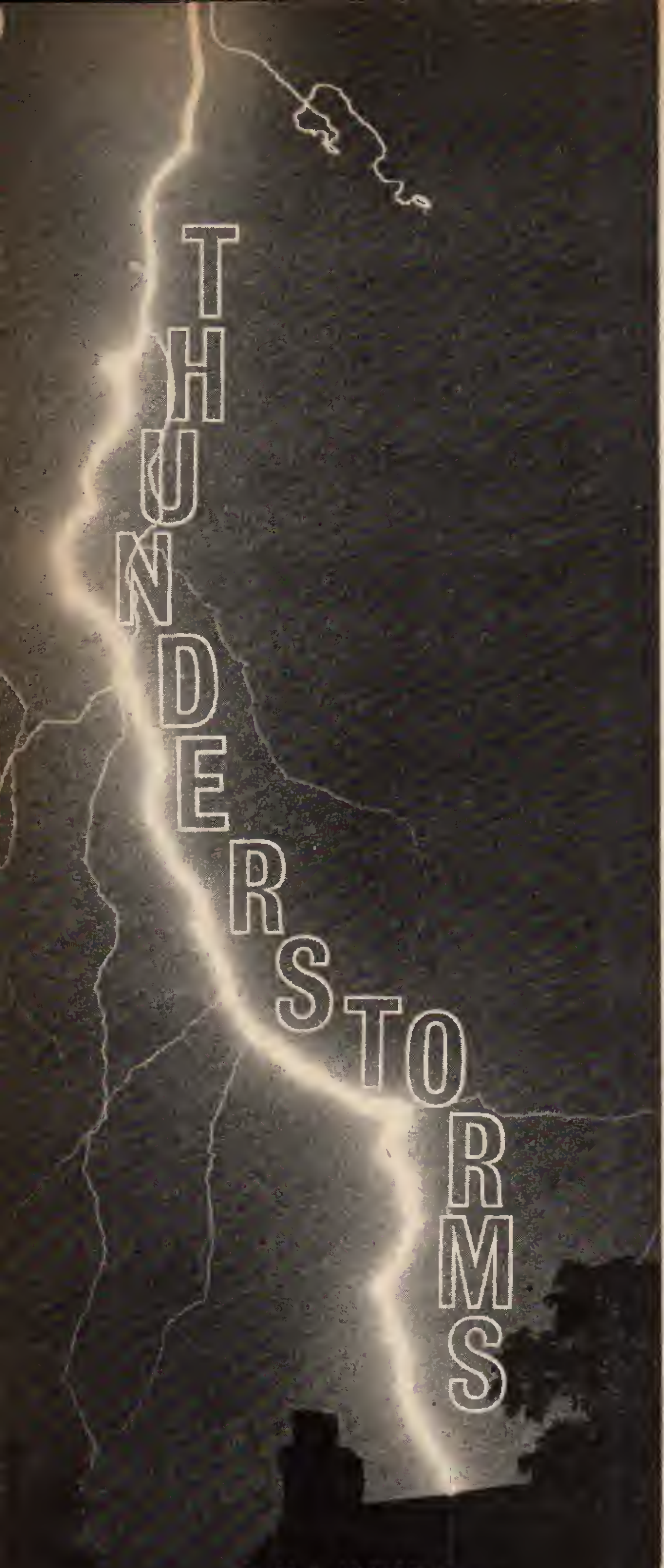
# THUNDERSTORMS



By M. L. MICHAELIS, M.A.

Nobody *really* knows how the electricity is generated by a thunderstorm.

In this article the established facts about thunderstorms are narrated and the author then goes on to formulate his own ideas which are based upon practical experiments

NATURE has been producing very effective electronic devices long before man had even conceived the idea of the electron. Twentieth century inventions have long been paralleled by natural creations of similar basic function. Thus the eye with associated nerves and brain section is an electronic equipment comprising an efficient navigational radar with information storage facilities, built to dimensions not reached by even the latest man-made micromodule circuit techniques. Even experienced technicians seldom pause to be impressed by these achievements of Nature.

Exceptions to this rule are those displays of natural electronics which lead to spectacular phenomena, and thunderstorms here rank high up on the list. Since at least one hundred years, scientists have been trying to find out how thunderstorms produce their immense electrical energies of several million kilowatt-hours per cumulonimbus cell (thundercloud), whereby a large storm system may consist of 100 or more such cells. To this day, no final answer has been found.

For the duration of its average active lifetime of about 15 to 30 minutes, each cumulonimbus cell runs at an electrical power of about ten thousand megawatts, which exceeds the rating of even the largest man-made turbo-generators feeding the national grid system.

The principle of this powerful natural electric generator is not yet understood. However, we do know a great deal about the qualitative properties and structure of thunderstorms, and the first sections of this article will be devoted to these accepted facts.

## AN EXPLOSION OF WARM MOIST AIR

Some meteorologists have aptly described the thunderstorm as an explosion of warm moist air.

The essential starting requirements for the development of a thunderstorm are warm air of high humidity located as close to the ground as possible. Such air already contains all the vast energy which is ultimately unleashed in the storm. It is latently present in two forms, neither of which are electrical. The first form is simply the compression of the low-lying air, due to the weight of the other air masses above it. The second form is the latent heat of vaporisation of the water vapour content. Most of the energy is locked-up in this second form, but the first form is sometimes more important in getting the process started, i.e. in lifting the moist air to a level at which condensation can start and the liberated latent heat can then take over control. Thus there is no mystery about the source of the energy as such.

The thermodynamic energy content of roughly one billion tons of air participating in each cumulonimbus cell, including the latent heat of a quarter of a million tons of water carried thereby, is about ten times greater than the ultimate electrical energy output of the cell. We thus know that its efficiency in converting heat energy into electrical energy is roughly 10 per cent The question is to determine the nature of the mechanism adopted for this energy conversion.

## TYPES OF THUNDERSTORMS

Thunderstorms are not ready-made structures which float along with air masses, approaching, passing overhead and then proceeding elsewhere. They are dynamic processes *involving* entire parcels of air which finally take the form of a cylinder with anvil crown, often ten miles high and ten miles in diameter.

When mature, the accompanying cloud structure has an appearance in many ways similar to the mushroom of an atomic explosion. This is not usually visible as

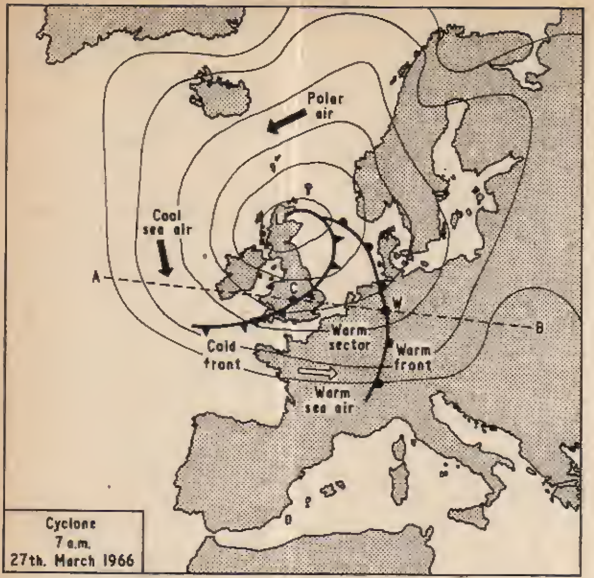



*Fig. 1 (left). Plan representation of a cyclone (depression)*

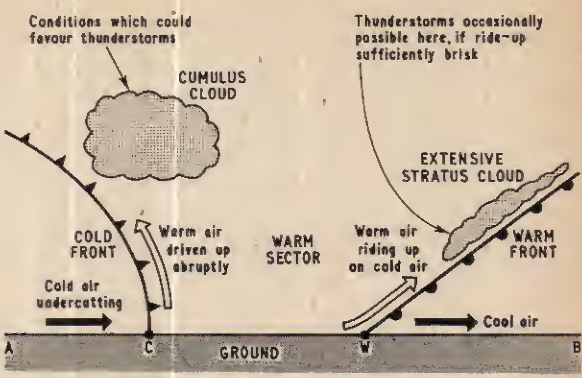



*Fig. 2. Vertical section through a cyclone at ACWB in Fig. 1*

such from the ground, also by no means always on aerial photographs either, because many cells in different stages of development may merge into a more extensive cloud structure covering large areas. It is well established that each cell undergoes a distinct life-cycle of its own, independent of neighbouring cells in a composite storm system and lasting about one hour inclusive of all phases. During the active part of its lifetime, which normally does not exceed half an hour, the cell seldom drifts further than through its own diameter, i.e. 5 to 15 miles. In some cases it may not move at all. When thunderstorms appear to travel over distances of hundreds of miles, this is always by way of regeneration of fresh independent cells adjacent to older spent ones. Large storm areas involve numerous cells which happen to be active simultaneously.

Thundercells are officially known as *cumulonimbus cells*. This term is derived from the cloud structure, whereby cumulus clouds are the frothy upward-rising structures so familiar on fine days and "nimbus" is the suffix for any cloud-type producing precipitation.

Thunderstorms are generally classified into two groups, the *thermal* (convectional) variety and the *frontal* (cyclonal) variety. The same cumulonimbus cell is produced in either case, the difference merely lying in the nature of the *initial* conditions which cause the warm moist air to rise to the point of water condensation. In practice, the distinction between thermal and frontal character is by no means clear-cut in many storms, the behaviour is also modified by the topography, and any distinction is largely irrelevant by the time the cell reaches maturity.

## CYCLONAL INITIATION

Initial lifts of moist air to the point where latent heat release can take over rapid thunderstorm development are very frequent at the fronts of cyclonal disturbances, particularly at the cold front, where cold air is undercutting the moist warm air and forcing it upwards abruptly.

## THE STRUCTURE OF A THUNDERCELL

Every thundercell passes through three phases, the *cumulus* phase, the *mature* phase and the *dissipating* stage.

During the cumulus phase, huge volumes of air are rushing into the rapidly growing cell, with towering production of cumulus cloud. In the mature stage the cell has attained its full dimensions of about a thousand cubic miles, strong precipitation is forming and raining or hailing out, ice and rain are present simultaneously in the cloud which is now towering far above the frost level, and downwind as well as upwind sections have developed, producing wind shear and friction surfaces.

The onset of ice production in the upper regions of the cell is coincident with the onset of strong radar reflections at centimetric wavelengths, so that it can be determined quite accurately. The first flash of lightning appears roughly eight minutes later. The electrostatic field near the cloud maintains normal fine-weather values of about $+250$ V/m at ground level until the ice production, marked by the appearance of centimetric radar reflections, commences. In the following two minutes, the field strength drops to zero and then reverses polarity, climbing to about $-3$ kV/m in the remaining six minutes before the first flash of lightning darts out of the cloudbase and strikes the ground.

From measurements of the wavelengths of electromagnetic radiations as well as instantaneous field changes, it is known that this first flash originates at a height of just over two miles. The cloudbase usually rests at a height of about a mile, so that at least one half of the track of the first lightning flash is inside the cloud. Subsequent flashes are found to originate from increasingly greater heights, finally from a height of about six miles, so that five miles of the track are invisible inside the cloud and one mile is visible in the air below.

These observations show that electric charges begin to build up when the crown of the thundercell has passed the frost level and ice is forming, not earlier. The lower regions of the cell thereby acquire negative charge (a surplus of electrons) and the upper regions a positive charge (deficiency of electrons). The negatively charged region encompasses a layer about one mile thick by the time sufficient potential difference has been established for the first lightning flash to take place. This negative region grows to a thickness of about five miles, i.e. to approximately half the total height of the thundercell, in the course of its further electrical activity. It appears that water and ice, but certainly ice, are essential before the generation of electricity can take place in the thundercell.

## CHARGING THE ICE-WATER MIXTURE

Most hypotheses so far put forward for an electrification mechanism are concerned with the possible behaviour of ice and water when in mutual contact under the extremely turbulent conditions inside a thundercell.

It can be demonstrated in the laboratory that a water spray or even an air jet directed at ice will cause electric charges to build up on the ice. Disruption of water drops also produces charges which can be collected on ice particles. The conversion of ice particles into sleet, subsequent breakup in lower regions of the cloud and all manner of analogous physical processes produce demonstrable electrostatic effects. If water droplets and ice particles thereby acquire opposite charge polarities, there is little difficulty in visualising their rapid separation through the influence of the mechanical turbulence, before neutralisation can take place.

Electronically this is equivalent to driving apart the plates of a capacitor whilst maintaining the charge. This is a straightforward way to boost voltage and convert mechanical energy into electrical energy. The problem is to obtain sufficient electric *charge* in the first place. It is just here that most hypotheses so far put forward fall short of actual requirements. To make matters worse, many of the processes with the best yields produce the incorrect polarity, or either polarity by chance. But thundercells are *always* negative at the base and positive at the crown.

## HOW MUCH CHARGE IS REQUIRED?

Electrostatic field measurements around thundercells and flashes of lightning have revealed that an average ground discharge dissipates 20 coulombs and the repetition rate is about 20 seconds. In other words, the charge source must be able to deliver an externally manifest mean current of 1 amp for 15 to 30 minutes before it is exhausted. It is rather difficult to visualise more than a small fraction of this current from most individual ice-water turbulence mechanisms, so that several of these would have to operate simultaneously, if it should turn out that the actual mechanism really is based on them.

*Aerial photograph of a mature thundercell*
(TIME and LIFE, New York)

## EQUIVALENT ELECTRICAL CIRCUIT

A discharge can take place when the accumulation of charges has built up to the breakdown voltage. The discharge may take place entirely within the cloud, between its oppositely charged regions, or via a circuit external to the cloud. It is found that about 85 per cent of the discharge current takes the former path, leaving only some 15 per cent for the external circuit involving ground strokes of lightning with their mean current of 1 amp for each thundercell. The net current including the internal dissipation is thus about 7 amp. Fig. 3 shows an equivalent circuit for describing the properties of the discharges in detail.

The internal shunt resistor $R_s$ represents the internal discharges. Its value is typically 200 megohms and since it carries a current of 6 amp, the e.m.f. of the thundercell is approximately 1,200 megavolts. This source of e.m.f. is depicted in series with a rectifier diode to emphasise the important fact that thunderstorms are never found with the opposite polarity. The power dissipated in $R_s$ is clearly about 7,200 megawatts, whilst some 1,200 megawatts mean power are dissipated in the resistors of the external circuit branch.

The lightning flashes to ground are depicted by the resistor $R_g$ whose value is typically 800 megohms and thus dissipates nearly two-thirds of the total external power. The ground discharges must be balanced by discharges into the ionosphere, which are usually of a corona or glow character. They are depicted by the resistor $R_t$ whose value normally lies around 480 megohms. The external circuit is completed by the leakage resistance $R_L$ between the ionosphere and ground. This has the very low value of 145 ohms, because the entire atmosphere of the world is available for it. It is common to the circuits of all thunderstorms throughout the world and is found to be carrying

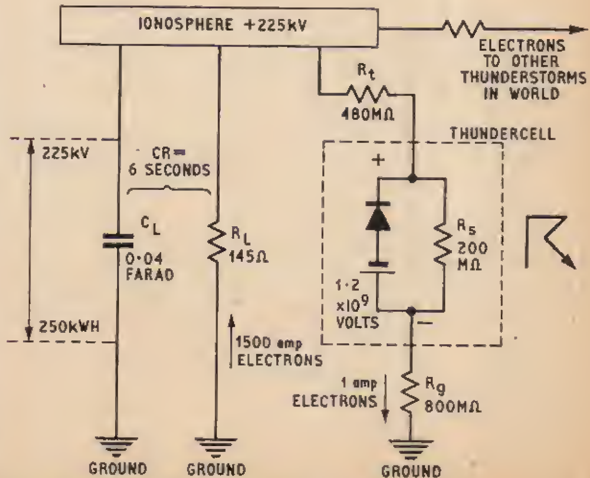



*Fig. 3. Equivalent electrical circuit of a thunderstorm*

a total current of 1,500 amp which is a measure of the average total thunderstorm current for the whole world. This current produces a voltage drop of about 225kV across $R_L$, i.e. between the ionosphere and ground. The conductivity giving rise to $R_L$ is largely due to ionisation in the atmosphere at large, due to cosmic radiation. If ground flashes of lightning individually transfer 20 coulombs and the combined world return current is 1,500 amp, there must be 75 ground flashes of lightning per second in the world taken as a whole. Thunderstorms are thus *extremely* common.

Although the height of the ionosphere layers differs and fluctuates, we may consider 0·04 farad as an approximate value for the spherical capacitor constituted by the ionosphere and the ground. In conjunction with $R_L = 145$ ohms, this gives a storage time constant of about six seconds, during which time a mean number of 450 flashes of lightning are expected throughout the world. Assuming normal statistical behaviour, we can expect a random fluctuation of about $\pm 5$ per cent. Fluctuations of ionospheric capacitance due to changes in height of the layers, sunspot activity, etc. are obviously much greater, so that it is not possible to employ observed fluctuations of the fine-weather return current through $R_L$ for drawing conclusions about non-random fluctuations of worldwide thunderstorm activity.

It is interesting to note that all the thunderstorms in the world may be treated as transformer and rectifier of a power pack, with the ionospheric capacitance as reservoir capacitor and the resistor $R_L$ as load resistor. The output power is then about 340 megawatts, whilst some 250kWh are stored in the reservoir capacitor. These figures clearly represent only a small fraction of the total electrical power, most of which is dissipated inside the thundercells and by the lightning flashes immediately below them.

Let us conclude this section by recapitulating the polarities. These are never the reverse. The ionosphere rests about 225kV *positive* with respect to ground. It draws up electrons from the ground. This fine-weather upstream of electrons takes place throughout the world, except at those isolated locations where thunderstorms happen to be taking place. The ionosphere delivers the electrons into the positive tops of all thundercells. The lightning flashes out of the negatively charged bases of all thundercells convey the electrons back into the ground, to complete the global circuit.

## LIGHTNING TRACKS

Lightning discharges out of the base of the thundercell are propagated by a pilot and return stroke, instead of by a direct-shot discharge. The pilot advances out of the cloud in steps of 10 to 100 yards at a time and consolidates each step by transferring negative charge out of the cloud to the extremity of the pilot. This process is usually accompanied by branching, whereby not all branches need reach the ground finally. When any heads of the pilot have come within a few dozen yards of the ground, they become able to distinguish differences in topography and conductivity and seek optimum points within their range for striking the ground. The return stroke is thereupon initiated and taps-off all the negative charges stored along the pilot track.

This process is almost instantaneous and gives rise to a massive current pulse of many thousands of amperes, accompanied by most of the visual and audible effects. Several further discharges out of the cloud usually follow in quick succession along the prepared track. The whole sequence, including the pilot, takes approximately one second. The essential function is to convey electrons from the cloudbase into the ground.

The discharge current will distribute roughly hemispherically from the point at which the discharge enters the ground. Even if the ground resistance is only a fraction of an ohm per yard, voltage drops of several kilovolts can still arise under these conditions between the legs of a walking person standing close to the point of direct entry into the ground, or entry via a lightning arrestor, tree or other tall object. Such potential differences can electrocute a person even if he has not been struck directly. When surprised by thunderstorms, it is thus important to keep away from preferred objects of entry, to keep both feet close together and not to touch the ground or other objects with the hands or other parts of the body. It is also advisable to squat down low.

All types of trees are dangerous to stand under, since they will attract the pilot if its head happens to pass sufficiently close. Certain types of trees with a smooth bark offer excellent surface conductivity when wetted by the torrential rainfall accompanying thunderstorms, so that the discharge current does little or no damage to the tree. Other rough-barked trees offer little surface conductivity, so that the discharge passes through the internal sap ducts and may explode the tree. This visible damage has led to the quite false belief that such types of trees are preferred by lightning.

The useful function, if any, of lightning conductors on buildings is still a debatable point. Lightning is not the only means by which a thundercell can discharge electrons to ground. Corona discharge, especially at elevated pointed objects, is also possible and some authorities maintain that a good lightning conductor can reduce the frequency and intensity of lightning flashes in its vicinity by draining off charge quietly. Other sources state that the chief function of the conductor is to provide an easy path to ground *if struck*, thus minimising the resulting damage. This is analogous to the smooth-barked trees which often survive unscathed when struck by lightning.

## WORLDWIDE DISTRIBUTION OF THUNDERSTORMS

An important fact is that thunderstorms are very much rarer at sea than over land, whilst inland they are most frequent over geologically disturbed areas. They are commonest over equatorial land masses and their frequency drops to zero approximately at the pack-ice boundary as polar regions are approached. This might well be expected and explained by the reduced solar radiation intensity in high latitudes. But not so the fact that thunderstorms are rare over equatorial and temperate oceans. Cyclonal lifts should here be possible, and indeed cloud formations and storm intensities akin to thunderstorms are produced—but often without the accompaniment of electrical phenomena.

## POSITIVE CHARGE ISLANDS

More detailed observations of the electrostatic fields around thundercells have shown that the potential gradient once again drops to zero and returns to fairly high positive values when a cell is directly overhead.

This means that small islands of positive charge must be located within the main region of negative charge in the cloudbase. These positive islands are independent of the main positive charge in the crown and they are much smaller. They appear to be associated with the region in which the heaviest rainfall is leaving the cloudbase (Fig. 4).

## ALPHA-RADIATION IN THUNDERCELLS

All land masses contain minute traces of uranium and radium, in whose radioactive decay chains exist isotopes of the *gaseous* element emanation, chiefly the gas radon. This seeps out of the rocks and into the air. In spite of the extremely minute quantities of material involved, the resulting radioactivity imparted to the air is quite appreciable, on account of the intense specific activity of these substances.

A useful unit for the radioactivity of a specimen is the *picocurie* ($10^{-12}$ curie), corresponding to 2·2 disintegrating atoms per minute. The radon activity in continental air masses is about 100 picocurie per cubic yard. At sea it is very much less, because water tends to dissolve emanation gases rather than injecting them into the air. Over geologically disturbed areas the radon content of the air can be much greater. A mature thundercell contains about $10^{12}$ cubic yards of air, so that over land masses it may be expected to contain *at least* 100 *curie* of radium emanation and its first daughter product radium A, both of which are intense alpha-emitters. Now 100 curie of an alpha-emitter produce $2{\cdot}2 \times 10^{14}$ alpha-particles per minute, representing an electric current of about 1 microampere.

The alpha-particles are ejected from the radioactive atoms with an energy of 6 million electron volts and are known to dissipate this energy by producing short tracks of dense ionisation. If each ionisation requires a volt or two, which is a reasonable figure for ice, it is clear that a charge multiplication factor of several million is feasible before the energy of the primary alpha-particles has been expended in this manner.

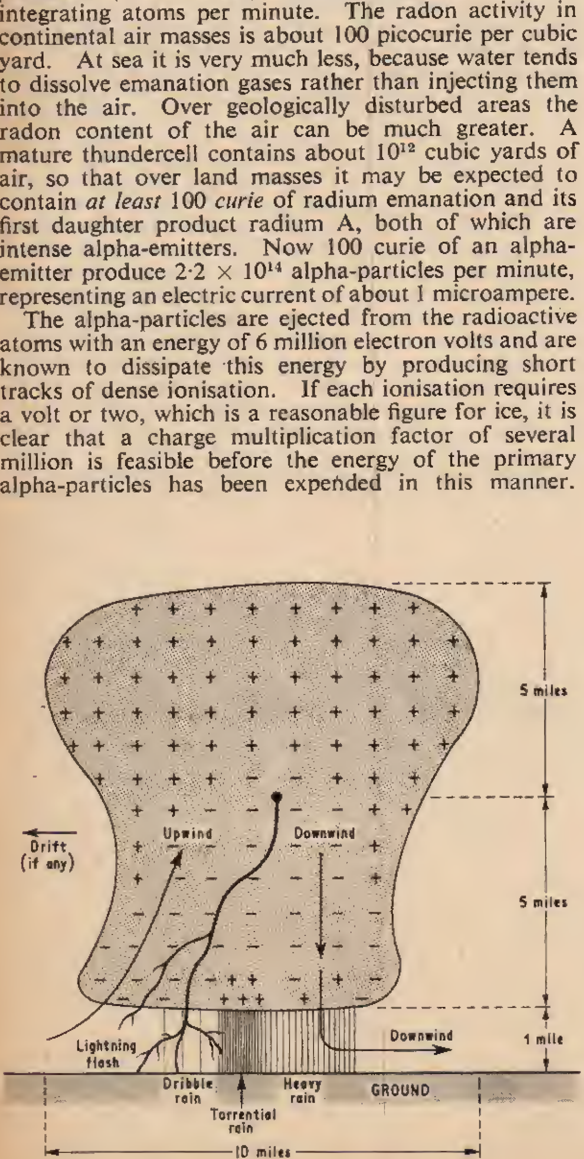



*Fig. 4. Sketch of a mature thundercell*

The total charge production by this mechanism alone could thus amount to several amperes, which is of the required order of magnitude to account for the observed electrical phenomena of the thundercell.

There can hardly be any doubt about the production of these charges. Continental air masses engaged in a thundercell contain this amount of alpha-radioactivity and the familiar ionisation phenomena thus *must* take place. The question open to discussion is whether these charges simply recombine on the spot and then contribute nothing to the electrification of the thundercell, or whether the turbulence can get a grip on them sooner, hurling them apart to build up the huge amounts of electrical energy produced in a thundercell. As an alternative, the alpha-ionisation may induce sufficient partial electrification for producing conditions favourable for large-scale exploitation of one or more of the conventional mechanisms.

This hypothesis would give a clear reason why thunderstorms are rare at sea although otherwise similar storms but lacking electrical phenomena are not infrequent there. The concentration of radium emanation in the air is inadequate remote from land masses. The time taken for air masses to move well out to sea is comparable with or long relative to the 3·5 day half-life of the emanation, so that there is not much left by the time the air gets there.

A second argument is more involved and is based on the author's own experimental observations of the emanation product radioactivity in thunderstorm rainfall. This work has been handicapped by the fact that only a single station was operated at a fixed site, waiting for whatever weather happened to come by chance. The results are necessarily more confused than if several mobile or airborne stations had been operated simultaneously to approach and encircle the weather patterns of interest, aided by all other meteorological services and methods of location.

## ELECTRONIC EQUIPMENT AND METHOD

The principle was to make comparative studies of the initial concentrations and decay rates of the mixed emanation products for successive small samples of rainwater taken in the course of thunderstorms and other kinds of rainfall, aiming to detect systematic trends and differences for drawing possible conclusions therefrom. This called for the construction of an efficient multi-channel ratemeter system with chart-recording facilities for comparing the radioactive decay of successive samples of rainwater on a common time scale. It is essential to ensure a high degree of circuit stabilisation against random electrical or thermal drifts. A great deal of work was involved in designing a fully satisfactory electronic equipment, but all problems on this score have been solved.

Coaxial Geiger-Muller counter tubes for liquid samples have chiefly been employed as radiation detectors. These are almost exclusively responsive to the high-energy beta and gamma radiation of radium C. If a sample contains equilibrium amounts of all the successive decay products of radium emanation, then a mean decay half-life of about 35 minutes will be observed, corresponding to the equilibrium sequential decay of the products. If radium C is deficient, then it must first of all be produced from its forerunners, so that the measured activity will initially *increase* over any time from 10 to 90 minutes, before a decay can commence for the mixture as a whole. On the other hand, if radium C is in excess, its forerunners may be ignored and the observed mean half-life of the sample will approach more closely to the short 19 minute half-life of pure radium C. A detection system which is exclusively responsive to radium C is thus quite sensitive to variations in the proportions of this isotope relative to its forerunners.

## RESULTS AND DISCUSSION

Of the various systematic trends indicated in the course of these experiments, only two are of outstanding importance in relation to thunderstorm electricity. The first effect was noted at an early stage, since it can interfere with the method of taking samples. These are caught in a large plastic photographic developing tray. If the rainwater is poured therefrom straight into the radiation detector system, rather low readings and short decays corresponding to an excess of radium C are generally observed. If the tray is subsequently washed down with an equal volume of dilute nitric acid and the washings are then run parallel on another ratemeter channel, rather high readings and long decay times, corresponding to deficiency of radium C, are observed. In many cases filtration of the water prior to measurement can bring this separation process to virtually quantitative completion. The earlier product radium B, possibly even radium A, thus shows a great tendency to deposit out of the water onto any available solid surface, whilst that portion of the radioactivity which has already decayed as far as radium C remains in homogeneous solution. This observation is significant, because it means that similar deposition phenomena might be expected inside a thundercell, once ice begins to form and presents a solid deposition surface.

This brings us to the second important trend which has been noted. Thunderstorms usually commence with isolated large drops of rain for a few minutes, followed by a fairly sudden transition to torrential rainfall. In most cases there appears to be an equally sudden transition in the nature of the radioactivity in the rainwater. The initial drops tend to show high specific concentrations, but short decay times, so that they contain radium C in excess, having lost the earlier products. The early portions of the torrential rainfall contain much lower specific concentrations (yet greater total amounts of activity), but have quite long decay times, showing that here radium C is deficient and the earlier products predominant.

Now it is known that the large raindrops of the torrential rain result from melted ice particles which have grown at the expense of smaller water or cloud particles in the upper regions of the cloud, often after several journeys up and down through the cloud in the turbulence streams. Thus the author's observations could be taken as evidence that the ice in a thundercell accumulates large fractions of the emanation product radioactivity arriving with the inrushing air.

Furthermore, in a mature thundercell the boundary between the indefinite earlier section and the start of the torrential rainfall is also roughly the dividing line between the inrushing upwind and the outgoing downwind, i.e. it is the wind shear and friction surface. If most of the alpha-radioactivity really is concentrated in this region of maximum turbulence, there would indeed be a better chance for the turbulence to get a grip on the resulting intense ionisation, in order to separate the charges to the observed magnitudes.

The author must emphatically point out that this is still pure conjecture. The observed behaviour of the radioactivity is fact, but the interpretation put forward may be right or wrong. Other explanations are conceivable, but the type of further experiments necessary to decide the issue are obvious and feasible.

## DETERMINATION OF POLARITIES

On the basis of the alpha-radioactivity hypothesis as a mechanism for the electrification of thunderstorms, it would be necessary to depart even further into the realm of pure conjecture in order to give a plausible explanation of the definite polarity, i.e. of the "rectifier behaviour" of the thundercell. Nevertheless, at least one reasonably straightforward mechanism is conceivable.

The crystal structure of ice is an array of rather loosely packed oxygen atoms, with interposed protons (hydrogen bonds) holding the oxygen atoms further apart than a spacing corresponding to close packing. It would be conceivable that the radiation of intense alpha-activity accumulated on the ice could smash-out protons, which are positively charged and very readily attached to small particles in the upstream which then carries them aloft to the crown of the cloud. The negatively charged ice crystals would ultimately drop out as rain to the base of the cloud. By the time they get there, the radioactive products could have decayed through radium B and radium C to radium C', which is once again an intense alpha-emitter and might thus attempt to repeat the process in miniature in the cloud base. This could account for the observed islands of positive charge inside the principal negatively charged region at the bottom of the mature thundercell.

In conclusion, it should be noted that the e.m.f. of a thundercell falls into the same class as many of the more powerful man-made particle accelerators, i.e. it is ample for inducing a whole variety of nuclear reactions. At the high beam currents involved, it might be worth considering whether nuclear reactions play any role in the behaviour of a thundercell. But this is really begging the question, for we are looking for a mechanism leading to the creation of the high voltages and powers, not for secondary effects produced by these voltages once they are established. ★