Lightning
by
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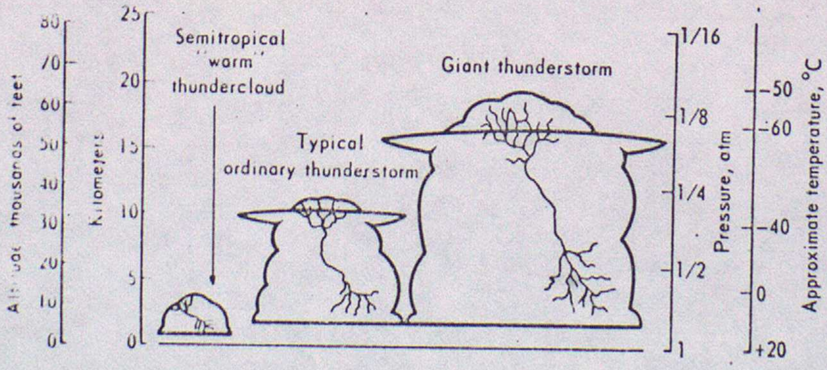
1 Introduction

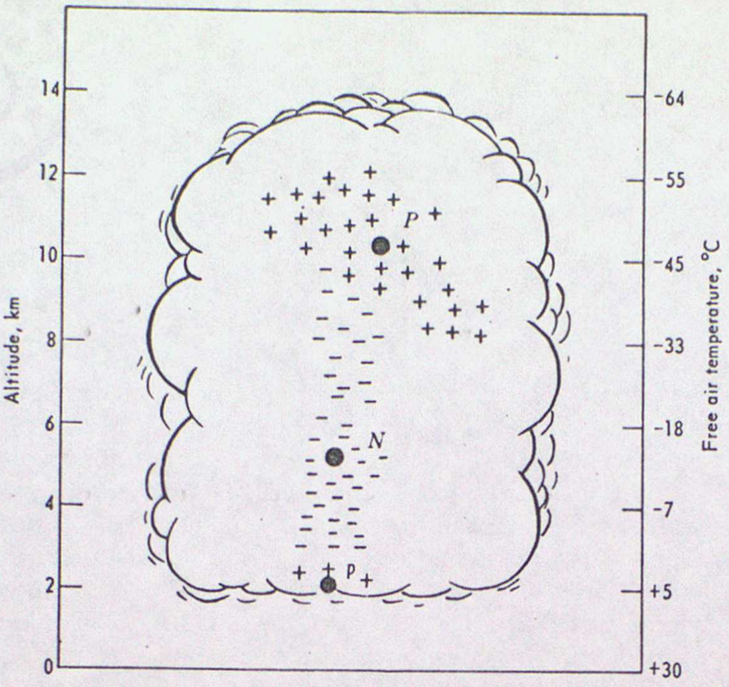
Despite attempts to understand the discharge process, we know as lightning, since the time of Benjamin Franklin, much of what can be said is descriptive rather than explanatory. The phenomenon has received little attention in the Meteorological Office beyond that necessary to sustain the Sferics programme and respond to simple enquiries from our customers. It is appropriate to review the present state of understanding. This is done by introducing some basic terminology and describing the main features of a number of individual processes involved in the lightning phenomenon. Where possible emphasis is placed on physical insight and the order of magnitude of key variables.

The most common producer of lightning is the vigorous convective cloud we know as cumulonimbus. However lightning also occurs in snow storms, sand storms and in the clouds over erupting volcanos. Very little is known about the latter and almost all of the ensuing discussion will be based upon discharges from Cbs. Such lightning can take place entirely within a cloud (intracloud or cloud discharges), between two clouds (cloud-to -cloud discharges) between a cloud and the earth (cloud-to-ground discharges).

The properties of thunderstorms will be described in more detail in the next lecture but their dimensions and classical distribution of charge are indicated below.



Comparison of various sizes of convective clouds that produce lightning discharges.



Probable distribution of the thundercloud charges, P, N and p for a South African thundercloud according to Malan (1952, 1963). Solid black circles indicate locations of effective point charges, typically P = +40 coul, N = −40 coul, and p = +10 coul, to give observed electric field intensity in the vicinity of the thundercloud.

Although the most frequently occuring form of lightning may not be the cloud to ground discharge, the greater part of the literature is concerned with it.

A cloud-to-ground lightning flash, which typically lasts about 0.5 secs, is usually composed of several intermittent discharges called strokes, each of which has a duration of milliseconds. A stroke, in turn, is made up of a leader phase and return stroke phase. The leader initiates the return stroke by lowering cloud charge (usually of negative sign) and cloud potential towards the earth. First or stepped leaders are heavily branched and carry charges of a few coulombs; dart leaders which precede subsequent strokes carry less charge and follow the main channels of previous strokes.

The N region of the thundercloud provides the negative charge which flows to ground in the cloud-to-ground flash. If it is assumed to be isolated and spherical within a radius a, then a lower limit can be estimated for a, by requiring that the maximum field (to be found at its boundary) is less than the breakdown field of the atmosphere. This varies inversely with pressure and is usually taken to be 39 volts cm^{-1} $torr^{-1}$ for dry air. ie. 21 KV cm^{-1} at 3 km or 30 KV cm^{-1} at sea level. As discussed below, in practice cloud lightning is initiated at a much lower threshold $\sim$ 4KV cm^{-1}. A typical value for the N charge is − 40 coulomb so that

$$a^2 \geqslant Q/4\pi\varepsilon_0 E_{max} \quad \text{or} \quad a \geqslant 1\,\text{Km}.$$

Immediately it is evident that the lightning process must be able to drain charge in less than 1 second from a rather large volume, $\sim$ 4 km^3

A similar analysis can be carried out, in a cylindrical volume, for the minimum leader radius. If the leader is typically a km or so in length, its charge per unit length must be $\sim 10^{-3}$ coulomb/m.

Assuming a maximum field of 30 KV cm^{-1}, $a_{leader} \geq \rho / 2\pi\varepsilon_0 E_{max}$ or $a_{leader} \geq 6m$.

The luminous radius is likely to be less than this as the existence of charge does not guarantee the emission of radiative energy.

The potential difference of an isolated sphere of radius 1 km and carrying a charge of 40 coulombs is

$$V = \frac{Q}{4\pi\varepsilon_0 a} \simeq 3\,10^{8} \text{ volts.}$$

The presence of the earth's surface reduces this but the order of magnitude of the potential difference between ground and charge is $\sim 10^8$ volts. Thus the energy available for dissipation is $\sim 4\ 10^9$ joules. A single lightning stroke brings ~ 5 coulombs to ground. If the channel is 5 km long the energy dissipated per metre is $\sim 10^5$ joules m^{-1}. This is capable of vapourising some 40 g of water per metre; if those metres are in buildings, trees or people! In the atmosphere the energy is converted to dissociation, ionisation, excitation and kinetic energy of the channel particles, to the energy of expansion of the channel and to radiation. As Uman (1969) points out most of it must go to channel expansion; of which, more anon.

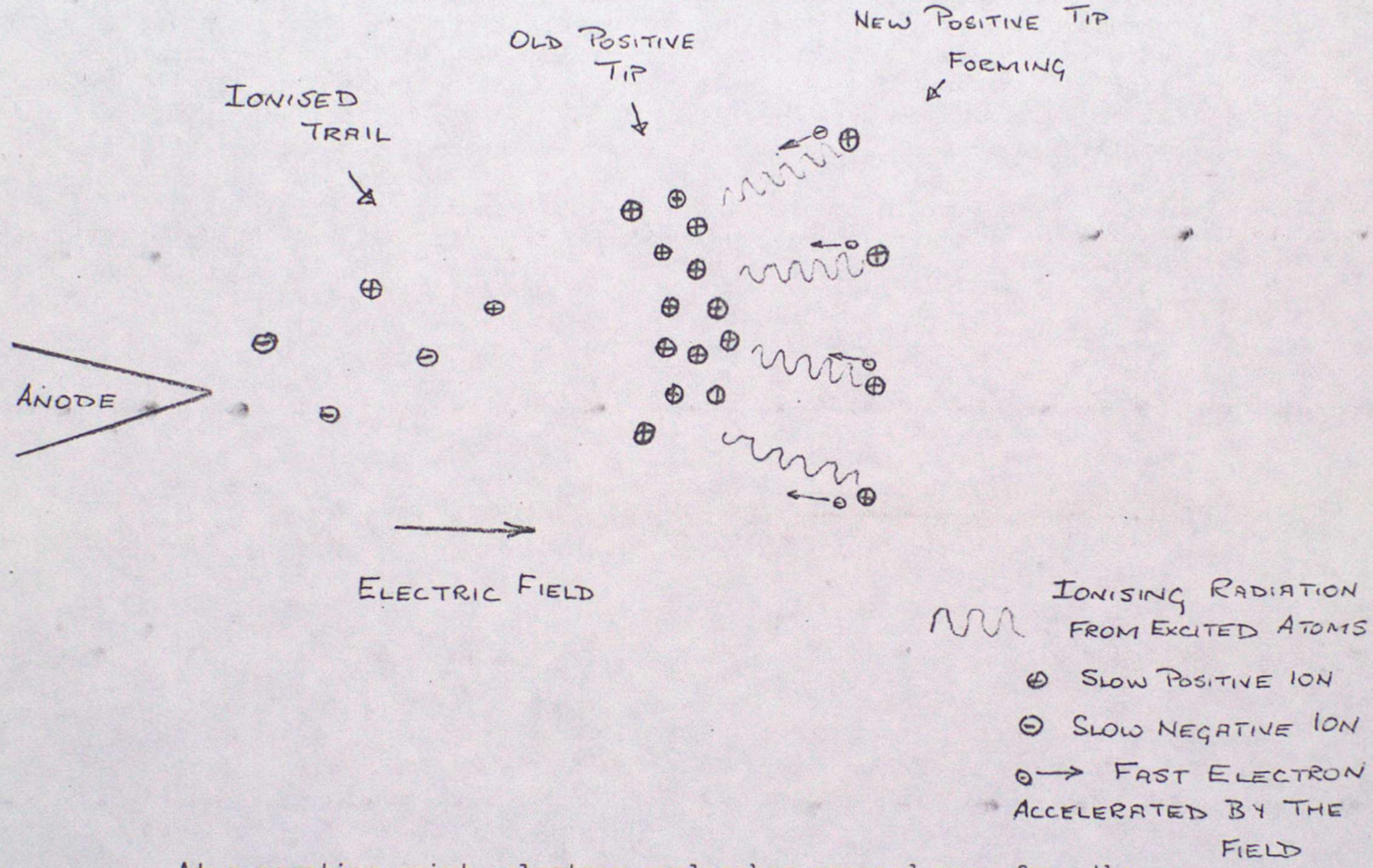
2. Initiation of lightning

2.1 The nature of corona discharges

Since the breakdown field in dry air, at normal atmospheric pressure, in the absence of particles, is about 30 KV cm^{-1}, while the largest fields that have been recorded within thunderstorms are about 4 KV cm^{-1}, some initiating process must be invoked. In recent years it has become clear that the emission of corona from the extremities of hydrometers is a very likely candidate for this.

For a pointed electrode, the discharge process begins in a small volume near to the tip, where the local electric field is high enough to permit ionisation of the gas molecules by any stray electrons. These latter must have been accelerated sufficiently by the electric field operating over their mean free path so that their kinetic energy exceeds the ionisation potential of the gas. Such activity releases further electrons at each subsequent collision. This process of cumulative ionisation is known as an electron avalanche, and is at the root of all forms of corona discharge. The threshold for corona reduces with reducing pressure as the mean free path increases.

For a positive electrode in air the discharge starts with short duration pulses known as outset streamers and longer burst pulses. The streamers are permitted to advance by virtue of their own space charge field, which enhances the field in one direction, and most importantly, by photoionisation of the O_2 molecules ahead of the tip. The electrons so released move inwards towards the generating tip where recombination leads to neutralisation but leaves a new positive charge centre ahead of the old. Thus propagation is one of successive replication. Provided that the electron avalanches reach a critical size of about 10^8 ions the streamer continues to propagate out into the low field region, (away from the pointed electrode) where the ambient field is too low to support avalanches on its own. The pulsed nature of the discharge is due to the accumulated space charge left behind by the propagating tip. This inhibits further streamers until it is cleared by the action of the field. Positive charge is moving in the direction of the field; if the energy so released is sufficient to match that used in the processes of ionisation and excitation, the streamer propagates independently of its source. Thus if the field exceeds a critical value, sustained but pulsed, positive streamers result. The elegant pioneering work of Dawson and Winn (1965), Phelps (1971, 1974), Griffiths and Phelps (1976) has worked out some, if not all of the details of this mechanism and identified a critical field of about 4 10^5 Vm^{-1}. (3 10^{-5} Vm^{-1} or less in cloud at lower pressure).



At a negative point, electron avalanches proceed away from the tip, in the direction of decreasing field strength. If the gas is one in which electron attachment can occur, such as oxygen or air, then negative ions are formed in the low field region. The space charge acts to inhibit further avalanches until it is cleared, so that the negative discharge is also in the form of pulses. The frequency of these is of the order of 10^3 S^{-1} at onset, rising to 10^6 S^{-1} at higher fields; the name Trichel pulses is commonly applied to them. At higher potentials the negative ion space charge forms sufficiently far out for a pulseless glow discharge to form which can give way to propagating negative streamers at even higher potential. These streamers tend to be weak, compared to positive streamers, due to the self replusion of the avalanches, the fact that they propagate in the direction of decreasing field and the high mobility of the negative charge carriers - thus resulting in rapid dissipation of the space charge. They do not propagate as far as their positive counterparts, except in fields near the breakdown level when it is suggested that the propagation velocity exceeds or is close to the electron drift velocity, Loeb(1970). The onset potentials are about the same for both polarities of streamer.

2.2 Atmospheric sources of corona

The possibility that positive corona is emitted from the surface of a raindrop, highly deformed by strong electric fields, has been studied in considerable detail by Dawson (1969, 1970) and Richards and Dawson (1971). These workers, who suspended large drops in a vertical wind tunnel in the presence of an electric field, found that corona occurred from pointed regions of drops. These regions resulted from hydrodynamic instability under the influence of strong electric forces. They found that the lower surface tended to be flattened by aerodynamic pressure and that corona was initiated from the rear surface.

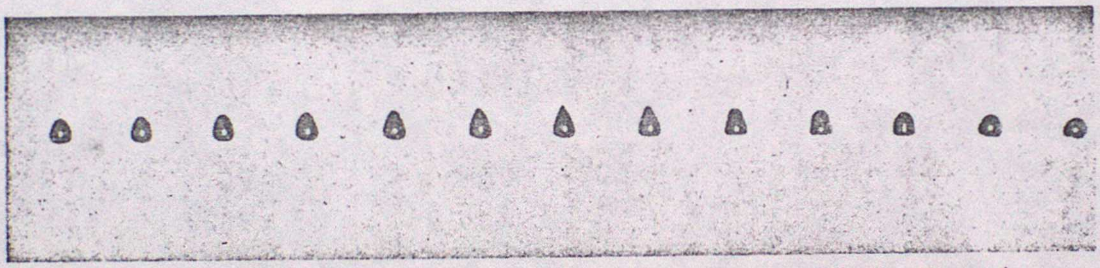
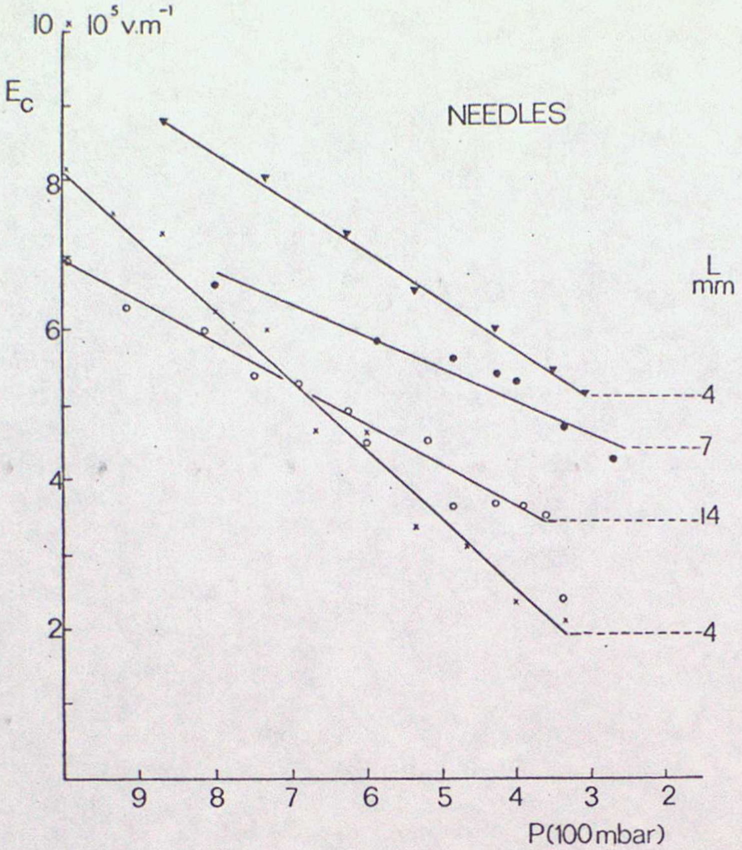


Fig. 1. Typical instability of a medium-sized uncharged water drop of radius 2.0 mm in a slowly increasing vertical field. In all figures, time increases from left to right, and successive frames are 2.5 msec apart. A drop oscillation ends with the formation on the upper surface of a point that then suddenly collapses.

For uncharged drops of radii greater than 2 mm the critical onset was about 9.5 KV/cm, somewhat greater than the Taylor instability value. If the drops carried a high charge of the appropriate polarity the threshold corona field was reduced to about 5.5 KV/cm and somewhat lower if the field was inclined to the vertical. However, even under the most advantageous conditions, the corona fields were higher than the maximum fields observed in thunderstorms.

Griffiths and Latham (1974) have examined the possibility that ice hydrometers may emit corona. They demonstrated that corona currents of both signs can be initiated at low threshold fields from ice specimens in the form of needles and plates, prisms and artificial hailstones provided the temperature is above a critical value, which is fixed by the electrical conductivity of the ice surface. This critical value is $\sim -18^{\circ}C$ for natural ice hydrometers.

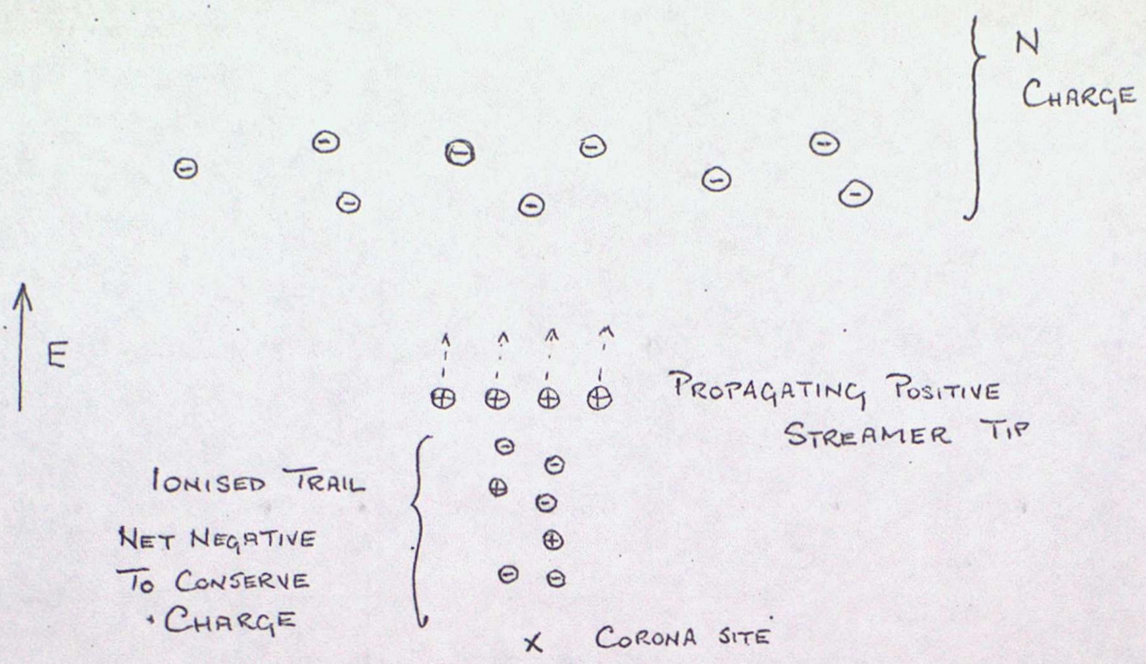


The measured variation of critical field E_c with pressure P for ice needles of length L mm. $T = -12°C$.

Crabb and Latham (1974) have studied the possibility that the collision of a pair of raindrops within a thundercloud may produce momentarily, a grossly deformed object whose shape is particularly conducive to corona onset. They found corona at fields as low as 2.5 Kv/cm for glancing collisions and about 5 Kv/cm for central collisions. Of course such events are probably rather rare and transitory. Nevertheless, the authors suggest that one such event per m^3 per minute is likely in precipitation of about 20 mm hr^{-1}.

2.3 <u>The start of the stepped leader</u>

Given that positive corona is likely to be produced on hydrometeors in the regions of strong field, (ie. close to the edge of the charged region perhaps enhanced by the p charge) how does this initiate the stepped leader? The direction of these coronas is directed along the local field lines; upwards in the region between the charge centre and ground.



By comparison with observations of such discharges from power lines, Loeb (1966) has suggested that highly branched streamers expanding laterally and toward the negative charge centre result. He suggests that the streamers adopt a broadly conical form with an opening angle of $\sim 35^{\circ}$, but in modelling the process Griffiths and Phelps (1976) have shown that this is not a critical requirement. The net upward movement of positive charge effectively increases the negative charge in the vicinity of the original corona site; as though such charge had been lowered from above. New corona streamers in the regions below are then promoted by the resulting field enhancement. The net result is a growing conical volume, rendered conducting by the distribution of positive and negative ions within it. High fields are concentrated at the top and bottom of the volume. In the process, charge from the upper broad end of the cone is lowered and concentrated towards the earthward apex, with the consequent field enhancement there. Loeb believed that this could easily reach the breakdown field of 30KV cm^{-1} and promote the propogation of a negative streamer; the first step of the stepped leader. Griffiths and Phelps (1976) modelled the process but showed that a small number (4 or 5) of successive streamers were necessary within the conical volume to achieve this. The result emphasises the relative ineffectiveness of short lived corona generating mechanisms.

3 The discharge processes

3.1 The stepped leader

Any theory devised to describe the stepped leader should take account of its observed characteristics. Namely (1) the minimum average velocity for negatively charged downward leaders is about 10^5 ms^{-1}, (2) the steps are typically 50 m in length, with a pause time between steps of $\sim 50\ \mu s$ (3) some 5 coulombs of negative charge are deposited over the length of the leader, requiring a current of about 100 amps flowing for a few tens of milliseconds. It is thought that this current passes down a narrow conducting core surrounded by a corona sheath carrying the residual charge, but this is largely a concept resulting from a need to marry substantial current flow with charge deposition.

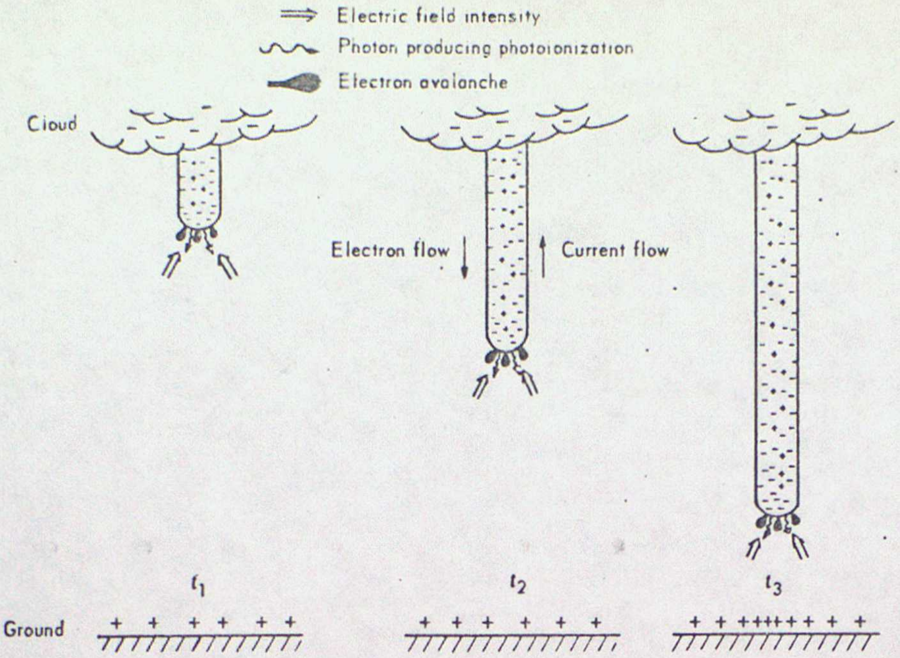


Fig. 7.1a *Diagram showing general features of streamer mechanism as applied to lightning leader into virgin air in absence of step mechanism. The times $t_3 > t_2 > t_1$.*

Loeb (1966, 1968) has suggested that the leader is formed by negative corona streamers. As described in para 2.1 these die out rapidly except in the strongest fields; radial and peripheral branches do not develop therefore. The stepped nature of the leader is a further manifestation of this tendancy to dissipate. However, Loeb argues that positive streamers also propagate upwards in the channel and their influence is to refresh the downward moving negative streamer thereby initiating the next step. Qualitatively it is possible to view the process as one which lowers negative charge and the potential of the N region. Although the channel is conducting, charge is distributed along it. Unfortunately the quantitative nature of the process has not been worked out. Other mechanisms due to Schonland (1956) and Bruce (1944) and others have been postulated but they suffer from the same general deficiency; their physics is obscure and unquantified. When a stepped leader is within a few tens of metres of the ground, an upward propagating positive streamer may result. When the junction is complete the first return stroke is initiated.

3.2 The return stroke

The negatively charged leader, which may have a tip potential of 10^7 to 10^8 volts with respect to the earth, is effectively short circuited to ground. Ground potential is then propagated up the channel. The intense electric field present between the ground potential and the negative channel potential forms a wavefront. This propagates at a third to a tenth of the velocity of light, making the trip between ground and cloud in about 70 μ secs. The excess negative charge deposited on the leader channel is lowered to ground in the form of mobile electrons. The current measured at the ground rises typically to 10 to 20,000 A in a few microseconds, and falls to one half of the peak value, typically in 20 to 60 μ sec. Currents of the order of hundreds of amps may continue to flow for several milliseconds.

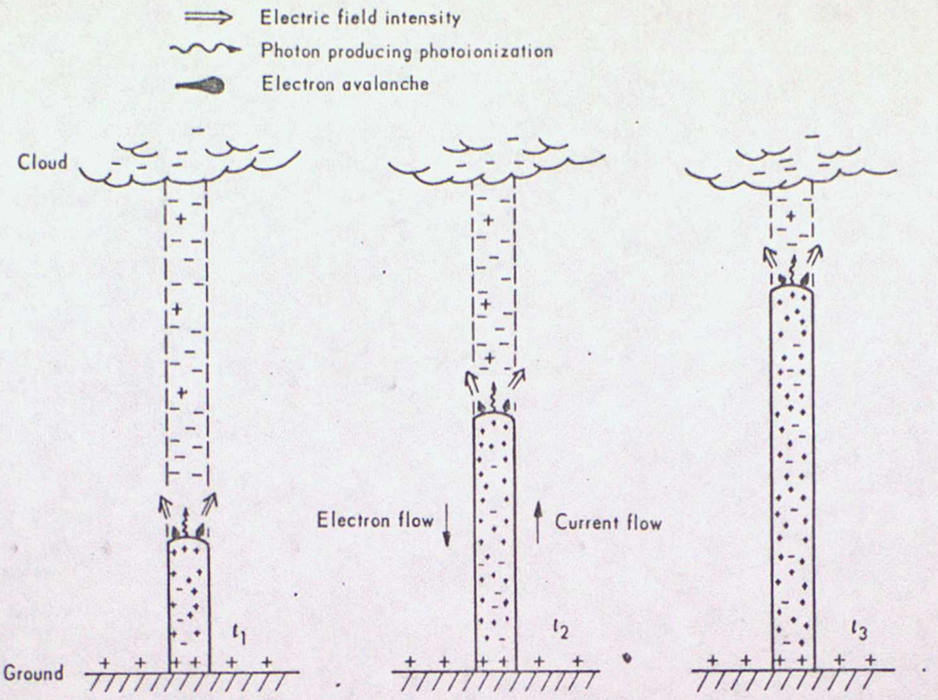


Diagram showing general features of streamer mechanism as applied to return stroke. Times $t_3 > t_2 > t_1$. Note that all current is carried by electrons since the mobility of positive ions is low.

3.3 The dart leader

When the very sharp voltage gradient reaches the source region of negative charge, most of the charge from the channel must have passed to ground. The stroke current therefore reduces. However the proximity of earth potential to the N region can initiate a new era of drainage by upwards positive streamer action as before. This drainage then funnels a new wave of negative charge from the area of propagating streamers to the relatively confined but somewhat decayed conducting channel of the previous stroke. This sweeps down the channel, presumably as a negative/positive streamer but in a continuous fashion, if this takes place in a time less than about 100 msecs. The degree of ionisation increases and charge is again deposited in the channel; albeit to a lesser extent than by the stepped leader. Cloud potential is carried earthward once more to initiate a new return stroke.

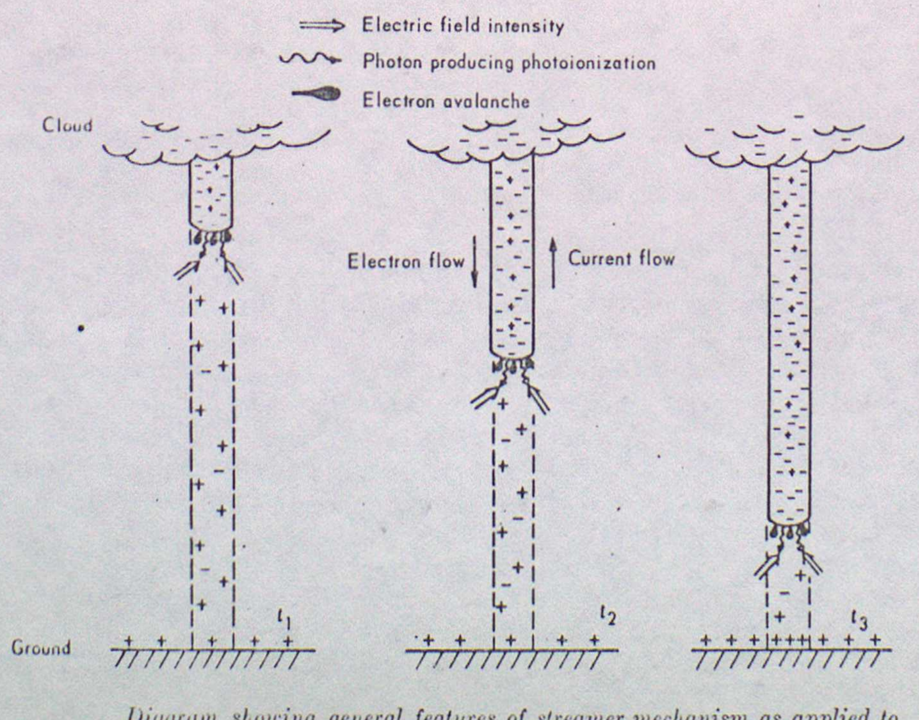


Diagram showing general features of streamer mechanism as applied to dart leader. The times $t_3 > t_2 > t_1$.

3.4 Fundamentals of the discharge

According to the above descriptions, it is suggested that the negative and positive streamers are fundamental mechanisms of the discharge, being modified in their speed, vigour and detailed characteristics by the conductivity and potential gradients in the atmosphere through which they propagate. Thus the leaders are to be seen basically as negative streamers initiated by relatively weak filamentary positive discharges discussed in section 2. The co-existance of positive streamers within the stepped leader channel probably plays a fundamental role in its propagation but their quatiative conribution remains obscure. The return stroke can be seen as a very fast vigorous form of positive streamer passing up a prepared path.

4 Bead lightning

Bead or chain lightning is a visually well documented phenomenon. in which the lightning channel breaks up or appears to do so, into luminous fragments generally reported to be metres to tens of metres long. The beads appear to persist for a longer time than does the usual cloud to ground discharge channel.

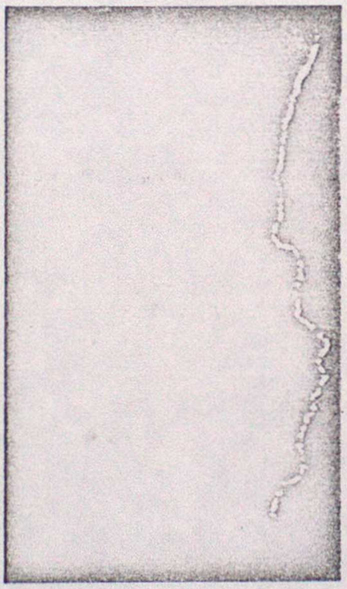


Figure 2.11. Movie camera photograph of the persistent illumination remaining after a triggered lightning discharge. The beadlike structure remained for about 0.3 sec. Reproduced with permission of P. Hubert and C.E.N. Saclay, France, after P. Hubert, "Tentative pour Observer la Foudre en Boule dans la Vaisinage d'Eclairs Declenches Artificiellement," Rapport DPH/EP/76/349, 5 Mai 1975, Commissariat à l'Energie Atomique, Service d'Electronique Physique, Center d'Etudes Nucléaires de Saclay, France.

Various theories of bead lightning have been proposed. Perhaps the most plausible is that the phenomenon is due to a pinch effect instability by which the current carrying channel is distorted into a 'string of sausages' with the strong light emission coming from the necked off regions of high current density.

To prevent radial expansion, the pressure resulting from heating of the channel must be balanced by a magnetic pressure

$$P_B = B^2/2\mu_0$$

where B is the magnetic field strength at the surface of the plasma forming the channel and μ_0 is the permittivity of free space.

Maxwell's equation relating current density to magnetic field strength can be used to predict the circular restraining field at the surface of a straight cylindrical channel carrying a total current I, thus:

$$I = \oint \frac{B}{\mu_0} ds = \frac{B}{\mu_0} \cdot 2\pi r$$

$$\text{or} \quad p_B = \frac{I^2 \mu_0}{r^2 8\pi^2}$$

To achieve a pinch, the pressure resulting from heating of the channel, p_T must fall off as $r^{-\alpha}$ where $\alpha \geqslant 2$. It is suggested in para 6 below that the pressure of the shock front, in the strong shock region at least, falls off as r^{-2}, so that some form of local equilibrium may be possible. However for a peak current of 30KA within a 1 cm radius channel the magnetic field pressure is only $\sim$ 1.5 atmospheres. This is much less than predicted to be necessary to counterbalance the shock. A current of $\sim$ 130KA in a 1 cm radius channel would be necessary to restrain an expansive pressure of 30 atmospheres; perhaps this is not impossible.

5 Ball lightning

Ball lightning is the name given to the mobile luminous spheres which have been observed, usually during thunderstorms. A typical ball lightning is said to have the dimensions of an orange or grapefruit and a lifetime of a few seconds. The literature consists, in general, of either compilations of eye witness reports or attempts to explain how these reports may be explained by some combinations of physical processes. As far as is known, no-one has succeeded in generating a ball lightning, or made measurements on such phenomena other than by reception and interpretation of light emitted by the object - most of which have been in real time! Some attempts have been made to place bounds on the energetics of ball lightning distruction by inspection of damage caused. The fact that such damage does occur suggests that the phenomenon is not always an optical illusion; as has been claimed. Nevertheless there is no known theory to explain how a luminous sphere capable of a lifetime of several seconds can move rather slowly horizontally and vertically, apparently of its own volition, and disappear either silently or explosively.

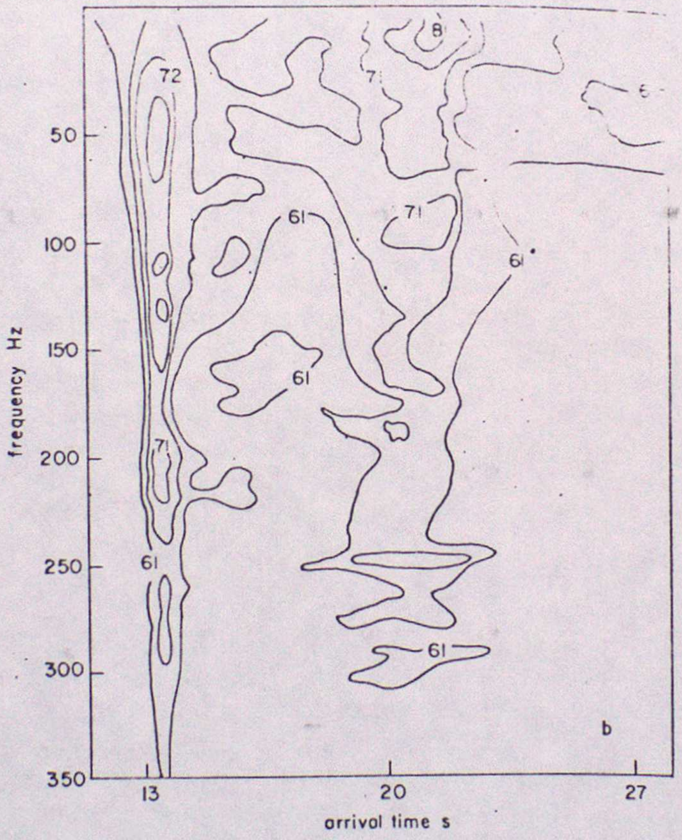
All ball lightning theories fall into one of two general classes: Those whose energy source is outside the ball and those which rely on an internal source. The former include rf energy or cosmic ray particles focussed by the nearby thunderstorms electric field and a steady current passing through a region of high conductivity; again with attendant focussing. The latter include reactions in a gaseous blob; excited metastable states of unidentified molecules; just hot air (!); a dense plasma perhaps in the form of counter-rotating vortex rings etc. In a recent book, Barry (1980) emphasises the association between the normal lightning flash and ball lightning and suggests that the latter may be an extreme form of bead lightning. The interested reader is referred to Singer (1971) Singer (1977) and Barry (1980) for comprehensive but somewhat tedious reviews of the subject.

In many ways the most intriguing aspect of this problem is knowing how to go about finding a solution - whatever that might be. A phenomenon which is not accessible to scientific observation is hardly accessible to scientific method.

6 Thunder

It is generally accepted that thunder is the result of intense, rapid heating of the lightning channel to form a high pressure shock wave which degenerates into a loud audible sound at large distances. However measurements have also shown that there are strong sub-audible sounds associated with thunder apparently having a very different origin.

In work carried out at the New Mexico Institute of Mining and Technology and reported by Holmes et al (1971), data recorded by a network of microphones have been analysed to display the joint temperal and frequency distributions of sound energy.



The general characteristics of such plots are the wide-band tongues of intense sound indictative of so called thunder 'claps', superimposed upon low frequency 'rumbles'. The presence of significant energy at a few Hz is also apparent.

Under assumptions of cylindrical symmetry simple models predict the variation of overpressure, generated close to the axis of the channel, shown below. The role of channel tortuosity in modifying this simple picture is not understood. There is no direct observational material to support the predictions.

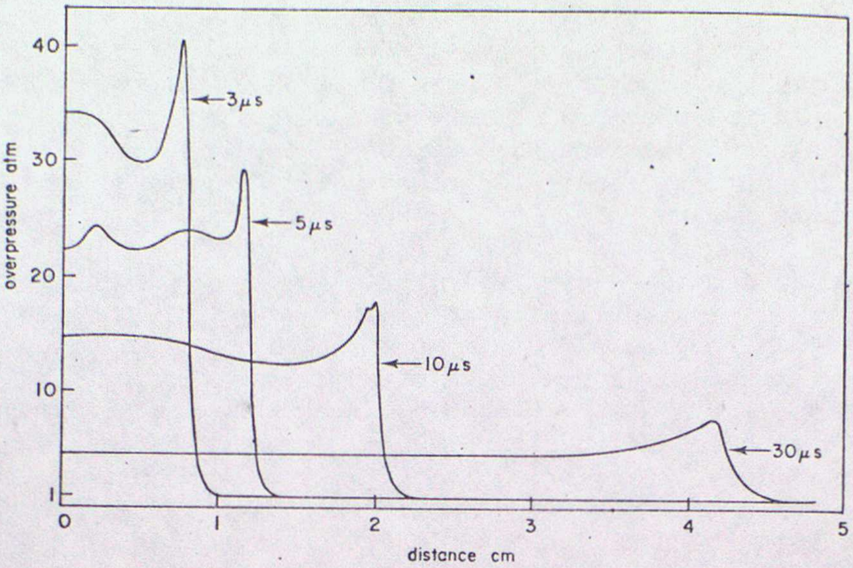


Fig. 3. Decay of shock front with distance from lightning channel. (After R. D. Hill, 1971.) Overpressures in channel and shock front versus distance are given for four times following onset of return stroke. Initial line source radius, 0·6 mm. Lightning current pulse, $I = I_0[(\exp - at) - (\exp - bt)]$, where $I_0 = 30{,}000$ A, $a = 3 \times 10^4\ s^{-1}$, $b = 3 \times 10^5\ s^{-1}$.

An intriguing aspect of thunder is the contribution of so-called infra-sound, or energy at very low frequency, ie. below 5 Hz. Wilson (1902) pointed out that the hydrodynamic pressure within the charged portion of thundercloud would be reduced when the electric stress, was relieved by a lightning discharge. A volume having a linear dimension of ~ 300 m is predicted to excite a fundamental frequency of ~1 Hz, for a speed of sound ~ 300 ms^{-1}. Pressure amplitudes of a small fraction of a millibar are predicted.

7 Some effects of lightning

7.1 Effects on aircraft

It is to be expected that aircraft often intercept cloud/cloud flashes as well as those from cloud to ground. Very little is known about the former, but it is usually assumed that the currents are not greater than those of the N type ground stroke and that the basic discharge process is much the same as that described below. As a lightning leader approaches an aircraft, high electric fields are to be expected at sharp points and edges. Indeed the mere presence of a conducting body such as an aircraft enhances the local field and perhaps helps to trigger lightning. In any event, the high fields give rise to streamer discharges which propagate away from the aircraft until one of them contacts the approaching leader. Further development of the stepped leader away from other extremities is then envisaged until a branch reaches ground or another charge centre. Thus an aircraft receiving a strike always exhibits at least one entrance and one exit point. However an aircraft moves a significant distance relative to a stationary lightning channel in the time taken for a flash to be completed. When a forward extremity such as a nose or the leading edge of a wing forms the initial attachment point, reattachment to small imperfections on the conducting surface passing through the channel can take place. This process can produce a number of discrete attachment points corresponding to successive strokes down stream of the initial point. Clearly these may be in areas which would not otherwise be expected to suffer strikes. An initial attachment point at a trailing edge cannot 'sweep'. Accordingly it carries the full current associated with the flash and may be expected to suffer maximum damage.

Two sorts of damage to aircraft are to be expected; one results from the energy dissipated in structure due to the high current phase ($\int i^2 dt$ has units of joules per ohm and is the energy dissipated in unit electrical resistance). For a given current this energy is a function of resistance - or more properly complex impedance. Considerable efforts are expended to ensure the lowest possible impedance between aircraft structures by efficient bonding. The effects of high energy dissipation are burning, eroding and structural deformation resulting from violent heating, vapourisation and associated shock waves. Magnetic forces proportional to i^2 can also be the source of structural damage when the current is constrained to flow along a tortuous path. Sparking at high impedance joints can produce fuel vapour ignition.

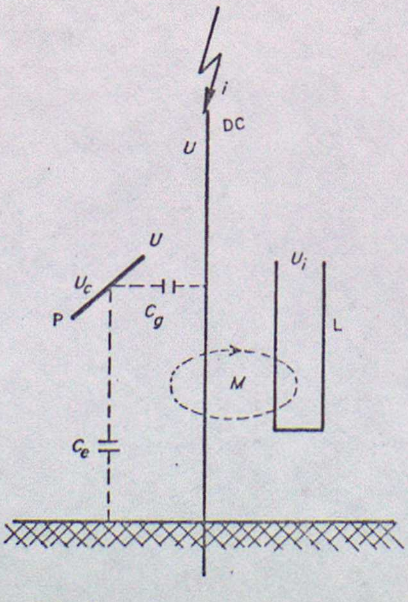
The other sort of damage is a consequence of the high peak current and its high rate of change - which can approach 80 KA/μs. This produces strong, varying electromagnetic fields which can disturb and/or damage electrical apparatus. Again, 'low impedance-at-high-frequency' bonding and the enclosures of sensitive components in shielded structures are sought for protection. Recent developments in the design of aircraft and avionic systems include the use of composite materials, with inherently poor electromegnetic shielding properties, and a shift to digital electronics with the attendant increased susceptibility to pulse interference. These have caused a resurgance of interest in lightning and its effects.

The incomplete 'Faraday cage' properties of an aircraft can also allow direct influence on the aircrew, ranging from flash blindness to physical and electrical shock. Such phenomena may be most severe beneath the bubble type canopies used in several military aircraft. Under such circumstances, the concept of low level flight beneath Cb cloud is not a pleasant one.

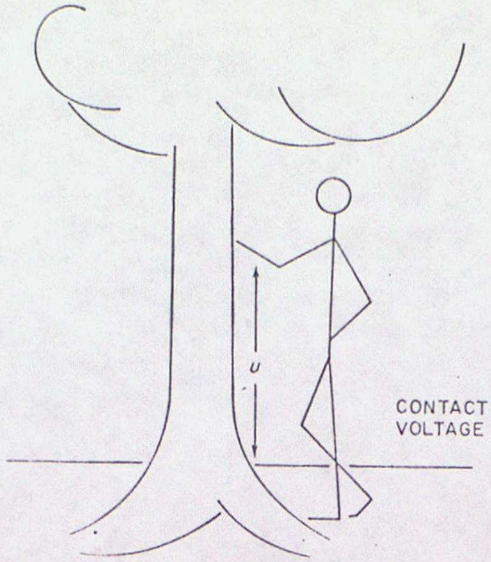
7.2 Effects on man/animals

Annual deaths from lightning in England and Wales have been between 1 and 6 per 10 million of the population since the 1920s, with a slight tendency to decrease with time; presumably as the population moves from country areas into town. Apparently death from lightning results when current through the heart or respiratory centre causes them to malfunction. Treatment for cardiac arrest or artificial respiration as appropriate can be successful. The body acts as a structureless gel for the sort of currents which result in death or injury so that the position of the points of exit and entry play a crucial role in defining the current path and hence whether or not the heart or brain are at risk. The skin surface, particularly when dry, presents a locally high resistence to current flow and as a result of heating proportional to R shows burning at the entry and exit points. Deep tissue burning is much less common. The gross impedance of the body is, of course a function of many factors but 1KΩ has been cited as a useful working figure. When the current injected into the body reaches ~1KA the potential difference between head and feet must be ~ 1MV. At a typical height of 2m this is sufficient to initiate an arc outside the body. Such an arc sustains a potential drop of about $2KVm^{-1}$. Thus the potential difference between head and feet drops to 4KV, driving a current of the order of 4A through the body. This may be expected to last for the duration of the stroke. There is ample evidence to confirm that external 'flashovers' do occur; sometimes they lie between the body and clothing and sometimes outside both. In the case of the former, the lightning current flowing over the surface may convert skin moisture to steam. The resulting pressure rise can cause clothing, including footwear, to be torn or ripped off. It is not certain whether cardiac and/or respiratory arrest are a function of charge ($\int i\,dt$) or energy dissipation($\int i^2 dt$) but almost certainly the threshold is often not reached until the low current stage. The reduction of the quiescent arc voltage, when some part of its length is shorted by a low resistance external path such as a zip, is thought to have decreased the body current sufficiently to have saved lives.

When (say) a tree is struck, people or animals beneath it may be at risk from induced effects. Thus the electrical impedance of a tree trunk to the lightning current is again a complex function of many variables but, between the ground and the height of a person, it is thought to be typically a few kilohms. A person standing alongside the trunk is at earth potential. As current through the trunk increases, a point may be reached when the potential drop across the lower part of the trunk exceeds the breakdown potential between the trunk and person. A side flash results. Obviously this phenomenon can occur in a number of situations and provides a mechanism for injury of people within buildings and possibly for multiple deaths when a strike occurs to several individuals in a crowd. The diagram below shows how currents may be induced in a building struck by lightning; that overleaf shows how an ohmic and inductive current may result in a person standing beneath a tree.

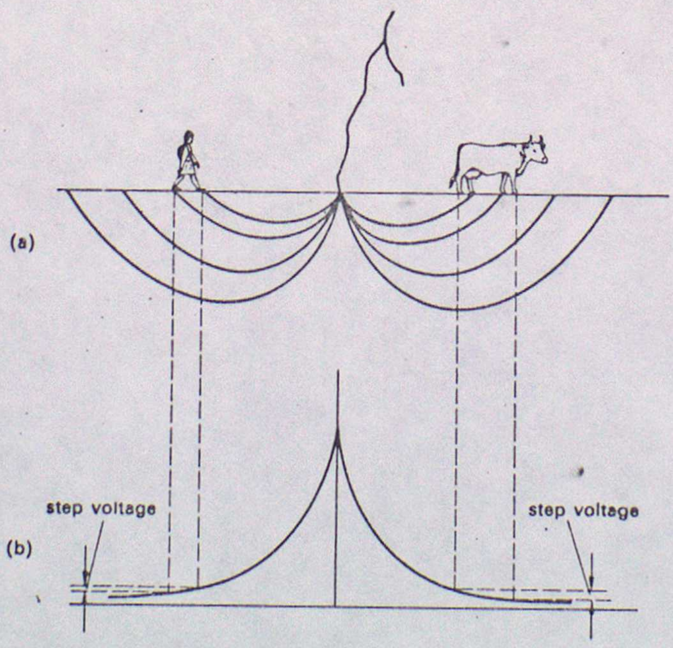


Inductive effects of the lightning current; i = lightning current, U = voltage of down conductor, DC = down conductor, P = isolated metal component with capacitance C_g to down conductor and capacitance C_e to earth, $U_c = UC_e/(C_e + C_g)$ capacitatively induced voltage on P, L = metallic loop with mutual inductance M to down conductor, $U_i = M(di/dt,)$ the inductively induced voltage.



Contact voltage: $u = i(R + R_e) + L\,di/dt + u_s$, where, i is current flowing through the tree, R is the resistance of the tree between the highest point of the body touching the tree and earth, R_e is the "effective" earthing resistance of the tree, L is the inductance between the highest point where the body touches the tree and earth, and u_s is the potential drop between the bottom of the tree and the feet.

A direct strike to open ground results in current flow into the surrounding earth. This creates potential gradients in the soil/rock around the strike point which are proportional to the current density and earth impedance. Feet in contact with the ground can be at different potential resulting in current flow through the body. Such currents are unlikely to be fatal to bipeds but may pass through the hearts of animals, causing death.



References

Barry, J D 1980: "Ball Lightning and Bead Lightning", Plenum

Bruce, C E R, 1944: Proc.Roy.Soc, A183, 228

Crabb, J A & Latham, J 1974: Quart.J Roy.Met Soc, 100, 191

Dawson, G A 1969: J Geophys Res, 74, 6859

Dawson, G A 1970:

Dawson, G A & Winn, W P 1965: Z Phys, 183, 159

*Golde, R H 1977, "Lightning", Academic Press

Griffiths, R F & Phelps, C T, 1976: J Geophys Res, 81, 3671

Griffiths, R F & Latham J, 1974: Quart J Roy Met Soc, 100, 163

Holmes, C R et al 1971: J Geophys Res, 76, 2106

Loeb, L B, 1966: J Geophys Res, 71, 4715

Loeb, L B , 1968: J Geophys Res, 73, 5813

Loeb, L B, 1970: J Geophys Res, 75, 5883

Phelps, C T, 1971: J Geophys Res, 76, 5799

Phelps, C T, 1974: J Atmos Terr., 36, 103

Richards, C N & Dawson, G A, 1971: J Geophys Res, 76, 3445

Schonland, B F J, 1956: "Handbook der Physik", 22, 576, Springer-Verlag

Singer, S, 1971: "The Nature of Ball Lightning", Plenum

Singer, S, 1977: "Lightning", R H Golde - Ed, Academic Press

*Uman, M A, 1969: "Lightning," McGraw-Hill

* Particularly useful general reference works.