# THE THUNDERSTORM AND ITS PHENOMENA.*

BY

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The downrush of air clearly produces a vertically directed pressure on the surface of the earth, in the same manner that a horizontal flow produces a horizontally directed pressure against the side of a house. But a pressure equal to that given by 2 mm. of mercury, a pressure increase frequently reached in a thunderstorm, would mean about 2.72 grammes per square centimetre, or 27.2 kilogrammes per square metre, and require a wind velocity of roughly 50 kilometres per hour or 14 metres per second. Now, the velocity of the downrush of air in a thunderstorm is not at all accurately known, but while at times probably very considerable, the above value of 14 metres per second seems to be excessive; in fact, its average value may not be even half so great. If in reality it is not, then, since the pressure of a wind varies as the square of its velocity, it follows that less than one-fourth of the actual pressure increase can be caused in this way. Hence it would seem that there probably is at least one other pressure factor, and, indeed, such a factor obviously exists in the check to the horizontal flow caused by vertical convection.

To make this point clear: Assume two layers of air, an upper and a lower, flowing parallel to each other. Let their respective masses per unit length in the direction of their horizontal movement be $M$ and $m$, and their velocities $V$ and $v$. Now, if, through convection, say, the whole or any portion of the lower layer is carried aloft, obviously it must be replaced below by an equal amount of the upper layer.

Let the whole of the lower layer be carried up. This layer, to produce the rain that was above assumed, 2 centimetres, will have to be at least 1 kilometre deep, and if it should merely change places with the upper air, or if the different layers should mingle and assume a common velocity, $V'$, there obviously would be no

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change in the total linear momentum, nor in the flow. In symbols we would have the equation

$$MV + mv = (M + m) V'.$$

Mere mingling, therefore, of the two air currents, upper and lower, cannot change the depth of the atmosphere, nor, therefore, the height of the barometer. But then in the case of atmospheric convection we have something more than the simple mingling of two air currents, and the linear momentum does not, in general, remain constant. The increased surface velocity following convection, a phenomenon very marked in the case of a thunderstorm, causes an increased frictional drag and therefore a greater or less decrease in the total flow. Suppose this amounts to the equivalent of reducing the velocity of a layer of air only 25 metres thick from $V$ to $v$, and let $V = 5v$. That is, the one three hundred and twentieth part of the atmosphere has its flow reduced to one-fifth its former value. This would reduce the total flow by about 1 part in 400, and thereby increase the barometric reading by nearly 2 millimetres.

It would seem, then, that the friction of the thunderstorm gust on the surface of the earth, through the consequent decrease in the total linear momentum of the atmosphere and, therefore, its total flow, must be an important contributing cause of the rapid and marked increase of the barometric pressure that accompanies the onset of a heavy thunderstorm.

To sum up: The chief factors contributing to the increase of the barometric pressure during a thunderstorm appear to be, possibly in the order of their magnitude: (*a*) Decrease of horizontal flow, due to surface friction. (*b*) Vertical wind pressure, due to descending air. (*c*) Lower temperature. (*d*) Decrease in absolute humidity.

*Thunderstorm Temperatures.*—Before the onset of the storm the temperature commonly is high, but it begins rapidly to fall with the first outward gust and soon drops often as much as 5° C. to 10° C. because, as already explained, this gust is a portion of the descending air cooled by the cold rain and by its evaporation. As the storm passes the temperature generally recovers somewhat, though it seldom regains its original value.

*Thunderstorm Humidity.*—As previously explained, heavy rain, at least up in the clouds, and therefore much humidity, and a temperature contrast sufficient to produce rapid vertical convection, are essential to the genesis of a thunderstorm. Hence during the early forenoon of a thunderstorm day both the absolute and the relative humidity are likely to be high. Just before the storm, however, when the temperature has greatly increased, though the absolute humidity still is high, the relative humidity is likely to be rather low. On the other hand, during and immediately after the storm, because chiefly of the decrease in temperature, the absolute humidity is comparatively low and the relative humidity high.

*"Rain-gush."*—It has frequently been noted that the rainfall is greatest after heavy claps of thunder, a fact that appears to have given much comfort and great encouragement to those who maintain the efficacy of mere noise to induce precipitation—to jostle cloud particles together into raindrops. The correct explanation, however, of this phenomenon seems obvious: The violent turmoil and spasmodic movements within a large cumulus or thunderstorm cloud cause similar irregularities in the condensation and resulting number of raindrops at any given level. These in turn, as broken by the air currents, give local excess of electrification and of electric discharge or lightning flash. We have, then, starting toward the earth at the same time and from practically the same level, mass, sound, and light. The light travels with the greatest velocity, about 300,000 kilometres per second, and therefore the lightning flash is seen before the thunder is heard; its velocity being, roughly, only 330 metres per second. But the rain falls much slower still and therefore reaches the ground after the thunder is heard. In reality it is the excessive condensation or rain formation up in the cumulus cloud that causes the vivid lightning and the heavy thunder. According only to the order in which their several velocities cause them to reach the surface of the earth it might appear, and has often been so interpreted, that the lightning, first perceived, was the cause of the thunder, which, indeed, it is, and that the heavy thunder, next in order, was the cause of the excessive rain, which most certainly it is not.

*Thunderstorm Velocity.*—The velocity of the thunderstorm is simply the velocity of the atmosphere in which the bulk of the cumulus cloud happens to be located. Hence as the wind at this level is faster by night than by day and faster over the ocean than over land, it follows that exactly the same relations hold for the thunderstorm, that it travels faster over water than over land and faster by night than by day. The actual velocity of the thunderstorm, of course, varies greatly, but its average velocity in Europe is 30 to 50 kilometres per hour; in the United States, 50 to 65 kilometres per hour.

*Hail.*—Hail, consisting of lumps of roughly concentric layers of compact snow and solid ice, is a conspicuous and well-known phenomenon that occurs during the early portion of most severe thunderstorms. But in what portion of the cloud it is formed and by what process the layers of ice and snow are built up are facts that, far from being obvious, become clear only when the mechanism of the storm itself is understood.

As before, let the surface temperature be 30° C. and the absolute humidity 40 per cent., or the dew point 15° C. Under these conditions saturation will obtain, and, therefore, cloud formation will begin when the surface air has risen to an elevation of 1.5 kilometres. Immediately above this level the latent heat of condensation reduces the rate of temperature decrease with elevation to about half its former value, nor does this rate rapidly increase with further gain of height. Hence, usually, for the above assumptions correspond in general to average thunderstorm conditions, it is only beyond the 4-kilometre level that freezing temperatures are reached. It is therefore only in the upper portions of cumulus clouds, the portions that clearly must consist of snow particles and undercooled fog or cloud droplets, that hail can either originate or greatly grow.

But what, then, is the process by which the nucleus of the hailstone is formed and its layer upon layer of snow and ice built up? Obviously such drops of rain as the strong updraft within the cloud may blow into the region of freezing temperatures will quickly congeal and also gather coatings of snow and frost. After a time each incipient hailstone will get into a weaker updraft, for this is always irregular and puffy, or else will tumble to the edge of the ascending column. In either case it will then fall back into the region of liquid drops, where it will gather a coating of water, a portion of which will at once be frozen by the low temperature of the kernel. But again it meets an upward gust, or falls back where the ascending draft is stronger, and again the cyclic journey from realm of rain to region of snow is begun;

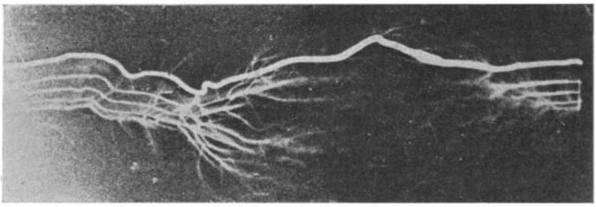
and each time—there may be several—the journey is completed a new layer of ice and a fresh layer of snow are added. In general the size of the hailstones will be roughly proportioned to the strength of the convection current, but since their weights vary approximately (they are not homogeneous) as the cube of their diameters while the supporting force of the upward air current varies, also approximately, as only the square of their diameters it follows that a limiting size is quickly reached. It is also evident, from the fact that a strong convection current is essential to the formation of hail, that it can occur only where this convection exists, that is, in the front portion of a heavy to violent thunderstorm.

Some meteorologists hold that the roll scud between the ascending warm and descending cold air is the seat of hail formation, but this is a mistaken assumption. Centrifugal force would throw a solid object, like a hailstone, out of this roll probably before a single turn had been completed. Besides, and this objection is, perhaps, more obviously fatal than the one just given, the temperature of the roll scud, because of its position, the lowest of the whole storm cloud, clearly must be many degrees above the freezing point. Indeed, as the above calculation shows, temperatures low enough for the formation of hail cannot often obtain at levels much less than three times that of the scud, and therefore it clearly is in the higher levels of the cumulus and not in the low scud that hail must have its genesis and make its growth.

*Lightning.*—About the middle of the eighteenth century Franklin and others clearly demonstrated that the lightning of a thunderstorm and the discharge of an ordinary electric machine are identical in nature, and thereby established the fact that many of the properties of the former may logically be inferred from laboratory experiments with the latter. There is, however, one important source of difference between the two phenomena that does not seem always to be clearly kept in mind, namely, the distribution of the charge. In the one case, that of the laboratory experiment, the charge commonly exists almost wholly on the surface of the apparatus used, while in the other, that of the thunderstorm, it is irregularly distributed throughout the great cloud volume. Hence the two discharges, lightning and laboratory sparks, necessarily differ from each other in important details.

Nevertheless in each case the atmosphere must be ionized before the discharge can take place freely, and this condition seems, at times at least, to establish itself progresso-spasmodically. That is, a small initial discharge, losing itself in a terminal brush, is rapidly followed by another and another, each losing itself in a manner similar to the first, until a path from pole to pole is sufficiently ionized to permit of a free flow and quick exhaustion of the remaining charge. Fig. 23, copied from a photograph obtained by Walter,[9] on a rapidly moving plate, shows how a laboratory spark spasmodically (doubtless at the period of electrical oscillation) ionizes the air from either pole and thus progressively extends and finally closes the conducting path of complete discharge. There appears also to be good evidence that the lightning discharge often builds itself up in a manner generally similar, though, perhaps, radically different, in certain details. As already implied, ordinary laboratory apparatus has a free period of electrical oscillation, and therefore an electrical discharge from such apparatus is oscillatory in nature, but as yet there seems to be no certain evidence that lightning discharges ever are distinctly oscillatory. They frequently are pulsatory, discharge after discharge taking place in the same direction and along the same path, as we shall see later; but this is an entirely different thing from being oscillatory, or consisting of a decreasing series the units of which are alternately in opposite directions.

FIG. 23.



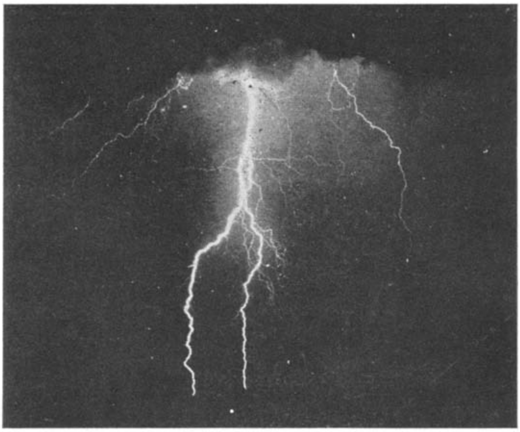
The growth of an electric spark discharge (Walter).

It will be convenient, in further discussing the facts known about lightning, to classify it according to its general appearance.

*Streak Lightning.*—When the storm is close by, the lightning discharge almost invariably appears to the unaided eye as one or more sinuous lines or streaks of vivid white or pink. Sinuous, because electrically the atmosphere is heterogeneous or unequally ionized. There often appears to be a main trunk with a number of branches, all occurring at the same time and instantaneously. At other times there seem to be two or more simultaneous but locally disconnected streaks. Frequently the discharge continues flickeringly (on rare occasions even steady, like a white-hot wire) during a perceptible time—occasionally a full second.

But all these phenomena are best studied by means of the camera, and have been so studied by several persons, among whom Walter, of Hamburg, and Larsen, of Chicago, are two of the most persistent and successful. Stationary cameras, revolving cameras, stereoscopic cameras, cameras with revolving plates, and cameras with spectrographic attachments have all been used, separately and jointly, and the results have abundantly justified the time and the labor devoted to the work.

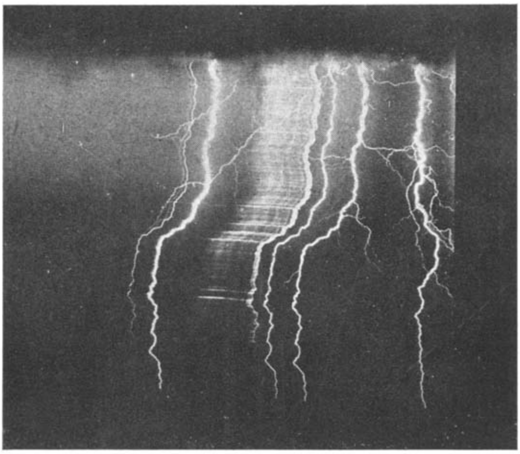
FIG. 24.



Streak lightning, stationary camera; companion to Fig. 25 (Walter).

Fig. 24, copied by permission from one of Walter's unpublished negatives, shows the ordinary tracery of a lightning discharge when photographed with a stationary camera. It is only a permanent record of the appearance of the lightning to the unaided eye. Fig. 25, however, also copied by Walter's kind permission from one of his unpublished photographs, is a record of the same discharge obtained with a rotating camera. It will be noted that the more nearly vertical discharge occurred but once, or was single; that this discharge was quickly followed by a second along the same path to about one-fourth of the way to the earth where it branched off on a new course; that the second discharge was followed in turn at short but irregular intervals by a whole series of sequent discharges; that most of the discharges appeared as narrow, intensely luminous streaks, and that one of the sequent discharges appeared, not to the eye, but on the plate of the rotating camera, as a broad band or ribbon. On close inspection it will be obvious that the plaid-like ribbon effect is due, the warp to irregularities in the more or less continuous discharge, and the woof to roughly end-on and therefore brighter portions of the streak. Another point particularly worthy of attention is the fact that while the first discharge has several side branches the following ones remain entire from end to end and are nowhere subdivided.

FIG. 25.

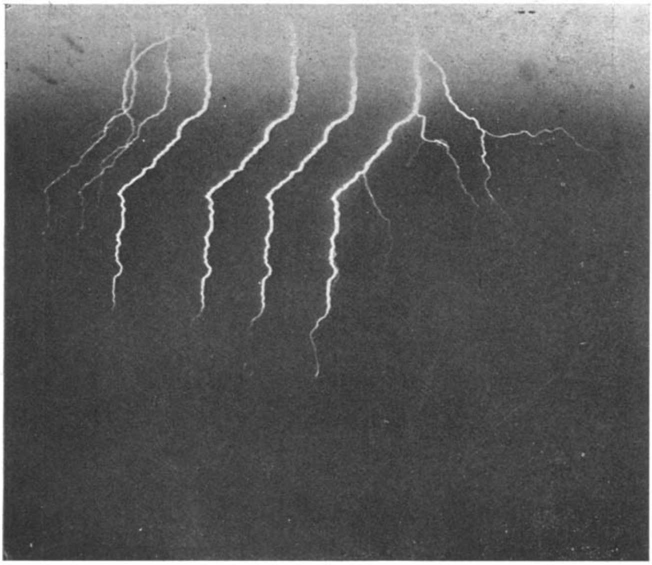


Streak lightning (sequent discharges), rotating camera; companion to Fig. 24 (Walter).

Fig. 26, taken from a photograph obtained by Mr. Larsen, of Chicago, and kindly loaned for use here by the Smithsonian Institution, shows another series of sequent discharges similar to those of Fig. 25, except that in this case there was no ribbon discharge. The time of the whole discharge, as calculated by Mr. Larsen, was 0.315 second. Here, too, side branches occur with the first, but only the first, discharge. This, however, is not an invariable rule for occasionally, as illustrated by Fig. 27, copied from a published photograph by Walter, the side branches persist through two or three of the first successive discharges, but not through all. In such case each tributary when repeated follows, as does the main stream, its own original channel.

The phenomenon of sequent discharges, all along the same path, and the disappearance of the side branches with or quickly after the first discharge both seem reasonably clear. The first discharge, however produced, obviously takes place against very great resistance, and therefore under conditions the most favorable for the occurrence of side branches or ramifications. But the discharge itself leaves the air along its path temporarily highly ionized—puts a temporary line conductor, with here and there a poorer conducting branch, in the atmosphere. This conductor is not only temporary (half the ions are reunited in about 0.15 second, the air being dusty) but also so extremely fragile as to be liable to rupture by the atmospheric violence it itself creates. Because partly, perhaps, of just such interruptions, and because

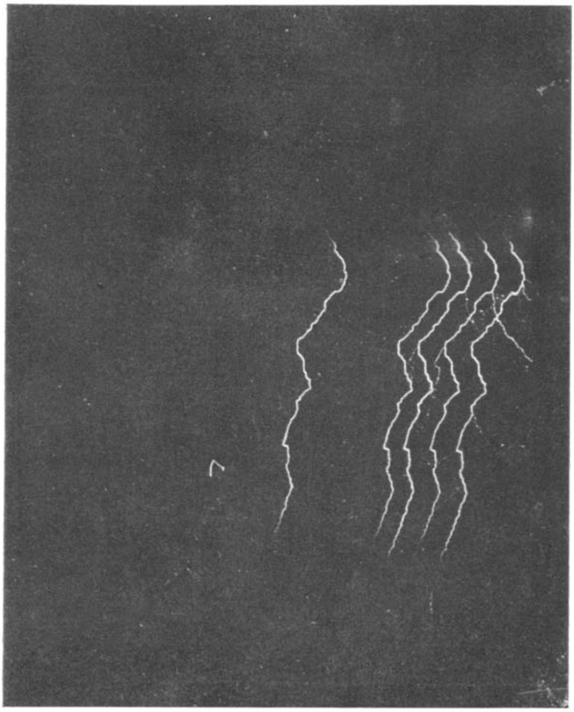
FIG. 26.



Streak lightning (sequent discharges), rotating camera (Larsen).

also of the volume distribution of the electricity which prevents a sudden and complete discharge, the actual discharge is divided into a number of partials that occur sequently. Obviously the breaks in the conducting (ionized) path, if they exist, are only here and there and but little more than sufficient to interrupt the flow. Hence the next discharge, if it occurs quickly, must follow the conducting and, therefore, original discharge path. Besides, in the subsequent discharges the original side branches will be quickly abandoned because of their greater resistance, or, what comes to the same thing, because of the more abundant ionization and consequent higher conductivity of the path of heaviest discharge.

Fig. 27.



Streak lightning (sequent discharges), rotating camera (Walter).

This leaves the genesis of the initial discharge, often if not usually the only one, to be explained, and indeed this probably is, at present, the least understood of all the many thunderstorm phenomena. Judging from the voltages required to produce laboratory sparks, roughly 30,000 volts per centimetre, it is not obvious how such tremendous voltage differences can be established between clouds or between a cloud and the earth as would seem to be necessary to produce a discharge kilometres in length, as often occurs. Of course the potential of individual drops may grow in either of two ways: (*a*) By coalescence of equally charged smaller drops into larger ones. In this case, since capacity is directly proportioned to the radius, the potentials of the individual drops must be proportional to the squares of their radii. (*b*) By evaporation of equally charged drops. Here the potentials of the individual drops obviously are inversely proportional to their radii. In each case the tendency of the separate drops to discharge is increased, but the potential of the cloud as a whole remains unchanged. At present, therefore, one can do but little more than speculate on the subject of the primary lightning discharge, but even that much may be worth while since it helps one to remember the facts.

As already explained the electrical separation within a thunderstorm cloud is such as to place a heavily charged positive layer (lower portion of the cloud) between the earth and a much higher, also heavily charged, negative layer (upper portion of the cloud). Hence the discharges, or lightning, from the intermediate or positively charged layer may be either to the negative portion above, in some cases even to an entirely different cloud, or to the earth below. Further, through the sustaining influence and turbulence of the uprushing air, there must be formed at times and places practically continuous sheets and streams of water, of course heavily charged and at high potential, and also layers and streaks of highly ionized air; that is, electrically speaking, heavily charged conducting sheets and rods, whether of coalesced drops or of ionized air, are over and over, so long as the storm lasts, momentarily placed here and there within the positively charged mass of the storm cloud.

Let us see, then, what might be expected as the result of this peculiar disposition of charges and conductors, the result, namely, of the existence of a heavily surface-charged vertical conductor in a strongly volume-charged horizontal layer or region, above and below which there are steep potential gradients to negatively charged parallel surfaces.

The conductor will be at the same potential throughout, and therefore the maxima of potential gradients normal to it will be at its ends, where, if these gradients are steep enough, and the longer the conductor the steeper the gradients, brush discharges will take place. Assume, then, that a brush discharge does take place and that there is a supply of electricity flowing into the conductor to make good the loss. The brush and the line of its most vigorous ionization necessarily will be directed along the potential gradient or toward the surface of opposite charge. But this very ionization automatically increases the length of the conductor, for a path of highly ionized air is a conductor, and as the length of the conductor grows so, too, does the steepness of the potential gradient at its forward or terminal end, and as the steepness of this gradient increases the more vigorous the discharge, always assuming an abundant electrical supply. Hence, an electric spark once started within a thunderstorm cloud has a good chance, by making its own conductor as it goes, of geometrically growing into a lightning flash of large dimensions. Of course when the electrical supply is small the lightning is feeble and soon dissipated.

Whether the discharge actually does burrow its way through the atmosphere in some such manner as that indicated probably would be difficult, though not necessarily impossible, of observation. Indeed, a roughly analogous phenomenon[10] can be produced on a photographic plate by bringing in contact with the film, some distance apart, two conducting points attached to the opposite poles of an influence machine. Brush discharges develop about each point, but the glow at the negative pole detaches itself and slowly meanders across the plate toward the positive point. As it goes it continually builds for itself, out of the silver of the emulsion, a conducting path.

*Rocket Lightning.*—Many persons have observed what at least seemed to be a progressive growth in the length of a streak of lightning. In some cases[11] this growth or progression has appeared so slow as actually to suggest the flight of a rocket, hence the name.

At first one might well feel disposed to regard the phenomenon in question as illusory, but it has been too definitely described and too frequently observed to justify such summary dismissal.

Naturally, in the course of thousands of lightning discharges, many degrees of ionization, availability of electrical charge, and slopes of potential gradient are encountered. Ordinarily the growth of the discharge, doubtless, is in a geometric ratio and the progress of its end exceedingly swift, but it seems possible for the conditions to be such that the discharge can barely more than sustain itself, in which case the movement of the flash terminal may, possibly, be relatively slow.

*Ball Lightning.*—Curious luminous balls or masses, of which C. de Jans [12] probably has given the fullest account, have time and again been reported among the phenomena observed during a thunderstorm. Most of them appear to last only a second or two and to have been seen at close range, some even passing through a house, but they have also appeared to fall, as would a stone,[13] or like a meteor, from the storm cloud, and along the approximate path of both previous and subsequent lightning flashes. Others appear to start from a cloud and then quickly return, and so on through an endless variety of places and conditions.

Doubtless many reported cases of ball lightning are entirely spurious, being either fixed or wandering brush discharges or else nothing other than optical illusions, due in most cases probably to persistence of vision. But here, too, as in the case of rocket lightning, the amount and excellence of observational evidence forbid the assumption that all such phenomena are merely subjective. Possibly in some instances, especially those in which it is seen to fall from the clouds, ball lightning may be only extreme cases of rocket lightning, cases in which the discharge for a time just sustains itself. A closely similar idea has been developed in detail by Toepler.[14] It may either disappear wholly and noiselessly, as often reported, or it could perhaps suddenly gain in strength and instantly disappear, as sometimes observed, with a sharp abrupt clap of thunder.

To say that all genuine cases of ball lightning, those that are not mere optical illusions, are stalled thunderbolts, certainly may sound very strange. But that indeed is just what they are according to the above speculation, a speculation that recognizes no difference in kind between streak, rocket, and ball lightning, only differences in the amounts of ionization, quantities of available electricity and steepness of potential gradients.

*Sheet Lightning.*—When a distant thundercloud is observed at night one is quite certain to see in it beautiful illuminations, looking like great sheets of flame, that often flicker and glow in exactly the same manner as does streak lightning for well-nigh a whole second. In the daytime and in full sunlight the phenomenon when seen at all appears like a sudden sheen that travels and spreads here and there over the surface of the cloud. Certainly in most cases, so far as definitely known in all cases, this is only reflection from the body of the cloud of streak lightning in other and invisible portions. Conceivably a brush or coronal discharge may take place from the upper surface of a thunderstorm cloud, but one would expect this to be either a faint continuous glow or else a momentary flash coincident with a discharge from the lower portion of the cloud to earth or to some other cloud. But, as already stated, only reflection is definitely known to be the cause of sheet lightning. Coronal effects seem occasionally possible, but that they are ever the cause of the phenomenon in question has never clearly been established and appears very doubtful. It has often been asserted, too, that there is a radical difference between the spectra of streak and sheet lightning, but even this does not appear ever to have been photographically proved.

*Beaded Lightning.*—Discontinuous or beaded streaks of lightning have been reported from time to time. Indeed the author himself has several times seen, or had the impression of seeing, this phenomenon, but with one or two doubtful exceptions he felt practically certain that it was only an optical illusion. In addition to visual observations of the kind just described many photographs showing streaks of light broken into more or less evenly spaced dashes have been obtained and reported as photographs of beaded lightning. Without exception, however, these seem certainly to be nothing other than the photographs of alternating current electric lights, taken with the camera in motion. The objective reality, therefore, of beaded lightning does not seem at all well established, at least not sufficiently well to justify any serious effort to explain it.

*Return Lightning.*—This is commonly referred to as the return shock, and is only those relatively small electrical discharges that take place here and there from objects on the surface of the earth coincidently with lightning flashes, and as a result of the suddenly changed electrical strain. These discharges are always small in comparison with the main lightning flash, but at times are sufficient to induce explosions, to start fires, and even to take life.

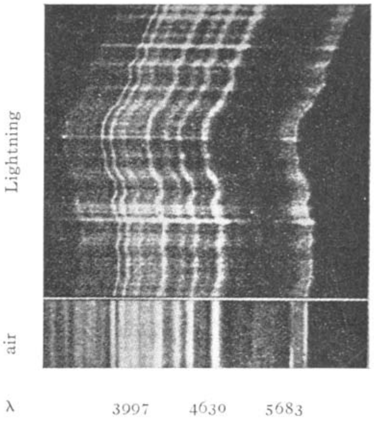
*Dark Lightning.*—When a photographic plate is exposed to a succession of lightning flashes, it occasionally happens that one or more of the streak images, on development, exhibits the "Clayden effect"—that is, appears completely reversed—while the others show no such tendency. Obviously, then, on prints from such a negative the reversed streaks must appear as dark lines, and for that reason the lightning flashes that produced them have been called "dark lightning." There is, of course, no such thing as dark lightning, but the photographic phenomenon that gave rise to the name is real, interesting, and reproducible at will in the laboratory.[15]

*Temperature.*—What the temperature along the path of a lightning discharge is no one knows, but it obviously is high, since it frequently sets fire to buildings, trees, and many other objects struck. In an ordinary electrical conductor the amount of heat generated in a given time by an electric current is proportional to the product $C^2RT$, in which $C$ is the strength of the current, $R$ the ohmic resistance, and $T$ the time in question during which $C$ and $R$ are supposed to remain constant. In a spark discharge of the nature of lightning some of the energy produces effects, such as decomposition and ionization, other than mere local heating, but as experiment shows, a great deal of heat is generated, according, so far as we know, to the same laws that obtain for ordinary conductors. Hence extra heavy discharges, like extra large currents, produce excessive heating, and therefore are far more liable than are light ones to set on fire any objects that they may hit.

*Visibility.*—Just how a lightning discharge renders the atmosphere through which it passes luminous is not definitely known. It must and does make the air path very hot, as we have seen, but no one has yet succeeded, by any amount of ordinary heating, in rendering either oxygen or nitrogen luminous. Hence it seems well nigh certain that the light of lightning flashes owes its origin to something other than high temperature, probably to internal atomic disturbances induced by the swiftly moving electrons of the discharge.

*Spectrum.*—Lightning flashes are of two colors, white and pink or rose. The rose-colored flashes, when examined in the spectroscope, show several lines due to hydrogen which, of course, is furnished by the decomposition of some of the water along the lightning path. The white flashes, on the other hand, show no hydrogen lines or, at most, but faint ones. As one might suspect, the spectrum of a lightning flash and that of an ordinary electric spark in air are practically identical. This is well shown by Fig. 28, copied from an article on the spectrum of lightning by Fox,[16] in which the upper or wavy portion is due to the lightning and the lower or straight portion to a laboratory spark in air.

FIG. 28.



It is often asserted that the spectrum of streak lightning consists wholly of bright lines and that sheet lightning gives only nitrogen bands; and from this it is argued that the latter is not a mere reflection of the first. This assertion is not supported by Fig. 28, the brightest portions of which, the portions that would the longest be seen as reflection grew steadily feebler, coincide with strong nitrogen bands. In this connection, however, it should be remembered that accurate wave-length measurements, and therefore positive identification of the lines of lightning spectra, is not possible, owing to the small dispersion or separation of the lines on all such negatives so far reported.

*Duration.*—The duration of the lightning discharge is exceedingly variable, ranging from 0.0002 second for a single flash to, in rare cases, even a full second or more for a multiple flash consisting of a primary and a series of sequent flashes. On rare occasions a discharge of long duration appears *to the eye* to be steady like a glowing solid. Possibly the best measurements of the shorter intervals were made by De Blois [17] with the aid of a high-frequency oscillograph. He found the durations of 38 single peaks, averaging 0.00065 second, to range from 0.0002 second to 0.0016 second. Flashes that last as long as a few tenths or even a few hundredths of a second are almost certainly multiple, consisting of a succession of apparently individual discharges occurring at unequal intervals. Occasionally a practically continuous discharge of varying intensity, but all the time strong enough to produce luminosity, will last a few hundredths of a second.

It must be remembered that the duration of even a single discharge and the length of time to complete the circuit, or ionize a path, from cloud to earth, say, are entirely different things. The latter seems usually (rocket and ball lightning may furnish exceptions) to be of exceedingly short duration, while the former depends upon the supply of electricity and the ohmic resistance directly and upon the potential difference inversely.

*Discharges Direct, not Alternating.*—Years ago some one for some reason or other, or for no reason, made the statement that the lightning flash is alternating and of high frequency, like the discharge of a Leyden jar, and forthwith, despite the fact that all evidence is to the contrary, it became a favorite dogma of the text-book, passed on unquestioned from author to author and handed down inviolate from edition to edition. There often are a number of successive discharges in a fraction of a second, as photographs taken with a revolving camera show, but they are not only along the same path but also in the same direction. This is obvious from the fact that when the side branches persist, as in Fig. 26, through two or more partial or sequent discharges, they are always turned in the same direction. It is also proved by the direct evidence of the oscillograph.[18]

In the case of each separate discharge also the direction seems constant. It may vary in strength, or pulsate, but, apparently, it does not alternate. There are several reasons for concluding that lightning discharges are direct and not alternating, of which the following cover a wide range and probably are the best:

(*a*) Lightning operates telegraph instruments. If the discharge were alternating it would not do so.

(*b*) At times it reverses the polarity of dynamos. This requires a direct and not a high-frequency alternating discharge.

(*c*) The oscillograph[19] shows each surge or pulsation, as well as the whole flash, to be unidirectional.

(*d*) The relative values of the ohmic resistance, the self-induction, and the capacity, in the case of a lightning discharge, appear usually, if not always, to be such as to forbid the possibility of oscillations.

It has been shown that whenever the product of the capacity by the square of the resistance is greater than four times the self-induction, or, in symbols, that whenever

$$CR^2 > 4L$$

oscillations are impossible. Undoubtedly all these terms vary greatly in the case of lightning discharges, but $R$, presumably, is always sufficiently large to maintain the above inequality and therefore absolutely to prevent oscillations.

Possibly a calculation giving roughly the numerical order of the terms involved would be helpful. For this purpose assume a cloud whose undersurface is circular with a radius of 3 kilometres, and whose height above the ground is 1 kilometre, and let there be a discharge from the centre of the cloud base straight to the earth: Find a probable value for the self-induction and capacity, and from these the limiting value of the resistance to prevent oscillations, or the value of $R$ in the equation

$$CR^2 = 4L.$$

To find $L$ we have the fact that the coefficient of self-induction is numerically equal to twice the energy in the magnetic field per unit current in the circuit, and the further fact that per unit volume this energy is numerically equal to $H/8\pi$, in which $H$ is the magnetic force. Let $a$ be the radius of the lightning path and assume the current density in it to be uniform. Let $b$ be the equivalent radius of the cylinder, concentric with the lightning path, along which the return or displacement current flows. In this case the energy $W$ of the magnetic field per centimetre length of the discharge is given by the equation

$$W = \log_e \frac{b}{a} + \frac{1}{2}.$$

Let $b = 2$ kilometres and $a = 5$ centimetres. Then $W = \log_e 4 \times 10^4 + \frac{1}{2} = 11$, approximately. Hence the energy of the magnetic field per unit current for the whole length, 1 kilometre, of the flash is represented by the equation

$$W10^5 = 11 \times 10^5,$$

hence the self-induction $= 22 \times 10^5 = 22 \times 10^{-4}$ henry.

To find $C$ we shall assume a uniform field between the cloud and the earth. As a matter of fact, this field is not uniform, and the calculated value of $C$, based upon the above assumption, is somewhat less than its actual value. Assuming, then, a uniform field we have

$$C = \frac{a}{4\pi d} = \frac{\pi 9 \times 10^{10}}{4\pi \times 10^5} = 225 \times 10^3 = 25 \times 10^{-8} \text{ farad, about.}$$

Hence, substituting in the equation

$$CR^2 = 4L,$$

we get

$$R = 190 \text{ ohms per kilometre, approximately.}$$

Neither $a$, the radius of the lightning path, nor $b$, the equivalent radius of the return current, is accurately known, but from the obviously large amount of suddenly expanded air necessary to produce the atmospheric disturbances incident to thunder it would seem that 1 centimetre would be the minimum value for $a$. Also, from the size of thunder clouds, it appears that 10 kilometres would be the maximum value for $b$.

On substituting these extreme values in the above equations, we get

$$R = 200 \text{ ohms per kilometre, roughly.}$$

From the fact that $C$ varies inversely and $L$ directly as the altitude of the cloud it follows that, other things remaining equal, the height of the cloud has no effect on the value of $R$ per unit length.

If the altitude is kept constant and the size of the cloud varied $C$ will increase directly as the area, and $L$ will increase directly as the natural logarithm of the equivalent radius of the cylinder of return current. Assuming the area of the cloud base to be 1 square kilometre, which certainly is far less than the ordinary size, and computing as above we find

$$R = 850 \text{ ohms per kilometre, roughly.}$$

Again, assuming the base area to be 1000 square kilometres, an area far in excess of that of the base of an ordinary thunderstorm cloud, we find

$$R = 35 \text{ ohms per kilometre, roughly.}$$

It would seem, therefore, that a resistance along the lightning path of the order of 200 ohms per kilometre, or 0.002 ohm per centimetre, would suffice, in most cases, absolutely to prevent electrical oscillations between cloud and earth. In reality the total resistance includes, in addition to that upon which the above calculations are based, the resistance in parallel of the numerous feeders or branches within the cloud itself. In other words, the assumption that the resistance of the condenser plates is negligible may not be strictly true in the case of a cloud. Nor is this the only uncertainty, for no one knows what the resistance along the path of even the main discharge actually is; though, judging from the resistance of an oscillatory electric spark,[20] it, presumably, is much greater than the calculated limiting value; and if so, then lightning flashes, as we have seen, must be unidirectional and not alternating.

*Length of Streak.*—The total length of a streak of lightning varies greatly. Indeed the brush discharge so gradually merges into the spark and the spark into an unmistakable thunderbolt that it is not possible sharply to distinguish between them, nor, therefore, to set a minimum limit to the length of a lightning path. When the discharge is from cloud to earth the length of the path is seldom more than 2 to 3 kilometres, but, in the case of low-lying clouds, may be much less, and especially so when they envelop a mountain peak.

On the other hand, when the discharge is from cloud to cloud the path generally is far more tortuous and its total length much greater, amounting at times to 10, 15, and even 20 kilometres.

*Discharge, Where to Where.*—As already explained, lightning discharges may be from cloud to earth, from one part to another of the same cloud, or from cloud to cloud. But since the great amount of electrical separation, without which the lightning could not occur, takes place within the rain cloud, it follows that this is also likely to be the seat of the steepest potential gradients. Hence it would appear that lightning must occur most frequently between the lower and the upper portions of the same cloud, and this is fully supported by observations. The next in frequency, especially in mountainous regions, is the discharge from cloud (lower portion) to earth, and the least frequent of all, ordinarily, those that take place between one and another entirely independent or disconnected clouds.

*Explosive Effects.*—The excessive and abrupt heating caused by the lightning current explosively and greatly expands the column of air through which it passes. It even explosively vaporizes such volatile objects as it may hit that have not sufficient conductivity to carry it off. Hence, chimneys are shattered, shingles torn off, trees stripped of their bark or utterly slivered and demolished, kite and other wire fused or volatilized, holes melted through steeple bells and other large pieces of metal, and a thousand other seeming freaks and vagaries wrought.

Many of the effects of lightning appear at first difficult to explain, but, except the physiological and, probably, some of the chemical, all depend upon the sudden and intense heating along its path.

*Chemical Effects.*—As is well known, oxides of nitrogen and even what might be termed the oxide of oxygen, or ozone, are produced along the path of an electric spark in the laboratory. Therefore one might expect an abundant formation, during a thunderstorm, of these same compounds. And this is exactly what does occur, as observation abundantly shows. It seems probable, too, that some ammonia must also be formed in this way, the hydrogen being supplied by the decomposition of raindrops and water vapor.

In the presence of water or water vapor these several compounds undergo important changes or combinations. The nitrogen peroxide (most stable of the oxides of nitrogen) combines with water to produce both nitric and nitrous acids; the ozone with water gives hydrogen peroxide and sets free oxygen; and the ammonia in the main merely dissolves, but probably also to some extent forms caustic ammonia and hydrogen. Symbolically the reactions seem to be as follows:

$$
\begin{aligned}
2NO_2 + H_2O &= HNO_3 + HNO_2. \\
O_3 + H_2O &= H_2O_2 + O_2. \\
2NH_3 + 2H_2O &= 2NH_3OH + H_2.
\end{aligned}
$$

The ammonia and also both the acids through the production of soluble salts are valuable fertilizers. Hence, wherever the thunderstorm is frequent and severe, especially, therefore, within the tropics, the chemical actions of the lightning may materially add, as has recently been shown,[21] to the fertility of the soil and the growth of crops.

*Danger.*—It is impossible to say much of value about the danger from lightning. Generally it is safer to be indoors than out during a thunderstorm, especially if the house has a well-grounded metallic roof. If outdoors it is far better to be in a valley than on the ridge of a hill, and it is always dangerous to take shelter under a tree—the taller the tree, other things being equal, the greater the danger. Some varieties of trees appear to be more frequently struck, in proportion to their numbers and exposure, than others, but no tree is immune. It seems that, in general, the trees most likely to be struck are those that have either an extensive root system, like the locust, or deep tap roots, like the pine, and this for the very obvious reason that they are the best grounded and therefore offer, on the whole, the least electrical resistance.

Finally, if one has to be outdoors and exposed to the danger of a violent thunderstorm it is advisable, so far as danger from the lightning is concerned, to get soaking wet, because wet clothes are much better conductors, and dry ones poorer, than the human body. In extreme cases it might even be advisable to lie flat on the wet ground.

As just implied, the contour of the land is an important factor in determining the relative danger from lightning because, obviously, the chance of a cloud-to-earth discharge, the only kind that is dangerous, varies inversely as the distance between them. Hence thunderstorms are more dangerous in mountainous regions, at least in the higher portions, than over a level country. For this same reason also, distance of cloud to earth, there exists on high peaks a level or belt of maximum danger, the level, approximately of the base of the average cumulus cloud. The tops of the highest peaks are seldom struck, simply because the storm generally forms and runs its course at a lower level.

Clearly, too, for any given section the lower the cloud the greater the danger. Hence a high degree of humidity is favorable to a dangerous storm, partly because the clouds will form at a low level and partly because the precipitation will be abundant. Hence, too, a winter thunderstorm, because of its generally lower clouds, is likely to be more dangerous than an equally heavy summer one.

*The Ceraunograph.*—Various instruments, based upon the principles of " wireless " receivers, have been devised for recording the occurrence of lightning discharges. Of course the sensitiveness of the instrument, the distance and the magnitude of the discharge all are factors that affect the record, but by keeping the sensitiveness constant, or nearly so, it is possible with an instrument of this kind to estimate the approximate distance, progress, and to some extent even the direction of the storm. Nevertheless there does not appear to be much demand for this information, and therefore at present the ceraunograph is but sparingly used.

*Thunder.*—For a long while no one had even a remotely satisfactory idea in regard to the cause of thunder, and it is not a rare thing even yet to hear such a childish explanation as that it is the noise caused by the bumping or rubbing of one cloud against another.

As above explained, because of the sudden and intense heating due to the lightning discharge the air column through which it passes is so greatly and so abruptly expanded as to simulate in every detail a violent explosion, and therefore to send out from every portion of its path a steep compression wave, which, of course, is the real physical cause of the thunder. The expansion, obviously, is followed by a cooling and contraction, but though this action is rapid it probably is not nearly rapid enough to have anything to do with the production of thunder, though many have suggested it as the whole cause.

*Rumbling.*—Probably the most distinctive characteristic of thunder is its long-continued rumbling and great variation in intensity. Several factors contribute to this peculiarity, among them:

Inequalities in the distances from the observer to the various portions of the lightning's path. Hence the sound, which ordinarily travels about 330 metres per second in the air, will not all reach him at the same time, but continuously over an appreciable interval of time.

Crookedness of path. Because of this condition it often happens that sections of the path here and there are, each through its length, at nearly the same distance from the observer or follow roughly the circumferences of circles of which he is the centre, while other portions are directed more or less radially from him. This would account for, and doubtless in a measure is the correct explanation of, some of the loud booming effects or crashes that accompany thunder.

Succession of discharges. When, as often happens, several discharges follow each other in rapid succession there is every opportunity for all sorts of irregular mutual interference and reinforcement of the compression waves or sound impulses they send out.

Reflection. Under favorable conditions the echo of thunder from clouds, hills, and other reflecting objects certainly is effective in accentuating and prolonging the noise and rumble. But the importance of this factor generally is greatly overestimated, for ordinarily the rumble is substantially the same whether over the ocean, on the prairies, or among the mountains.

*Distance Heard.*—The distance to which thunder can be heard seldom exceeds 25 kilometres, while ordinarily, perhaps, it is not heard more than half so far. To most persons, familiar with the great distances to which the firing of large cannon is still perceptible, the relatively small distances to which thunder is audible is quite a surprise. It should be remembered, however, that both the origin of the sound and often the air itself as a sound conductor are radically different in the two cases. The firing of cannon or any other surface disturbance is heard farthest when the air is still and when, through inversion or otherwise, it is so stratified as in a measure to conserve the sound energy between horizontal planes. Conversely, sound is heard to the least distance when the atmosphere is irregular in respect to either its temperature or moisture distribution, or both, for these conditions favor the production of internal sound reflections and the dissipation of energy. Now the former or favorable conditions occasionally obtain during the production of ordinary noises, including the firing of cannon, but never obtain during a thunderstorm. In fact, the thunderstorm is especially likely itself to establish the second set of the above conditions, or those least favorable to the far carrying of sound.

Then, too, when a cannon, say, is fired the noise all starts from the same place, the energy is concentrated, while in the case of thunder it is stretched out over the entire length of the lightning path. In the first case the energy is confined to a single shell; in the second it is diffused through an extensive volume. It is these differences in the concentration and the conservation of the energy that cause the cannon to be heard much farther than the heaviest thunder, even though the latter almost certainly produces much the greater total atmospheric disturbance.

*Normal Atmospheric Electricity.*—The only reason for mentioning normal atmospheric electricity in connection with thunderstorms is to emphasize the fact that, contrary to what many suppose to be the case, there is but little relation, in the sense of cause and effect, between these two phenomena. Thus while the difference in electrical potential between the surface of the earth and a point at constant elevation is roughly the same at all parts of the world, the number and intensity of thunderstorms vary greatly from place to place. Further, while the potential gradient at any given place is greatest in winter the number of thunderstorms is most frequent in summer, and while the gradient, in the lower layer of the atmosphere, at many places, usually is greatest from 8 to 10 o'clock, both morning and evening, and least at 2 to 3 o'clock P.M. and 3 to 4 o'clock A.M., no closely analogous relations hold for the thunderstorm.

Probably the most interesting conclusion in regard to normal atmospheric electricity so far drawn from observation and experiment is this: That the earth everywhere, land and water and from pole to pole, is a negatively charged sphere of practically constant surface density, surrounded by an atmosphere so conducting that it is constantly carrying away a current that amounts on the whole to about 1000 ampères.

Where the supply of negative electricity comes from that keeps the surface of the earth on the whole negatively charged in spite of this steady great loss, or how the outgoing current is compensated, no one knows. Rain does not help matters, for, as we have seen, that is prevailingly positive, whereas we need, to compensate the loss, to bring back negative electricity and a great deal of it. Neither, so far as known, is compensation supplied by means of the lightning, for, in the great majority of cases, this, too, is positive from cloud to earth. And so the puzzle remains. As Simpson[22] puts it:

"A flow of negative electricity takes place from the surface of the whole globe into the atmosphere above it, and this necessitates a return current of more than 1000 ampères; yet not the slightest indication of any such current has so far been found, and no satisfactory explanation for its absence has been given."

Much more, of course, might be said on this subject, for it is a big one on which many have labored, but perhaps the above is sufficient for the purpose of this final section, namely, to show that, contrary to opinions often held, there is no obvious and close relation between the thunderstorm and normal atmospheric electricity; that, according to our best evidence, they are distinct and independent phenomena.

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**The United States Bureau of Mines** has begun the collection of a general library of petroleum literature, under the direction of W. A. Williams, chief petroleum technologist. The details of this work have been assigned to Dr. David T. Day, who has recently been transferred from the United States Geological Survey as petroleum technologist, and who will also assist in a thoroughly organized research into the chemistry of oils, which is being developed by the Bureau of Mines. The importance of such a library is so manifest that it is hoped all technologists will aid in the work by exchanging with the bureau all available books and maps on this subject.