If the field is strong enough to cause ionisation by collision for any considerable distance below the original level of the conducting layer, it is possible that sudden discharge of the upper pole of the thundercloud to the upper atmosphere may occur.

The presence of the conducting layer increases the vertical electric force at points below it. Again, the value taken for the critical field (the sparking value) corresponds according to Townsend's theory to ionization by collision by positive ions; a smaller field is sufficient to give to negative ions the energy necessary for ionization. Thus the estimate given above for the electric moment required to

cause discharge at 60 km. is probably an excessive one, especially when the cloud is of positive polarity.

The vertical electric force at a point at a height of 60 km. may be due, not solely to a thundercloud vertically below it ; all thunderclouds within a considerable area will contribute to it.   A cloud 10 km. away from the centre of this area would produce at the given point a vertical force exceeding 9/10 of that which it would produce if it were at the centre.   It is possible that the electrical field of a large rain cloud, which would not be regarded as a thundercloud, may be strong enough to cause discharge in the atmosphere above it.   An average electric moment of about 5×10^{15} per sq. km. would be more than sufficient to produce discharge at 60 km. if the cloud covered a circular area of 10 km. radius.   This value of the electric moment may easily be attained while the electric force within and below the cloud remains far short of the sparking value.   The discharges above the cloud would doubtless give rise to atmospherics.   If, as has been maintained, atmospherics frequently originate in regions of rain unaccompanied by thunder, they may in such cases be due to discharges of this nature.

II. IONIZATION BY POINT DISCHARGE FROM EARTH-CONNECTED CONDUCTORS.

The electric field at the ground below a thundercloud very often exceeds 10,000 volts per metre, and below the centre of the cloud it probably considerably exceeds this value ; observations made in a properly exposed situation below the centre of a thundercloud are naturally difficult to obtain.   Even below rainclouds without thunder potential gradients of several thousand volts per metre are common.   Any pointed earth-connected conductor, such as a lightning conductor, projecting to a height in a field of a few thousand volts per metre must give rise to a glow or brush discharge, and a conductor need not end in a sharp point or project to a great height in order that it should begin to act as a discharger.   A very simple calculation is sufficient to show that an earth-connected sphere of 1 cm. radius need only be raised to a height of 3 metres in a field of 10,000 volts per metre in order that the electric force at its surface may reach the critical value of 30,000 volts per cm.   That considerable currents should be obtained in experiments like that made long ago by Benjamin Franklin with his kite, and that " St. Elmo's fire " should occur in exposed situations, is not therefore surprising.

A considerable part, possibly the greater part, of the current between a thundercloud and the ground must be carried by trees and other natural lightning conductors. It is even more difficult to obtain measurement of this portion of the current (that down a tree, for example) than of the charges carried by rain or by lightning.   Useful information bearing on the matter—and particularly on the very fundamental question whether the current between the ground and a thundercloud is on the whole mainly upward or downward—is likely to be obtained by observations with lightning conductors erected for the purpose and connected to instruments for recording the current through them.   Observations of the sign and magnitude of the intense potential gradients below thunderclouds will also help towards obtaining some estimate of the currents.   I have lately been testing methods for making both types of observations.

Some years ago I made experiments to determine what is the magnitude of the potential gradient which has to be applied over the surface of a field of grass to make the tips of the grass blades come into action as point dischargers.   With a

positive potential gradient, i.e., with the grass negatively charged, the discharge from a square metre of the grass-covered ground begins to be measurable when the applied potential gradient reaches about 15,000 volts per metre, and the current increases with great rapidity as the potential gradient is further increased ; it soon reaches values of the order of 1 micro-ampere per sq. metre, i.e., of 1 ampere per sq. kilometre. A somewhat larger potential gradient, about 20,000 volts per metre, is required to start the point discharge when the ground is positively charged, i.e., when the potential gradient is negative, and a larger gradient is required to produce a given current. This difference is in accordance with what is known of positive and negative point discharges.

It is of interest to consider the vertical current due to such discharge from grass-covered ground below a thundercloud under ideally simple conditions. Let us suppose that no rain is falling and that the whole current between the ground and the cloud is carried by ions supplied by point discharge from the grass. To simplify the problem, suppose that we have immediately below the thundercloud a vertical field which is uniform over an area of dimensions great compared with the height of the base of the thundercloud. Let us suppose that this field approaches the sparking limit in intensity, and that it is directed upwards, the base of the cloud being positively charged.

If an electric field of this intensity extended as far as the grass-covered ground, this condition could only last momentarily, since a continuous discharge of negative electricity would at once occur from the grass until the potential gradient at the ground only slightly exceeded that required to maintain point discharge from the grass. If a steady condition is reached there must be a streaming of negative ions upwards from the ground to the positively charged base of the cloud ; the space between the ground and the cloud will then contain a negative volume charge and the field will increase with increasing height above the ground. If, in spite of the upward stream of negative ions the electric force immediately below the cloud is maintained at a high value, this can only mean that the positive charge at the base of the cloud is being replenished (by the source of E.M.F. within the cloud) as fast as it is being neutralised by the upward streaming negative ions. The conditions are not essentially different when the potential gradient is negative, so that the upward streaming ions are positively charged.

If k is the mobility of the upward streaming ions (their velocity under unit electric force), ρ the charge carried by the ions in 1 cubic cm. of the air, F the vertical electric force, h height above the ground, and γ the vertical current per square centimetre, then, since

$$\gamma = k \rho F$$

and

$$\frac{dF}{dh} = 4\pi \rho = \frac{4\pi\gamma}{kF},$$

$$F_h{}^2 - F_1{}^2 = \frac{8\pi\gamma h}{k}$$

F_h and F_1 being the vertical electric force at a height h and at the surface of the ground respectively.

The vertical electric force F_1 immediately over grass-covered ground cannot much exceed 30,000 volts per metre ($=1$ unit of electric force in e.s. measure).

Let us assume that just below the cloud the electric force approaches the sparking value, 30,000 volts per centimetre, or 100 in e.s. measure. Then at all except quite small heights, F_1 will be negligible in comparison with F_h, and we have approximately

$$F_h{}^2 = \frac{8\pi\gamma h}{k} \text{ or } \gamma = \frac{F_h{}^2 k}{8\pi h}.$$

Assuming that the base of the cloud is at 2 km., and that the vertical force there almost reaches the sparking limit, and that the mobility of the ions is that of the ordinary small ion, we find for the magnitude of the vertical current about 6 e.s.u. per square centimetre per second or 2 amperes per square kilometre. The number of ions per cubic centimetre (of mobility of the order of 1 cm. per second for a field of 1 volt per centimetre) would vary from something of the order of 3×10^6 near the ground, where the field is of the order of 300 volts per centimetre, to about 1/100 of this just below the cloud.

The current and ionization found above are those which would exist if the electric field below the thundercloud were maintained almost up to the sparking limit. The field immediately below the cloud could not, as a result of separation of charges within the cloud, reach the limit required for a discharge to earth, unless the rate of separation of charges exceeded the value found above for the current. Thunderstorms, in which discharges pass at frequent intervals between the base of the cloud and the ground, are, of course, quite common. It would, however, be unsafe to assume that the conditions in such storms are necessarily like those we have assumed. It is, for example, possible that the field below the cloud may only approach or reach the sparking value as a result of discharges of the upper pole of the nature of those discussed in section (I); the large currents and ionizations would in such cases only last for a very short time.

III. Production of Penetrating Radiation.

As I have elsewhere pointed out,* intense electric fields which, like those of thunderclouds, extend over considerable distances, may have important effects if β-rays are present. A β-particle is, under normal conditions, continually losing energy in ionizing and otherwise affecting the atoms which it traverses. The rate of loss of energy per centimetre of path is less the faster the particle is moving, varying approximately as the inverse square of the velocity. In air at normal pressure the mean rate of loss of energy per centimetre for a particle of which the kinetic energy is the equivalent of 20,000 volts (range about 1 cm., velocity about 9×10^9 cm. per second), is about 10,000 volts per centimetre. A field of 10,000 volts per centimetre directed along the path of such a particle would, on the average, just compensate for this loss, and would more than compensate for the loss and give a balance of acceleration if its velocity were any greater. In a field of 20,000 volts per centimetre (only two-thirds of the sparking field) the energy gained by a 20,000 volt β-particle would exceed the loss by about 10,000 volts per centimetre. The faster the β-particle moves the smaller is the rate at which it loses energy in collisions; the rate of loss will approach a limit of less than 1,000 volts per centi-

* Camb. Phil. Soc., Nov. 24 (1924).

metre as the velocity becomes comparable with that of light. The chances of accidental deflections out of the accelerating field also become less and less as the energy of the particle increases.

There can be no doubt that β-particles are continually being emitted in the strongest parts of the field of a thundercloud (where the field approaches the sparking limit), as elsewhere in the atmosphere. A considerable proportion of these, and of others secondarily produced, must under the influence of the field acquire large additional energy. The greater the energy acquired by the particle the greater is its chance of surviving to gain more energy. The net rate of gain of energy by a particle which has travelled more than a few centimetres in the strongest part of the field may exceed 10^4 volts per centimetre, or 10^6 volts per metre. Thus, β-particles which have traversed a few metres in the direction of the field have already acquired energies exceeding those of the fastest known β-particles from radioactive substances. And the energy gained from the field will continue to exceed that lost in collisions even when the particles have reached regions where the field has fallen to 1,000 volts per centimetre.

A particle may thus acquire energy corresponding to the greater part of the whole potential difference between the poles of the thundercloud, which may be of the order of 10^9 volts. Such a particle may be expected to have important effects (when, for example, it strikes the nucleus of an atom), as its mass will be comparable with that of the hydrogen nucleus.

It has been assumed above that the air is at atmospheric pressure. The results remain essentially the same at low pressures; the maximum electric force which can exist in the air without discharge is proportional to the density, while the length of path required for a given energy loss by a particle of given velocity is inversely proportional to the density. For corresponding fields (which are proportional to density) the net gain of energy in corresponding distances (which are proportional to the density) remains the same; the linear dimensions of the β-ray system are inversely proportional to the density. At great heights where the electric force is much reduced the deflecting action of the magnetic force becomes important, and the β-rays will tend to run mainly along the direction of the magnetic lines of force.

The corpuscular radiation originating in the field of a thundercloud and the γ radiation which it may excite will constitute a penetrating radiation very similar in character to that which is known to occur normally in the atmosphere.