CHAPTER 4

THE THUNDERCLOUD

4.1 THERMAL DYNAMICS

On a warm and sunny day heat is absorbed by the earth's surface causing both water vapour and hot air to rise to higher atmospheric levels.   The warmer the air the more water vapour it can hold before saturation.   The secret of a thunderstorm and its devastating power lies in the amount of water vapour present.   The latent energy of water vapour is the key factor in thunderstorm formation and electrification. At the beach most of us have experienced the sensation of cold after getting out of the water. The explanation is that water takes away heat from the body surface at a rate of about 540 calories or 2250 joules per gramme when it evaporates. When water condenses to form drops, the same amount of energy, in the form of heat, is released. When a cloud is formed by warm humid air reaching higher and cooler levels, condensation will create small drops between 5 - 10 microns dia.   During condensation   latent heat is released warming the surrounding air which will rise further (the hot air balloon effect) to considerable heights pulling more humid air up from below to take its place.   A chain reaction starts when humid air is fed in from below pumping more and more energy into the cloud in the form of heat and convection. A cloud might grow up to 60,000 feet or 20 km in height in

very narrow columns. Updraft velocities can easily reach 30 m/s. Each column is called a cell and a thundercloud usually consists of several cells. Each cell has an average life time of 30 minutes.   When a cell reaches a maximum altitude it is in a so-called mature stage, at which time the cloud top usually flattens out to form the typical anvil shape often associated with thunder heads.   The flat top is believed to occur when a cloud reaches the stratosphere or the boundary in the atmosphere where air temperatures begin to rise with altitude which will cause the cloud to evaporate again. In the growing stage of a cloud, drops increase in size as they reach higher levels and eventually become heavy enough to overcome the updraft velocities of the convection. At this point rain or precipitation starts to fall down and the cell has reached its dissipating stage.   At greater latitudes, thundercloud precipitation   without exception always reach temperatures below freezing. Hail and sleet are formed which often fall down and reach ground before melting. The cold precipitation will cool the air in the cell which becomes heavy and begins to move downward as well. The cold heavy air   might cause considerable down drafts which, when reaching ground, supply the outward rush of cool air often felt as a relief to most of us after a hot day.   When precipitation and down drafts occur the cell is said to be in its dissipating state and although some lightning activity is still going on its life is nearly over. New cells are formed adjacent to the old ones and often while observing their growth one can see small bubbles or turrets developing above and around each cell.   The thunder cloud described is a typical heat cloud or isolated storm. Also common are lines of thunderstorms or squall lines. Lines of thunderstorms are formed when a cold front wedges in under the warm humid air mass along a warm front and squall lines can extend for several hundred miles.   The energy source is the same, namely condensation of water and release of latent energy. Thunderstorms along a squall line often seem to lean over on their sides because of the heavier and cooler air wedging in underneath the warm front.   Although there is considerable entrainment of air through the sides of such storms, the main energy

is still being supplied by the updraft winds caused by condensation and convection.

4.2 THE ENERGY OF THUNDERSTORMS

  The energy of a thunderstorm is determined by the amount of water vapour present. Typically, a single cell contains 8×10^8 kg of water (Israel 1973) of which about 60% is converted into heat and precipitation. The total energy dissipated by a cell is therefore 1.4×10^{14} joules per cell. If the average life time of a cell is 30 minutes then the average power per cell equals 7.8×10^{10} watts. Since it is estimated that about 2,000 thunderstorms are active at the same time around the earth then the total energy dissipated must equal about 1.6×10^{14} watts which is about 0.1% of the energy reaching the earth's surface from the sun.

4.3 THE ELECTRICAL ENERGY IN THUNDERSTORMS

The electric energy of a thunderstorm can be determined in several ways.   Schonland (1950, 1953) for example, estimated the potential difference involved in a typical lightning flash to be about 10^8 and 10^9 volts while the average charge transferred is about 20 coul. The total amount of free charge separated in a thundercloud is about 1400 coul according to Wormell (1953).   From the above information we can determine the total electric energy involved to be of the order of $\frac{1}{2}VQ = 7 \times 10^{11}$ joules.   A more realistic method presented by Israel (1973) yields a larger value of 1.7×10^{13} joules.   In Israel's approach the average   thunderstorm cell is compared to an electric circuit diagram (Kasemir 1965) such as shown in Fig. 26. According to Wait (1950), on the other hand, a thunderstorm cell generates on the average 2.5 amperes of current and from Ohm's law one then finds that the total power output of a cell is $RI^2 = 9.4 \times 10^9$ watts,   which

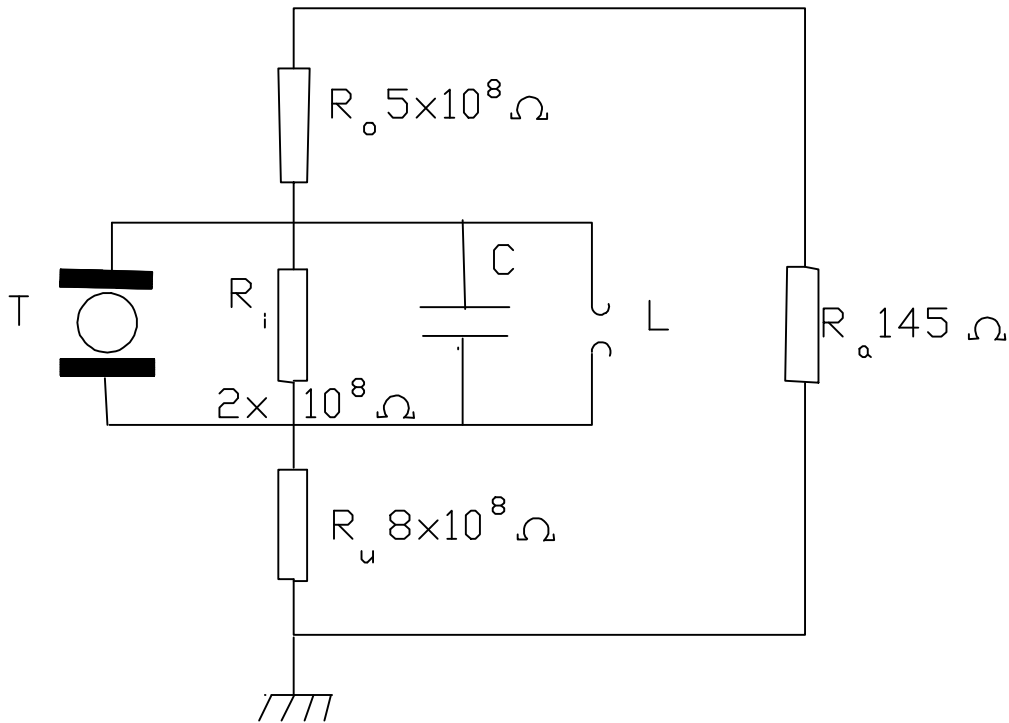when integrated over the duration of a cell (30 min.) amounts to 1.7×10^{13} joules.

Fig. 26   Electric circuit diagram of a thunderstorm (Kasemir).

There is at least one serious objection to the use of Ohm's law in determining the electric power of a thunderstorm. There is no doubt that the internal resistance of a thundercloud, such as represented in Fig. 26, is an accurate measurement since it has been determined in situ by conductivity   measurements.   The   problem is that the conductivity or resistance depends on the number of ions available in the cloud. Ions   are the   charge carriers in the cloud and solely responsible for the flow of electric current.   Considering that the normal ion production in the atmosphere is about ten ion pairs or 1.6×10^{-18} coul of charge per cubic centimetre per second and that the average thunder cloud cell measures fifty cubic kilometres in volume, then the total charge production within the cell is only 0.08 coul per second which translates to a meagre saturation current of 80 mA.

Ohm's law will not hold once a state of saturation has been reached. An ohmic current of 2.5 amperes used by Israel might, therefore, not be a representative value. If the charging current in thunderstorms is non-ohmic the only other alternative is a mechanical transfer of charge by means of convection and updraft currents or by the process of gravitation in which charge is transported by falling precipitation particles.   The   author has reason to believe that when Israel calculated the average electric power involved in charging of clouds he not only considered the ohmic current but also took the mechanical currents into account.

An interesting thought is that if one could harness a lightning bolt there would be 100 kW hours of energy available, enough to keep a 100 watt light bulb burning for a month and a half. There are nearly 50,000 thunderstorms active around the world per day, and if each storm produced 100 lightning bolts, there would be close to 20,000 megawatts, which is only enough power to satisfy the needs of a large city such as New York.

4.4 THE LIGHTNING DISCHARGE

There are two types of lightning discharges, namely cloud to ground lightning and intracloud lightning or cloud to cloud discharges. As the reader   recalls from section 1, Benjamin Franklin observed   that thunderclouds tend to form gigantic electric dipoles in the atmosphere where the lower portion of the cloud is predominantly negative and the top positively charged. Occasionally a small pocket of positive charge can be found in the lower cloud section during the clouds dissipating stage in the vicinity of the precipitation shaft. There is about three times as many intracloud discharges as cloud to ground flashes, a ratio which seems to vary somewhat with geographical location. Normally negative charge is brought to ground by lightning that originates from the lower section of a cloud. However, as more

and more negative charge is drained by successive lightning bolts to ground, the more the positive charge in the upper half of the dipole becomes dominant. The imbalance of the dipole will eventually cause a positive discharge to appear from the upper region of the cloud to ground. The ratio of positive to negative ground strokes is about 1 to 10 but a positive discharge from the upper region of the cloud is as a rule ten times more powerful and carries ten times more charge.

A lightning flash to ground might consist of several ground strokes which appear in such a rapid sequence not distinguishable to the naked eye but easily observable with the aid of a Boys camera (see Fig. 6).   In fact, pictures taken with a Boys camera reveal   quite a complicated discharge mechanism of lightning.   It appears that lightning is triggered by faint pilot streamers (Schonland, 1938) which provide the initial ionized path from cloud to ground by weak corona discharges.

The pilot streamer is usually followed by a stepped leader which can be described as small current surges catching up with the pilot streamer in small steps averaging 50 metres in length. As the pilot streamer works its way down to ground, followed by the stepped leader, charge is   brought down at a rate of 600 to 2,600 amperes (Hodges, 1954).   As soon as the pilot streamer and stepped leader reach ground a conducting path between cloud and earth is established and the main stroke starts. The main stroke will transfer charge between the cloud and earth at a rate of 20,000 or sometimes 400,000 amperes.   One peculiar behaviour of the main stroke is that it starts from ground and travels upwards which means that large amounts of charge are transferred from the earth's surface to the cloud.   This is why it is often said that lightning travels up to the cloud rather than down. Although the main stroke only lasts for a thousandth of a second, it is visible to the naked eye and the sound or acoustic shock wave that follows is unmistakably that of a lightning bolt. The main stroke often breaks up into several subsequent strokes usually three or four per lightning flash.   Lightning flashes having as many as 42

subsequent strokes have been reported.   There are usually no pilot streamers or stepped leaders present between ensuing strokes in a multi-stroke flash since an ionized path has already been established after the first stroke. The stepped leader is replaced by a so-called dart leader which works its way down from the cloud in one single jump.

One of the most challenging problems in lightning research is the mystery of how lightning bolts drain charge from the thunder cloud. How does the lightning bolt connect up to the myriads of charged drops involved, and how can this be accomplished in a small fraction of a second? This is a question that has not yet been answered satisfactory. One of the best solution so far, in the author's opinion, is offered by Kasemir (1950b) who believes that the mechanism involved
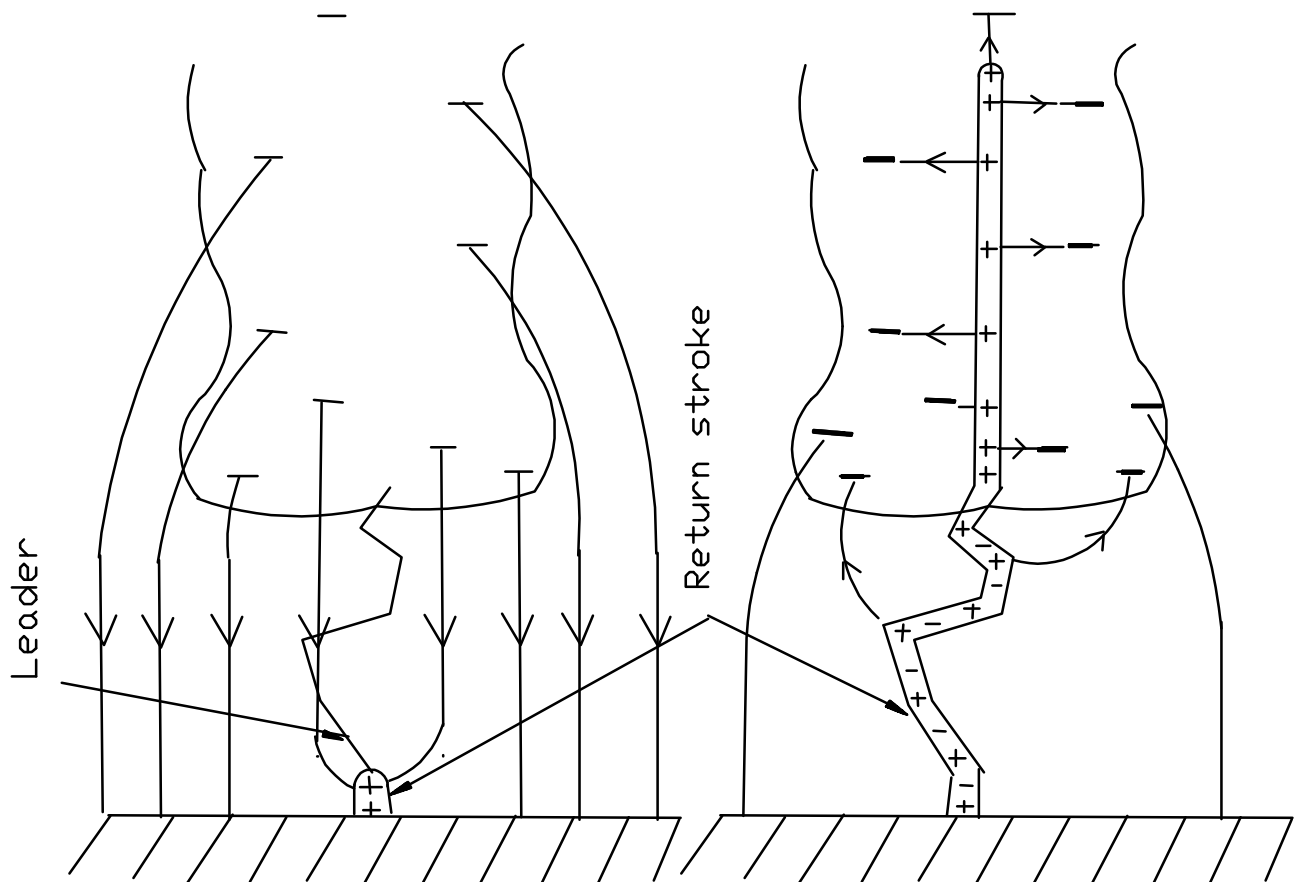

Fig. 27. Lightning discharge theory by Kasemir. (a) Start of return stroke. (b) Charge transfer by induction.

is that of induction. For example, consider a negative charge centre in the lower portion of a cloud (see Fig. 27a.) from which a leader stroke has just reached ground. Not much charge is brought down because the negative charge in the cloud is bound on small drops or precipitation particles. On the other hand the earth's surface, which is a good conductor, can easily supply positive charge up to the cloud through the ionized channel provided by the stepped leader. When the positive charge in the return stroke reaches the cloud it will penetrate the charge centre like a giant lightning rod which causes the cloud potential to drop drastically since many field lines now are much shorter (see Fig. 27b). In this way much of the electric energy is drained without contact or charge being removed from the drops in the cloud. Another way to look at Kasemir's lightning mechanism is to compare the electric potential and capacitance of the cloud before and after a lightning bolt has penetrated the cloud. A 25 coul charge centre measuring 1 km in diameter and located several kilometres above ground has a capacitance of roughly

$$C = 4pe_0 R \approx 6 \times 10^{-8} \text{ Farad}, \tag{8}$$

which yields an electrical potential of

$$V = \frac{Q}{C} \approx 4 \times 10^8 \text{ volts} \tag{9}$$

If one assumes that the charge centre is cylindrically shaped and extends $\ell = 1$ km in height then the capacity between the charge centre and the ionized channel of the lightning bolt can be estimated from

$$C = \frac{2pe_0 \ell}{\ln(b/a)} \approx 9 \times 10^{-9} \text{ Farad}, \tag{10}$$

where a is the radius of the lightning channel and b the average distance of the charges in the charge centre with respect to the lightning channel. The radius of the lightning channel was taken as 1.5 m. The result is that the capacity is lowered by about 15 percent

which corresponds to a charge transfer of approximately 3.5 coulombs. Since there are on average three or four main strokes per lightning flash, then the total charge transferred by a lightning flash can easily be between 10 to 15 coulombs. In fact, Kasemir's capacitor model does not only explain why the bulk of charge is moving upwards, from ground to cloud under the influence of induction, it also presents us with a RC circuit which might explain the occurrence of multiple strokes. The time constant of the circuit (average 200 micro seconds) is the product of (9) and (10) divided by the average discharge current of 20,000 amperes. Once the capacitor is charged the lightning current will cease and the time elapsed is of course determined by the time constant. After an average length of 0.07 s (Bruce and Golde, 1942) the next stroke will follow but this time triggered by a dart leader. The ensuing stroke will form a branch which will penetrate the cloud in a different direction. More strokes might follow until the negative potential of the entire region has been drastically lowered. The induced charge transferred in this manner must slowly leak off to the individual drops by means of corona and quiet discharges that will produce numerous ion pairs inside the cloud.

In an intracloud discharge a lightning bolt starts between two charge centres where the electric field is high and where electric breakdown of air first occurs. After a small parcel of air becomes conducting from the electric break-down of the air, it will grow rapidly in length under the influence of induction. As the lightning rod type discharge grows and becomes more and more polarized, positive charge will rush towards the end facing the negative charge centre while negative charge collects at the end nearest the positive charge centre. Once the lightning bolt penetrates both charge centres, enough charge is transferred by the polarization effect to account for the observed electric field changes.

One important implication of Kasemir's discharge mechanism is that the electric breakdown of air, and formation of small ionized air parcels in the strong field region between two charge centres, can trigger lightning bolts.   This means that aircraft flying in the high field region between two charge centres can become electrically polarized and trigger lightning as well.   The risk of damage is therefore much greater than previously thought when it was believed that lightning would only strike aircraft in a random fashion.   Pilots usually refer to two kinds of lightning strokes; the "static discharge" when lightning seems to originate from the aircraft when it is trying to rid itself of excess charge or the direct hit when lightning is believed to come from a nearby charged cloud centre. The "static discharge" is controversial in that the charge on an aircraft, as pointed out by many scientists, is by far to small (about 0.1 coul) to create a lightning bolt. Kasemir's induction mechanism, however, explains that the strongly polarized electric field on the aircraft, which causes corona discharges and electric break down of air, will supply all the charge necessary for the lightning bolt.   For example,   although the net charge on the aircraft is small, the amount of ionic charge produced in the surrounding air by corona is enough to feed a lightning bolt by the inductive mechanism. One cubic centimetre of completely ionized air contains as much as 5 coulomb of ionic charge.

    The size of a lightning bolt or the diameter of the lightning channel is not well known.   A rough idea of the channel diameter can be obtained if one uses Gauss's law to determine the maximum radius of electric break down of air due to the strong field and corona produced by the charged lightning channel.   For example, an average lightning bolt which carries a current of $I = 25000$ amperes and propagates at a typical velocity of $v = 10^8$ m / s will contain a charge of

$$l = I / V \approx 2.5 \times 10^4 \text{ coul / m},$$
(11)

 which by the use of Gauss's law equals a channel radius of

$$R = l \, / \, (2pe_0 E),\tag{12}$$

where $E = 3 \times 10^6$ volts / meter is the breakdown field of air. It is believed that the bulk of the lightning current is confined within a small core having a cross section of about 0.15 m in diameter. The lightning channel can be pictured as narrow current core surrounded by a large ionized envelope.

4.5 PROTECTION AGAINST LIGHTNING

Modern lightning research has proved that the function of a lightning rod is not necessarily to attract lightning and lead it to ground in order to dissipate its power. Careful studies show that large amount of corona discharges occur at the point of a lightning rod before lightning strikes. The corona discharges produce numerous ions which often develop a protective dome around structures fitted with lightning rods. A large conductive dome or sphere has a smoothing effect over protruding surfaces and will lower the electric field strength in its vicinity. Experiments by Vonnegut and Moore have shown that a conducting wire supported between two mountain tops did not get struck by lightning as often as the mountain sides. In fact, the lightning seemed to avoid the wire which can be explained by the above effect that corona must produce a large diameter ion cloud around wire. This has the effect of lowering the field strength in its vicinity.

The lightning rod is an important device for protecting houses and other structures from lightning. This is accomplished in two ways. First, corona from the sharp tip of a lightning rod creates a protective ion cloud above the structure and secondly, in the event of a direct hit by lightning, the lightning rod will force the electric power to dissipate into ground and prevent damage to the building. When protecting a house or structure from lightning damage, some fundamental rules should be followed. Basically, there are two types of protection

internal and external. External protection concerns the safety of the roof and sidings of a house while interior protection deals with sparks between metal object inside the house including appliances, radios and telephone lines. An effective exterior lightning protection can be described as follows:

1. Lightning rods and guard wires must be symmetrically placed over the roof to ensure uniform distribution of the discharge current.

2. Lightning rods and guard wires should be symmetrically attached to vertical conductors which distribute the discharge current to ground.

3. A good ground connection, far away from under-ground cables and pipes, must be established in order to let the energy dissipate into the earth's surface as effectively as possible.

4. No point on a roof should be further than 10 m (30 feet) away from a lightning rod or guard wire.

5. All large metal objects on the roof should be electrically connected to the system.

6. Any large protruding non-conducting structures or objects on the roof should be fitted with an individual lightning rod.

7. A building should have at least two vertical conductors to ground.

8. Sharp bends or curves in the conductors should be avoided since they might cause unnecessary induction and build-up of sparks.

9. Large metal objects on the outside walls such as balconies and fire escapes must be connected to the system.

The recommended cross sectional area of guard wires and vertical conductors should be at least 2.5 mm^2 $(0.04$ in$^2)$ and twice that area for the buried wires that serve as ground connections. Fig. 28 shows
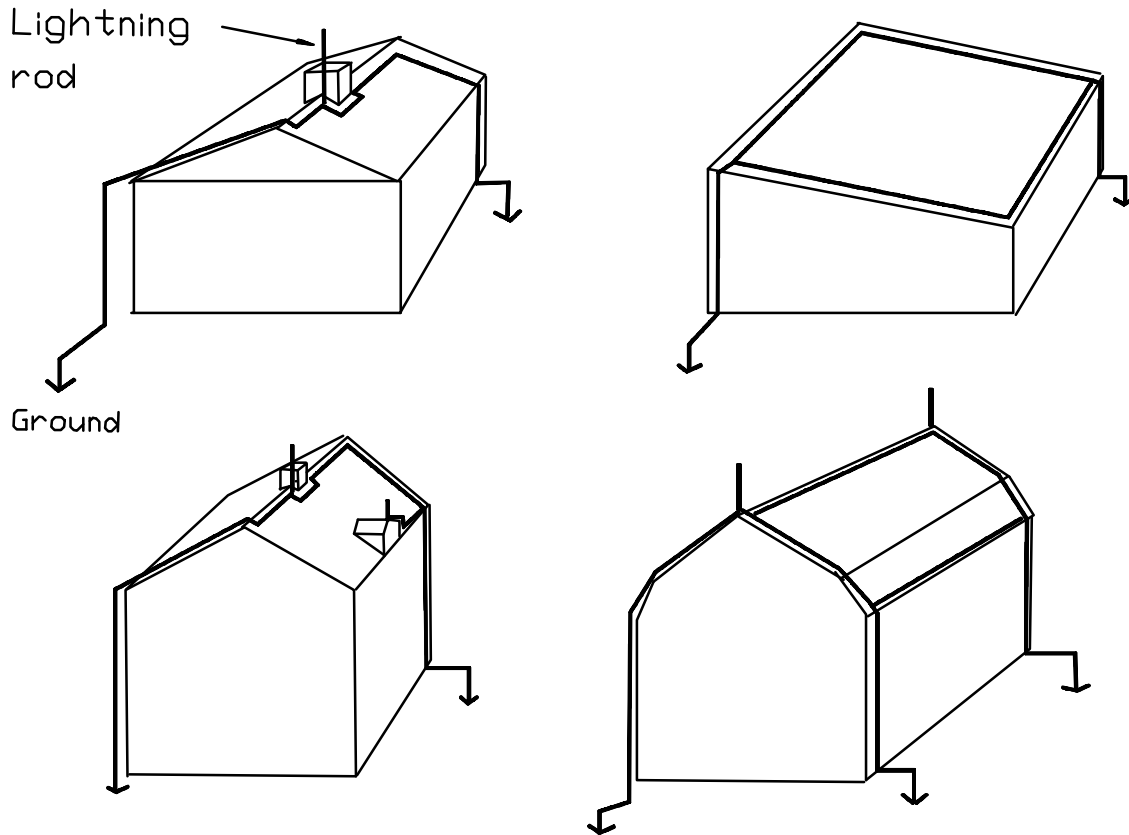
Lightning rod

Ground

Fig. 28 Lightning protection for houses.

several different ways of protecting houses and similar structures. Fig. 29 demonstrates a simple lightning protection for sail boats. Thousands of people around the world are killed by lightning every year. Most fatalities occur in open fields and usually when lightning strikes within a range of 50 to 100 metres of a victim. The danger is that when lightning strikes ground a tremendous amount of current radiates out in all directions from the point of impact. Since the current travels on the surface, which offers a certain electric resistance, a voltage drop will develop which can easily reach 1,000 volts per metre 100 metres from the point of impact. A person walking might bridge a lethal voltage in one step or could easily be thrown off his feet by muscular contractions from the electric shock. It has often been said

that it is safer to run than to walk across a field during an overhead lightning storm. This might not be far from
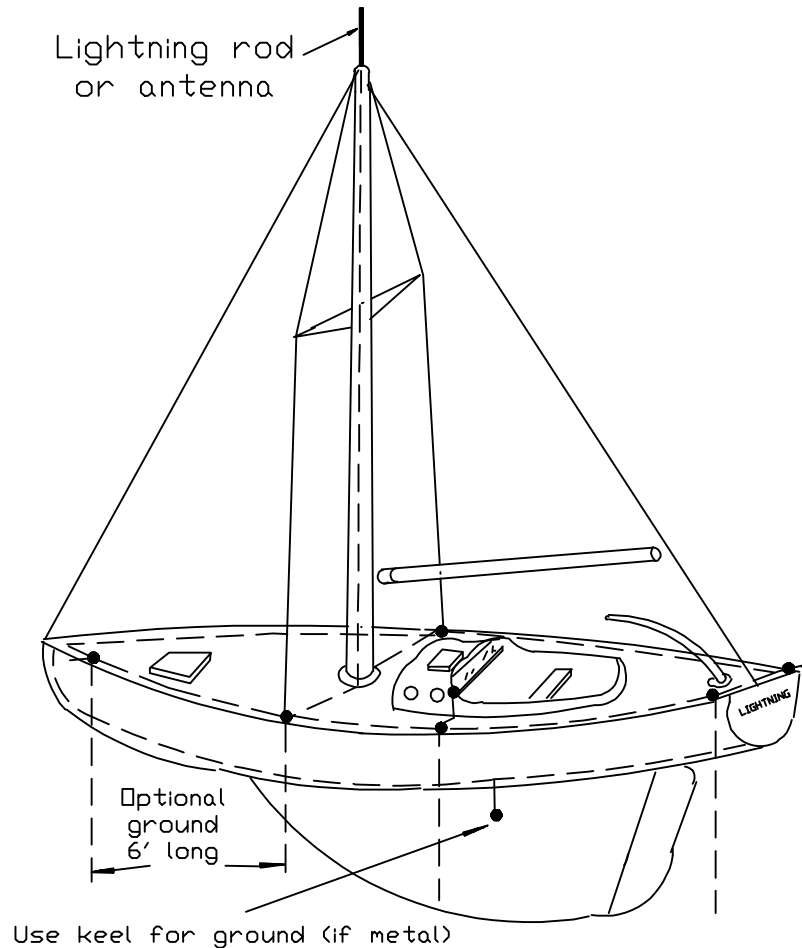

Fig. 29 Lightning protection for sail boats.

the truth since only one foot would be in contact with ground in case lightning strikes. Lightning often strikes trees, consequently one should never take shelter under trees, near power lines, *etc.*

4.6 THE ELECTRIC CHARGING OF CLOUDS

Numerous observations and measurements have shown that a thundercloud theory must satisfy certain conditions:

    1.   It must explain a positive charge in the upper region of the cloud and a negative charge in its lower portion and during the

later stage in the cloud's life cycle it must justify the appearance of a small pocket of a positive charge near its base.

2. The theory must clarify why it takes approximately 20 min. to generate enough charge for the first lightning flash and only a few second for the ensuing flashes.

3. The process must be capable of separating a charge of at least 1,000 coulomb per thunder cloud during an average life time of 30 minutes. A typical diagram of a thunder cloud is shown in Fig. 30.
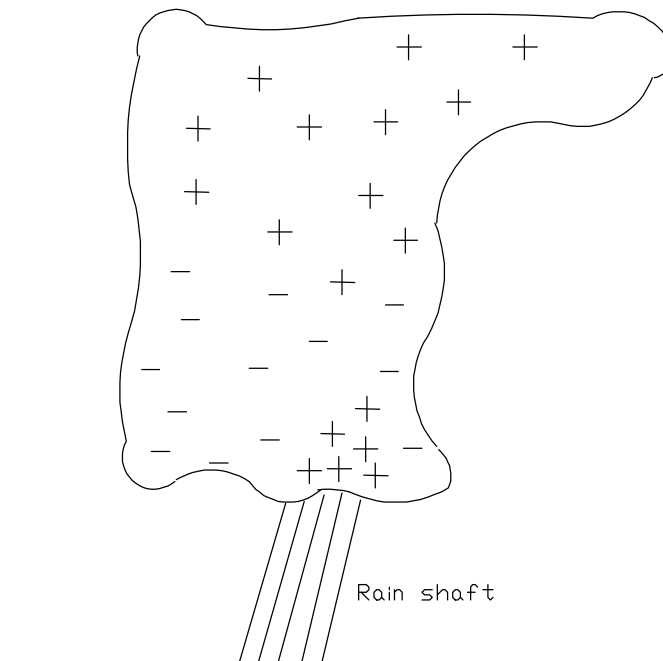

Fig. 30 Typical charge distribution in a thundercloud.

Many theories have been developed ever since Franklin's and D'Alibard's discoveries over 200 years ago. A theory must resort to some kind of energy source and most thundercloud theories seem to fall within two such categories, namely that of gravitational energy and energy provided by convection. Gravitational mechanisms rely on the gravitational potential energy available as precipitation particles fall from the upper part of a cloud to its lower region. Convection mechanisms make use of energy supplied by the intense updraft winds in thunder clouds.

Most theories such as the Wilson mechanism, influence charging, icing and ice splintering mechanisms all fall under the gravitational process.   Charge is produced on precipitation particles by one of the above processes in which negative charge is preferentially attached to larger and heavier drops which fall down and separate from the smaller drops causing a large build up of the electric field within the cloud.   One serious problem with gravitational mechanisms is that according to the data presented by Israel (see sec. 4.2 and 4.3) an average   thunderstorm cell which contains 8×10^8 kg of water must produce 1.7×10^{13} joules of electric energy,   which is not possible. Simple calculations show that the gravitational energy available in a cell which contains 8×10^8 kg of water has a potential gravitational energy of $0.6\, mgh / 2 = 1.2 \times 10^{13}$ joules   (g is the gravitational acceleration, h the average vertical separation of roughly 5 km between the charge centres and m is the total water content). This means that there is not enough gravitational energy available to account for the electric energy present in the cell.   If the above reasoning holds true then all charging mechanisms which rely on gravitational potential energy can be ruled out. However, more careful evaluation of existing data and more measurements are needed before   such a decision can be made.

Convection mechanisms on the other hand can easily provide the energy and charge needed through the continuous ventilation of near stationary drops.   There are essentially only two theories developed so far which are based on convection, the theory by Grenet (1947) and the electrochemical mechanism (Wåhlin 1973).   Grenet and later Vonnegut (1955) suggested that natural positive space charge is brought in from below the cloud and carried to the top by convective updraft currents.   The positive charge at the top of the cloud will attract negative ions from the outside air volume which are captured by down draft currents and thus assumed to be brought to the bottom of the cloud.   As the process continues, the increased electric field will produce more positive ions under the cloud by corona point discharges

at the earth's surface which in turn are carried through to the top by updrafts.   One objection (Chalmers, 1957) is that it is difficult to understand how the updraft and downdraft currents can distinguish between negative and positive ions in a way that only negative ions can be transported by down drafts and positive ions by updrafts.

In   the electrochemical charging mechanism   convection currents simply bring natural ions of both signs in from outside and ventilate them through the drop population of the cloud. However, negative ions which are extremely reactive attach themselves to drop surfaces at the bottom of the cloud while the inert positive ions sieve through and are carried by the updrafts to the upper regions.   The electrochemical charging mechanism, which is described in Chapter 3, is very effective and despite   criticism by Vonnegut, Moore, Griffith and Willet (see section 2.7.3) is the only process which can easily be modelled in the laboratory. The diagram in Fig. 31 shows such a model constructed from two clumps of steel wool. The two sections of steel wool, one representing the bottom and the other the top of a thunder cloud,   are electrically insulated from each other.   A fan blows air through the cloud model to simulate the updraft winds inside a thunder cloud.   A radioactive alpha particle source (Po 210, 500 micro Cu) near the fan feeds positive and negative ions at equal number into the cloud model. Negative ions are immediately captured by the electrochemical process in the bottom section while the inert positive ions pass through and reach the upper steel wool section where they stop together with the air flow.   In a model the size of a large football over one hundred volts of charge separation is readily achieved.   A small neon light, connected across the cloud model, demonstrates the lightning discharge in a realistic manner. The polonium 210 is readily available from several mail order suppliers and does not require a license.
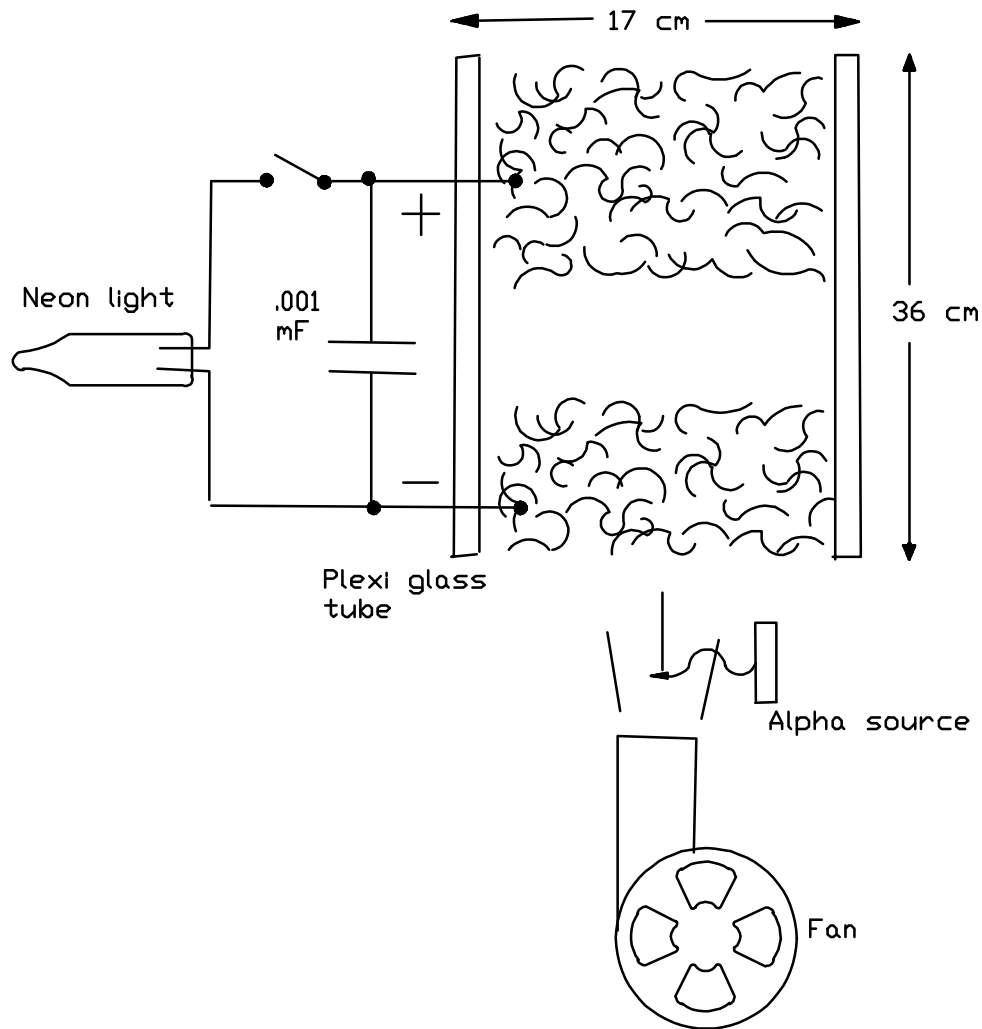
Fig. 31 Laboratory model of thundercloud.

The electrochemical charge separation in clouds has been theoretically scrutinized by Pathak, Rai and Varshneya (1980) who determined that enough charge can be separated from atmospheric ions within 10 minutes to trigger the first lightning discharge. Once lightning has occurred numerous ion pairs are created by the discharge itself which will increase the charge rate drastically to allow for ensuing lightning discharges to occur within seconds of each other. In the dissipating stage when down drafts begin to appear in an organized way, the charging process can reverse and form a small positive charge centre near bottom of the cloud.   This explains the small pocket of positive charge near the cloud base which is often observed by investigators (see Fig. 30).

4.7.1 BALL LIGHTNING

Ball lightning is a controversial subject and such a rare phenomenon that many investigators in the field still doubt its existence.   Many sightings have been reported dating back hundreds of years, but no convincing photographs or scientific records have ever been produced. Nevertheless, ball lightning has intrigued a great number of reputable scientists and   has resulted in many exotic theories.   Certain fundamental characteristics of ball lightning has been agreed on which can be described as follows: The geometrical shape of ball lightning is that of spheroid with a diameter of 10 - 20 cm although diameters as small as 2 cm and as large as 150 cm have been reported. The colour of ball lightning varies from white, bluish-white, greenish-white, red or orange-red.   The light or glow seems to be steady throughout its duration which might be a few seconds to several minutes.   Ball lightning might decay slowly and faint out or disappear in a sudden explosion often causing severe damage.   Ball lightning has been reported to pass through window panes and walls, a phenomenon which is difficult to conceive. In most cases it moves silently above ground or along fence wires and power lines. Occasionally it is accompanied by small sparks and corona discharges which indicate the presence of electrostatic charges. Ball lightning appears only during severe thunderstorms that produce intense lightning discharges.   It is believed that ball lightning might originate from the ionized lightning channel of super bolts.

   Small electric plasma balls have often been observed in submarines when battery banks have been accidentally shorted out. The high short-circuit currents cause intense arcs to appear across contacts of reverse current relays which are fitted with magnetic blow-out coils. Occasionally a fire ball is blown out which will float off into the engine room and remain visible for a short time while decaying by the normal electron-ion recombination process.

As previously mentioned, there are many theories proposed in order to explain ball lightning (Barry, 1980). One such theory is the ring current plasmoid model which is derived from observations and experiments performed with submarine batteries (see Silberg, 1965). The ring current model does not mention what mechanism creates a ball lightning but deals more with the decay time of the plasma itself. Other more exotic theories are the standing wave model which is based on microwave resonance and the crystal model which treats the problem from a quantum mechanical point of view.

4.7.2 THE QUANTUM MODEL

The quantum model is interesting in that it tries to explain how a completely ionized plasma is maintained at very low temperatures, less than 340 C. Neugebauer (1937) used quantum mechanical arguments, derived from well-known free-electron gas models, to show that once a plasma ball has been created it will require very little energy too sustain itself. For example, from the black body radiation of such a plasma it can be determined that a completely ionized ball of 10 cm in diameter would require less than 24 watts and a 20 cm ball about 90 watts to remain completely ionized. The quantum model does not explain where the power comes from that generates the heat or how the plasma was created in the first place.

4.7.3 THE STANDING WAVE MODEL

Cerrillo (1943) and Kapista (1955) advanced a model of ball lightning in which the ionized plasma is produced and maintained by radio frequency oscillations. It is believed that a standing wave is created inside a plasma where the size of the plasma is equal to one quarter wavelength of its cavity frequency. If the radio frequency is suddenly cut off, the ball will produce a weak shock wave when collapsing. If the

RF energy is gradually diminishing then the ball will slowly faint away without any drastic after effects.   How to explain the mechanism that is responsible for producing such a high intensity RF field remains a problem.

4.7.4 THE RING CURRENT MODEL

Fire balls formed in engine rooms of submarines have led to the speculation that ring currents might be responsible for the production of plasmoids with reasonable long life times. The long life time is based on the idea that a plasmoid must have a very low ohmic resistance R and a certain amount of induction L, due to the magnetic field of the ring current. The time constant $t = L/R$ is therefore a measure of the plasmoids life time.   Fig. 32 shows a diagram of the
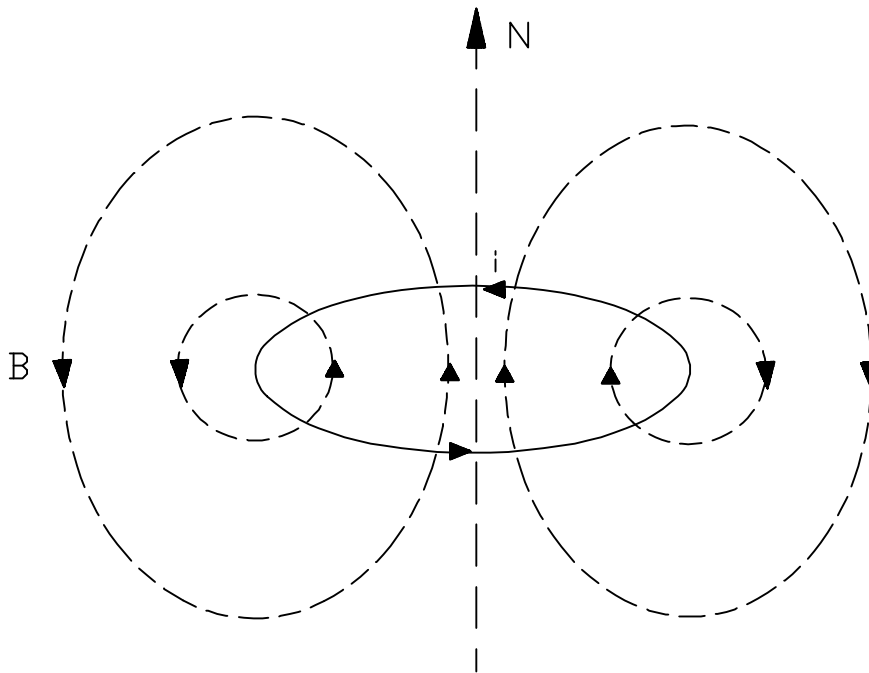

Fig. 32 The ring current model of ball lightning.

plasmoid itself. Also, it is not clear how such a ring current might be produced and how it can obtain a spherical shape.

4.7.5 THE PINCH EFFECT

The pinch effect is a well known   phenomenon.   It   explains how lightning bolts sometimes break up into small balls called bead lightning or pearl lightning, an event which has been observed by the
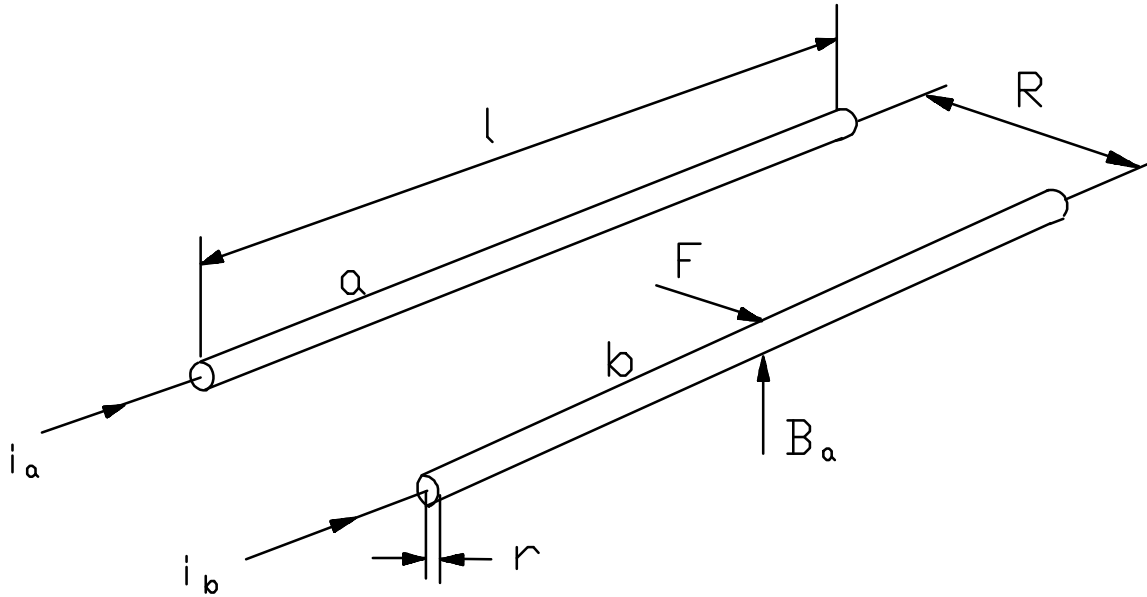

Fig. 33 Two parallel wires which carry currents in the same direction attract each other.

author in both Africa and Sweden.   The strong magnetic field produced by the   lightning bolt current can force the flow of charge to bend inward towards the centre of the lightning channel to such an extent that it will choke and pinch itself off.   The pinch effect can be better understood if one   examines   Ampere's law, see Fig. 33, which states that the attractive force between two parallel conductors, which carry currents i' and i" respectively, is equal to

$$F = \frac{\ell\, i'\, i''\, m_0}{2pR} = \ell\, i'\, B\,, \tag{13}$$

where ℓ is the length of the current elements which are separated by a distance R. The magnetic field generated by one current at the site of the other is B and m_0 is the permeability constant.
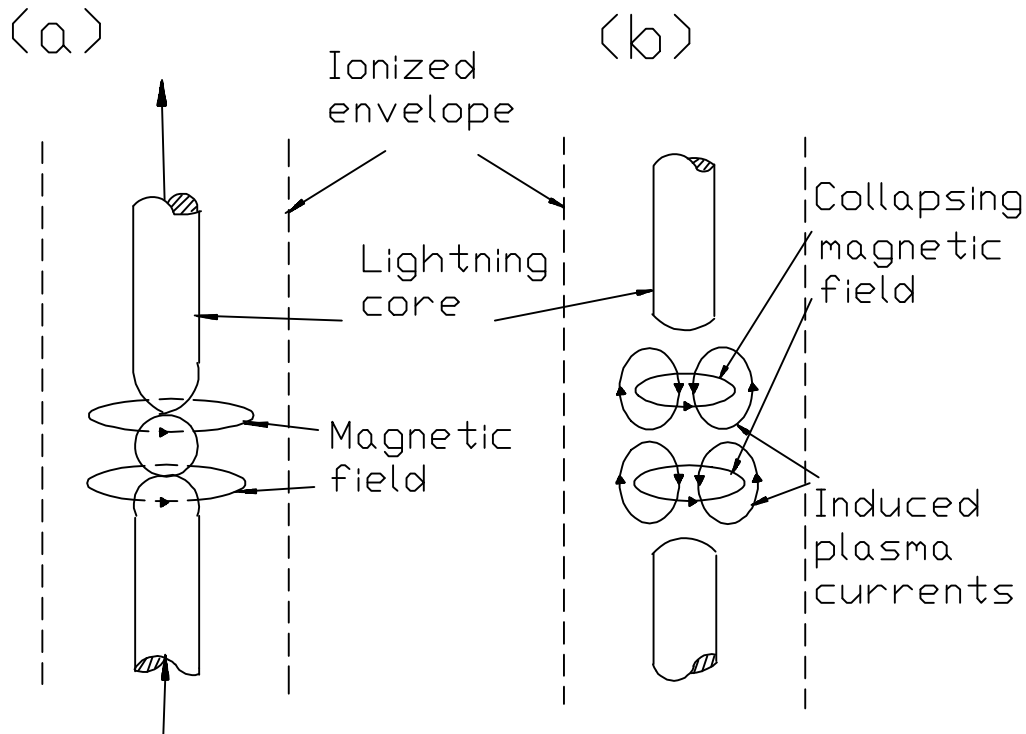
Fig. 34   The pinch effect causes the lightning core to break up into small segments (bead or pearl lightning). permeability constant.

In a   lightning channel, where   numerous charges or current elements move in the same direction, a   mutual attractive force is developed which will cause the lightning channel to contract, see Fig. 34 a.   The force of contraction can reach a magnitude where   the lightning channel gets pinched off and becomes separated into small spherical sections (beads or pearls) see Fig 34 b.   Once the flow of charge is pinched off, the electric current will cease which causes the magnetic field to collapse. The collapse of the magnetic field, on the other hand, will induce eddy currents in the ionized plasma, isolated by the electromagnetic pinch effect, which will   maintain the electric discharge and   prevent the magnetic field from rapid decay. The plasma ball formed can be pictured as a magnetic ring field trapped inside a toroid electric plasma current, see Fig. 35.   One of the conditions required is that the plasma must be completely ionized and super-conducting in order to offer minimal resistance or ohmic loss. Any presence of neutral particles will cause recombination and rapid decay. A collision with a conductive object such as an iron stove, for

example, could drastically neutralize the plasma ball in an explosive manner. The theoretical model described implies that that a ball 10 cm in diameter, completely ionized, would contain an ionization energy o 7 kilo joules and eight times that amount for a 20 cm diameter plasma ball. The field of induction set up by the plasma current is

$$B = m_0 I ,$$ (14)

where I is equal to the lightning current at the moment of pinch-off. The energy density of the trapped magnetic field is

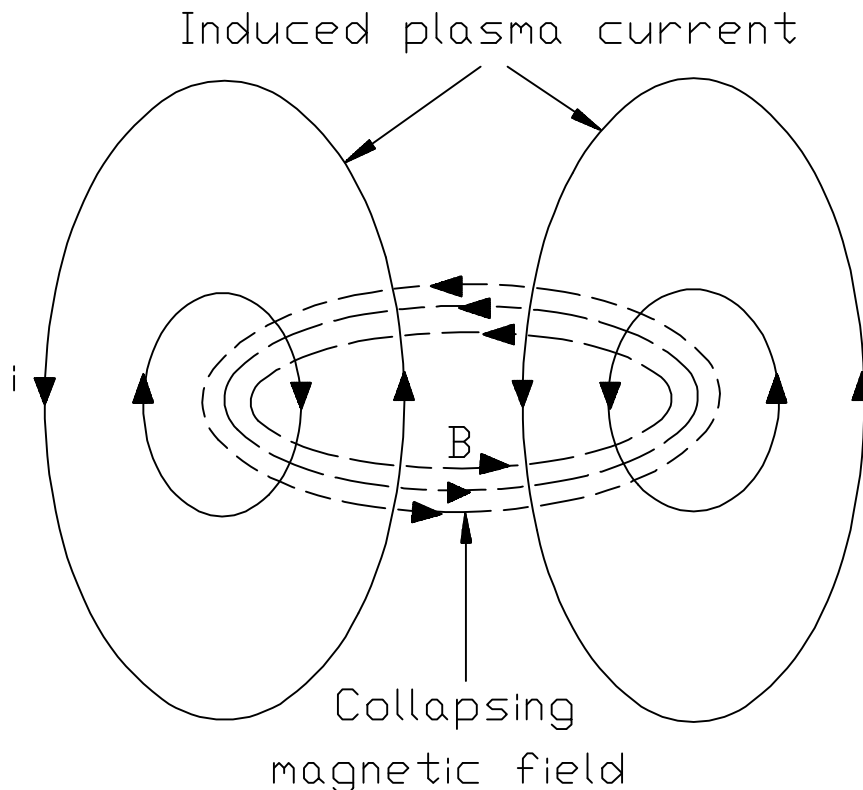$$U_B = \tfrac{1}{2} \frac{B^2}{m_0} .$$ (15)

Fig. 35 Magnetic ring field model of ball lightning.

The energy of the magnetic field in a 20 cm diameter ball, produced by a super bolt delivering 400 kA peak current,   is equal to about 400 joules. Using Neugebauer's argument that 20 watts is sufficient to

maintain a 20 cm plasma ball (see 4.7.2) means that 400 joules will make the plasma ball last for about 20 seconds.