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Lightning, the Science. Part 1: Modern View

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Lightning can be defined as a transient, high-current (typically tens of kA) electric discharge in air whose length is measured in km. As for any discharge in air, lightning channel is composed of ionized gas, that is, of plasma, whose peak temperature is typically 30,000 K, about five times higher than the temperature of the surface of the Sun. Lightning was present on Earth long before human life evolved and it may even have played a crucial role in the evolution of life on our planet. The global lightning flash rate is some tens to a hundred km per second. Each year, some 25 million cloud-to-ground lightning discharges occur in the United States, and this number is expected to increase by about 50% due to global warming over the 21st century. Lightning initiates many forest fires, and over 30% of all electric power line failures are lightning related. Each commercial aircraft is struck by lightning on average once a year. A lightning strike to an unprotected object or system can be catastrophic. In the first part of the article, an overview of thunderclouds and their charge structure is given, basic lightning terminology is introduced, and different types of lightning (including the so-called rocket-triggered lightning) are described. For the most common negative cloud-to-ground lightning, main lightning processes are identified and the existing hypotheses of lightning initiation in thunderclouds are reviewed. .

Key words: *lightning, thunderclouds, charge structure, rocket-triggered lightning, negative cloud-to-ground lightning, lightning processes*

Thunderclouds and Their Charge Structure. The primary source of lightning is the cloud type termed cumulonimbus, commonly referred to as the thundercloud. Sometimes the term "thunderstorm" is used as a synonym for thundercloud, although thunderstorm is usually a system of thunderclouds rather than a single thundercloud. Lightning-like electrical discharges can also be generated in the ejected material above volcanoes, in sandstorms, and in nuclear explosions.

Before reviewing the electrical structure of thunder clouds, it is worth outlining their meteorological characteristics. In effect, thunderclouds are large atmospheric heat engines with the input energy coming from the Sun and with water vapor as the primary heat-transfer agent (Moore and Vonnegut [1]). The principal outputs of such an engine include (but are not limited to) (1) the mechanical work of the vertical and horizontal winds produced by the storm, (2) an outflow of condensate in the form of rain and hail from the bottom of the cloud and of small ice crystals from the top of the cloud, and (3) electrical discharges inside, below, and above the cloud, including corona, lightning, sprites, halos, elves, blue starters, blue jets, and gigantic jets. The processes that operate in a thundercloud to produce these actions are many and complex, most of them being poorly understood. A thundercloud develops from a small, fair-weather cloud called a cumulus which is formed when parcels of warm, moist air rise and cool by adiabatic expansion; that is, without the transfer of heat or mass across the boundaries of the air parcels. When the relative humidity in the rising and cooling parcel exceeds saturation, moisture condenses on airborne particulate matter to form the many small water particles that constitute the visible cloud. The height of the condensation level, which determines the height of the visible cloud base, increases with decreasing relative humidity at ground. This is why cloud bases in Florida are generally lower than in arid locations, such as New Mexico or Arizona. Parcels of warm, moist air can only continue to rise to form a cumulus and eventually a cumulonimbus if the atmospheric temperature lapse rate, the decrease in the temperature with increasing height, is larger than the moist-adiabatic lapse rate of about 0.6 ^{o}C per 100 m. The atmosphere is then referred to as unstable since rising moist parcels remain warmer than the air around them and thus remain buoyant. When a parcel rises above the 0 ^{o}C isotherm, some of the water particles begin to freeze, but others (typically smaller particles) remain liquid at temperatures lower than 0 ^{o}C. These are called supercooled water particles. At temperatures lower than about -40 ^{o}C all water particles will be frozen. In the temperature range from 0 ^{o}C to -40 ^{o}C liquid water and ice particles coexist forming a mixed phase region where most electrification is thought to occur.

Convection of buoyant moist air is usually confined to the troposphere, the layer of the atmosphere that extends from the Earth's surface to the tropopause. The latter is the boundary between the troposphere and the stratosphere, the layer which extends from the tropopause to a height of approximately 50 km. In the troposphere the temperature decreases with increasing altitude, while in the stratosphere the temperature at first becomes roughly independent of altitude and then increases with altitude. A zero or positive temperature gradient in the stratosphere serves to suppress convection and, therefore, hampers the penetration of cloud tops into the stratosphere. The height of the tropopause varies from approximately 18 km in the tropics in the summer to 8 km or so in high latitudes in the winter. In the case of vigorous updrafts, cloud vertical growth continues into the lower portion of the stratosphere. Convective surges can overshoot the tropopause up to 5 km in severe storms.

Although the primary thunderstorm activity occurs in the lower latitudes, thunderclouds are occasionally observed in the Polar Regions. Thunderstorms commonly occur over warm coastal regions when breezes from the water are induced to flow inland after sunrise when the land surface is warmed by solar radiation to a temperature higher than that of the water. Similarly, because mountains are heated before valleys, they often aid the onset of convection in unstable air. Further, horizontal wind blowing against a mountain will be directed upward and can aid in the vertical convection of air parcels, a process which is referred to as the "orographic effect". While relatively-small-scale convective thunderstorms (also called air-mass thunderstorms) develop in the spring and summer months when the potential for convection is usually the greatest and an adequate water vapor is available, larger-scale storms associated with frontal activity are observed in temperate latitudes at all times throughout the year.

Lightning is usually associated with convective cloud systems ranging from 3 to 20 km in vertical extent. The horizontal dimensions of active air-mass thunderstorms range from about 3 km to greater than 50 km. Seemingly merged thunderstorms may occur in lines along cold fronts extending for hundreds of kilometers. Ordinary thunderstorms are composed of units of convection, typically some kilometers in diameter, characterized by relatively strong updrafts (≥10 m/s). These units of convection are referred to as cells. The lifetime of an individual cell is of the order of 1 hour. Thunderstorms can include a single isolated cell, several cells, or a long-lived cell with a rotating updraft, called a supercell. At any given time, a typical multicell storm consists of a succession of cells at different stages of evolution. Large frontal systems have been observed to persist for more than 48 hours and to move more than 2,000 km. Thunderstorms over flat terrain tend to move at an average speed of 20 to 30 km/hr. Further information on thunderstorm morphology and evolution can be found in the book by MacGorman and Rust [2] and in the book chapter by Williams [3].

The distribution and motion of thunderstorm electric charges, most residing on hydrometeors (various liquid or frozen water particles in the atmosphere) but with some free ions, is complex and changes continuously as the cloud evolves. Hydrometeors whose motion is predominantly influenced by gravity (fall speed ≥0.3 m/s) are called precipitation. All other hydrometeors are called cloud particles. In calculating remote electric fields due to cloud charges and lightning-caused field changes, the typical gross thundercloud charge structure is often approximated by an idealized model in which three vertically stacked point charges (or spherically symmetrical charged volumes): main positive at the top, main negative in the middle, and lower positive at the bottom (see Fig. 1). This charge configuration is assumed to be located in an insulating atmosphere above a perfectly conducting ground. The magnitudes of the main positive and negative charges are typically some tens of coulombs, while the lower positive charge is probably about 10 C or less.

It has been inferred from a combination of remote and in-situ measurements that, regardless of the stage of storm development, location, and season, negative charge is typically found in the same relatively narrow temperature range, roughly -10 to -25 °C, where the clouds contain both supercooled water and ice. This feature has important implication for the dominant cloud electrification mechanism and is illustrated in Fig. 2.

Many cloud electrification theories have been proposed. There is growing consensus that the so-called graupel-ice mechanism is the dominant one, at least at the initial stages of cloud electrification. In this mechanism, the electric

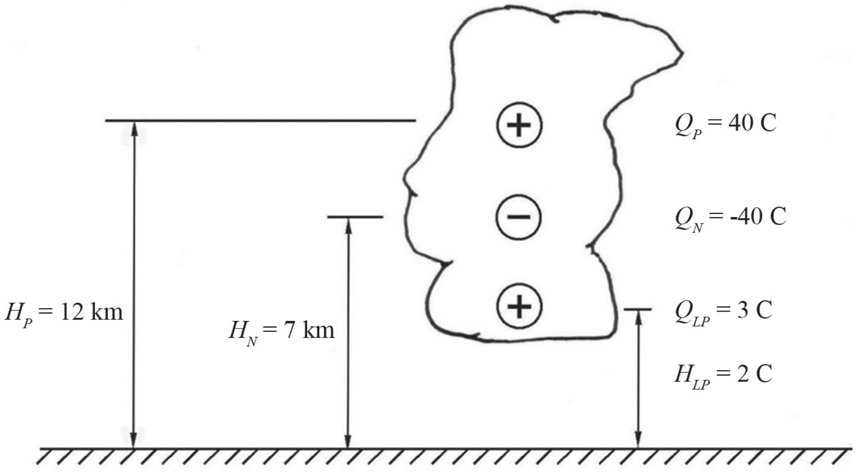


Fig. 1. A vertical tripole representing the idealized gross charge structure of a thundercloud

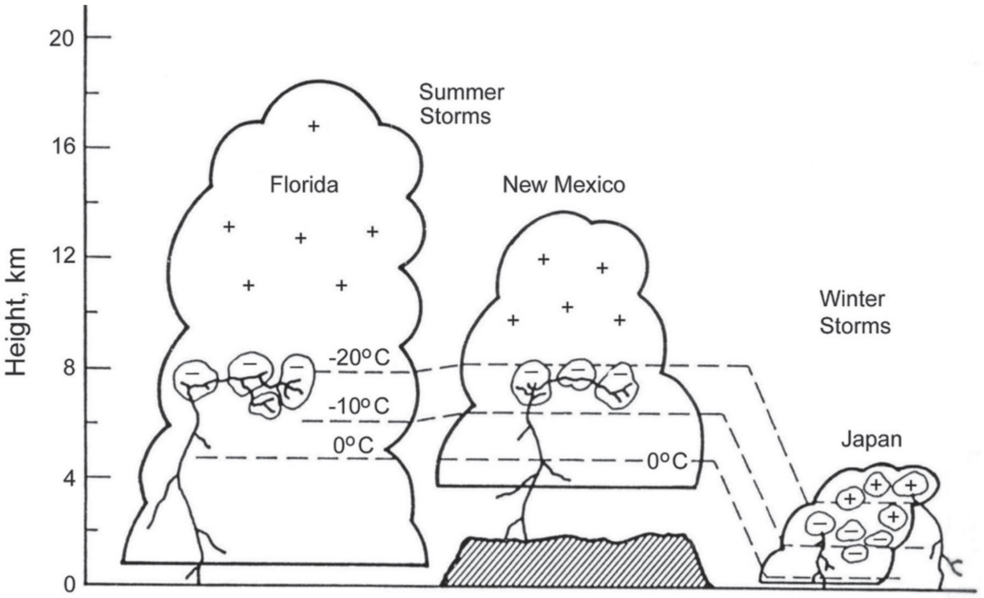


Fig. 2. The locations, shown by the small irregular contours inside the cloud boundaries, of ground-flash charge sources observed in summer thunderstorms in Florida and New Mexico and in winter thunderstorms in Japan using simultaneous measurements of electric field at a number of ground stations [4]

charges are produced by collisions between graupel (millimeter-size soft hail) and small ice crystals in the presence of water droplets, and the large-scale separation of charged particles is provided by the action of gravity. The presence of water droplets is necessary for significant charge transfer, as shown by the laboratory experiments. A simplified illustration of this mechanism is given in Fig. 3. The heavy graupel particles (two of which are shown in Fig. 3) fall through a suspension of smaller ice crystals (hexagons) and supercooled water droplets (dots). The droplets remain in a supercooled liquid state until they contact an ice surface, whereupon they freeze and stick to the surface in a process called riming. Laboratory experiments (e.g., Jayaratne et al. [5]) show that when the temperature is below a critical value called the reversal temperature, TR, the falling graupel particles acquire a negative charge in collisions with the ice crystals. At temperatures above T_R they acquire a positive charge. The charge sign reversal temperature T_R is generally thought to be between -10 °C and -20 °C, the temperature range characteristic of the main negative charge region found in thunderclouds. The graupel which picks up positive charge when it falls below the altitude of TR could explain the existence of the lower positive charge region in the cloud. It is believed that the polarity of the charge that is separated in ice-graupel collisions is determined by the rates at which the ice and graupel surfaces are growing. The surface that is growing faster acquires a positive charge.

It appears that the graupel-ice mechanism is capable of explaining the "classical" tripolar cloud charge structure shown in Fig. 1 and the location of the negative charge region in the -10 °C to -20 °C temperature range seen in Fig. 2.

Initiation, Propagation, and Attachment. The lightning discharge in its entirety, whether it strikes ground or not, is usually termed a “lightning flash” or just a “flash.” A lightning discharge that involves an object on ground or in the atmosphere is referred to as a “lightning strike.” A commonly used nontechnical term for a lightning discharge is a “lightning bolt.” About three-quarters of lightning discharges do not involve ground. They include intracloud, intercloud, and cloud-to-air discharges and are collectively referred to as cloud discharges or flashes (see Fig. 4) and sometimes as ICs. Lightning discharges between cloud and Earth are termed cloud-to-ground (or just ground) discharges and sometimes referred to as CGs. The latter constitute about 25% of global lightning activity.

About 90% or more of global cloud-to-ground lightning is accounted for by downward (the initial process begins in the cloud and develops in the downward direction) negative (negative charge is effectively transported to the ground) lightning. The term “effectively” is used to indicate that individual charges are not transported all the way from the cloud to ground during the lightning processes. Rather the flow of electrons (the primary charge carriers) in one part of the lightning channel results in the flow of other electrons in other parts of the channel. Other types of cloud-to-ground lightning include downward positive, upward negative, and upward positive discharges (see Fig. 5). Downward flashes exhibit downward branching, while upward flashes are branched upward. Upward lightning discharges (types (b) and (d) in Fig. 5) are thought to occur only from tall objects (higher than 100 m or so) or from objects of moderate height located on mountain tops. There are also bipolar lightning discharges (not shown in Fig. 5) sequentially transferring both positive and

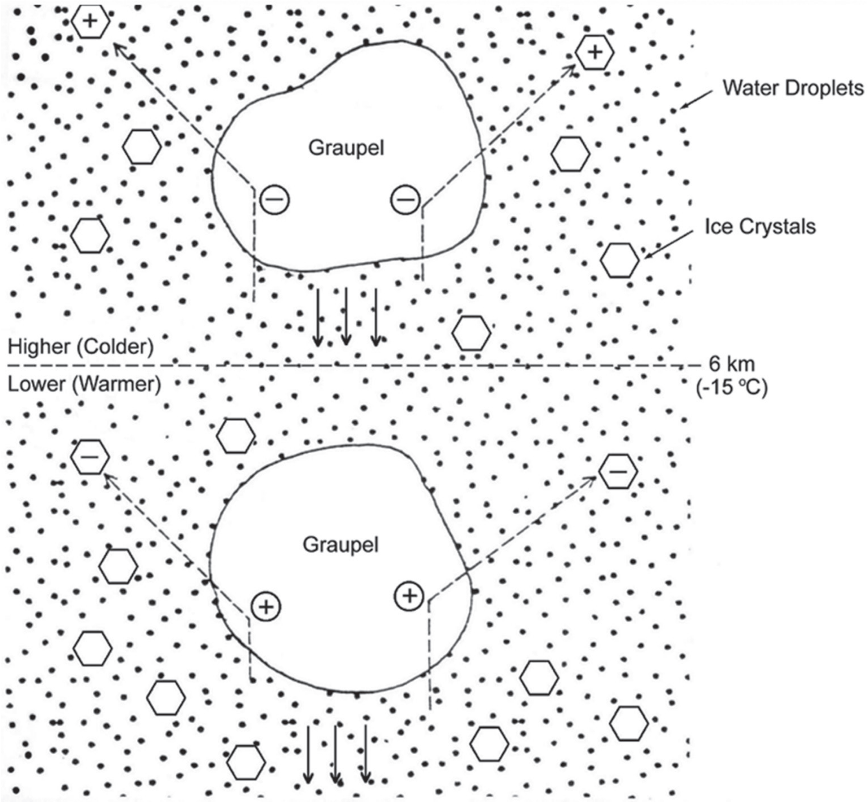


Fig. 3. Schematic representation of the graupel-ice mechanism of cloud electrification, in which the charge transfer occurs via collision of graupel with small ice crystals in the presence of supercooled water droplets. It is assumed that the reversal temperature T_R is -15 °C, and that it occurs at a height of 6 km

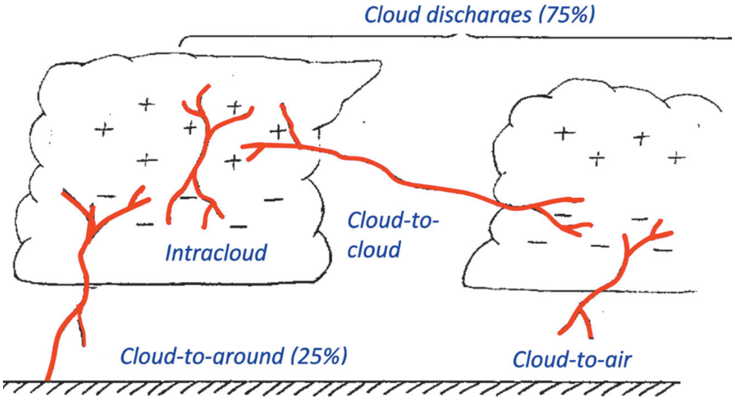
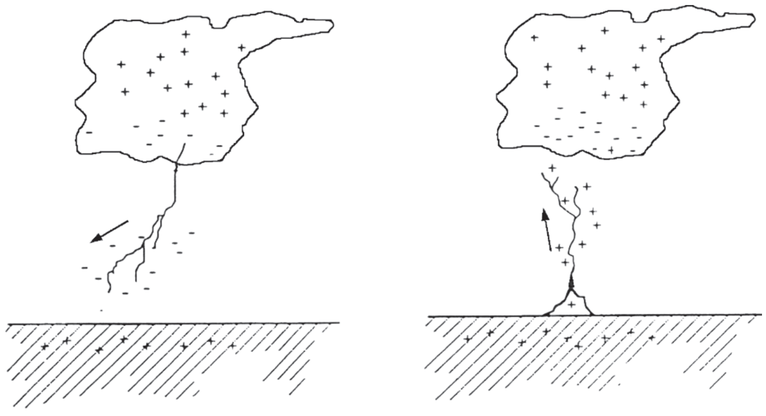


Fig. 4. General classification of lightning discharges from cumulonimbus (thunderstorm clouds). Cloud discharges constitute 75% and cloud-to-ground discharges 25% of global lightning activity

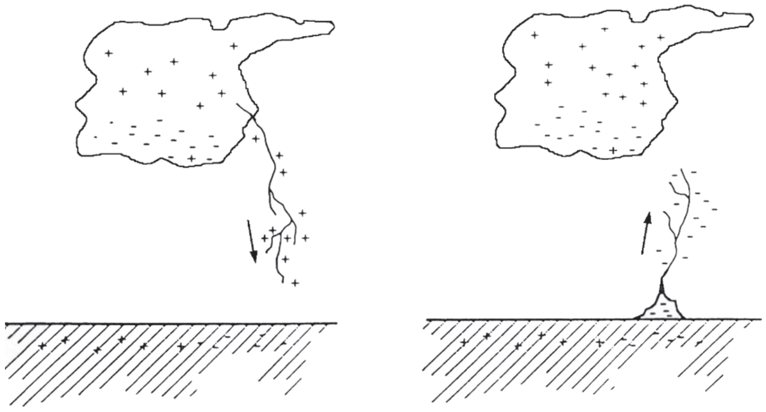
negative charges during the same flash. Bipolar lightning discharges are usually initiated from tall objects (are of upward type). Downward bipolar lightning discharges do exist, but appear to be rare.

We first introduce, referring to Fig. 6,*a* and *b*, the basic elements of the negative downward lightning discharge, termed component strokes or just strokes. Then, we will introduce, referring to Fig. 7, the two major lightning processes comprising a stroke, the leader and the return stroke, which occur as a sequence with the leader preceding the return stroke.

Two photographs of the same negative cloud-to-ground discharge are shown in Fig. 6,*a* and *b*. The image in Fig 6,*a* was obtained using a stationary camera, while the image in Fig. 6,*b* was captured with a separate camera that was moved horizontally during the time of the flash. As a result, the latter image is time resolved showing several distinct luminous channels between the cloud and ground separated by dark gaps. The distinct channels are associated with individual strokes, and the time intervals corresponding to the dark gaps are typically of the order of tens of milliseconds. These dark time intervals between



(a) Downward Negative Lightning (b) Upward Negative Lightning



(c) Downward Positive Lightning (d) Upward Positive Lightning

Fig. 5. Four types of cloud-to-ground lightning discharges (CGs). Only the initial leader is shown for each type. For each lightning-type name given below the sketch, direction (downward or upward) indicates the direction of propagation of the initial leader and polarity (negative or positive) refers to the polarity of the cloud charge effectively lowered to ground. In (*a*) and (*c*), the polarity of charge lowered to ground is the same as the leader polarity, while in (*b*) and (*d*) those polarities are opposite

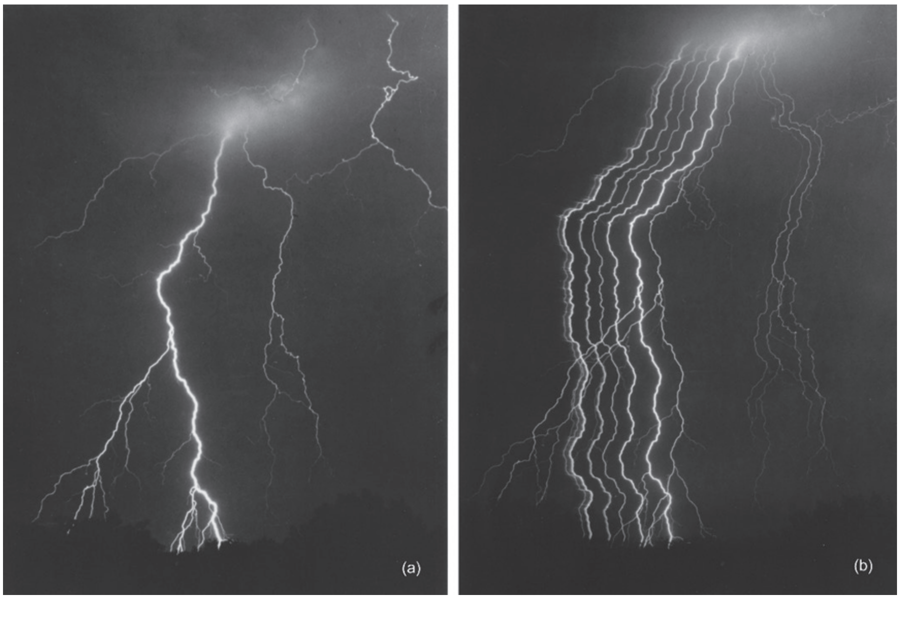


Fig. 6. Lightning flash which appears to have at least 7 (perhaps as many as 10) separate ground strike points: *a* – still-camera photograph, *b* – moving-camera photograph. Some of the strike points are associated with the same stroke having separate branches touching ground, while others are associated with different strokes taking different paths to ground [6]

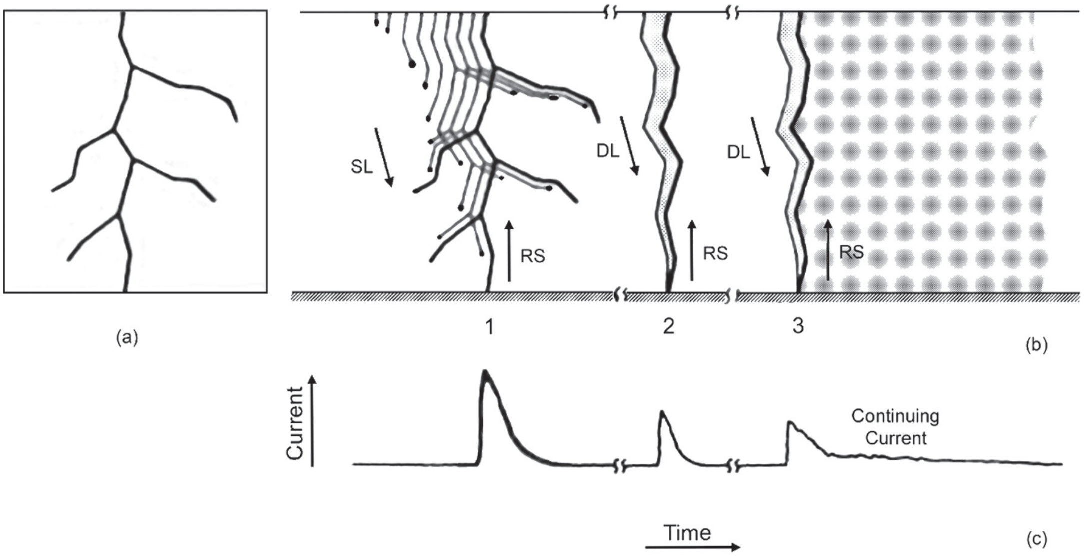


Fig. 7. Schematic diagram showing the luminosity of a three-stroke downward negative flash and the corresponding current at the channel base: *a* – still-camera image; *b* – streak-camera image; *c* – channel-base current

strokes explain why lightning often appears to the human eye to "flicker." In Fig. 6,*b*, time advances from right to left, so that the first stroke is on the far right. The first two strokes are branched, and the downward direction of branches indicates that this is a downward lightning flash.

Now, we consider sketches of still and time-resolved (much better than in Fig. 6,*b*) optical images of the three-stroke lightning flash shown in Fig. 7,*a* and *b*, respectively. A sketch of the corresponding current at the channel base is shown in Fig. 7,*c*. In Fig. 7,*b*, time advances from left to right, and the time scale is not continuous. Each of the three strokes in Fig. 7,*b*, represented by its luminosity as a function of height above ground and time, is composed of a downward-moving process, termed a leader, and an upward-moving process, termed a return stroke. The leader creates a conducting path between the cloud charge source region and ground and distributes negative charge from the cloud source region along this path, and the return stroke traverses that path moving from ground toward the cloud charge source region and neutralizes the negative leader charge. Thus, both leader and return-stroke processes serve to effectively transport negative charge from the cloud to ground. As seen in Fig. 7,*b*, the leader initiating the first return stroke differs from the leaders initiating the two subsequent return strokes (all strokes other than first are termed subsequent strokes). In particular, the first-stroke leader appears optically to be an intermittent process, hence the term stepped leader, while the tip of a subsequent-stroke leader appears to move continuously. The continuously moving subsequent-stroke leader tip appears on streak photographs as a downward-moving "dart," hence the term dart leader. The apparent difference between the two types of leaders is related to the fact that the stepped leader develops in virgin air, while the dart leader follows the "pre-conditioned" path of the preceding stroke or strokes.

The electric potential difference between a downward-moving stepped-leader tip and ground is probably some tens of megavolts, comparable to or a considerable fraction of that between the cloud charge source and ground. The magnitude of the potential difference between two points, one at the cloud charge source and the other on ground, is the line integral of electric field intensity between those points. The upper and lower limits for the potential difference between the lower boundary of the main negative charge region and ground can be estimated by multiplying, respectively, the typical observed electric field in the cloud, 10^5 V/m, and the expected electric field at ground under a thundercloud immediately prior to the initiation of lightning, 10^4 V/m, by the height of the lower boundary of the negative charge region above ground. The resultant range is 50–500 MV, if the height is assumed to be 5 km.

When the descending stepped leader attaches to the ground, the first return stroke begins. The first return-stroke current measured at ground rises to an initial peak of about 30 kA in some microseconds and decays to half-peak value in some tens of microseconds. The return stroke effectively lowers to ground the several coulombs of charge originally deposited on the stepped-leader channel including all the branches. Once the bottom of the dart leader channel is connected to the ground, the second (or any subsequent) return-stroke wave is launched upward, which again serves to neutralize the leader charge. The subsequent return-stroke current at ground typically rises to a peak value of 10–15 kA in less than a microsecond and decays to half-peak value in a few tens of microseconds.

The high-current return-stroke wave rapidly heats the channel to a peak temperature near or above 30,000 K and creates a channel pressure of 10 atm (1 megapascal) or more, resulting in channel expansion, intense optical radiation, and an outward propagating shock wave that eventually becomes the thunder (sound wave) we hear at a distance. Each cloud-to-ground lightning flash involves an energy of roughly 10^9 to 10^{10} J (one to ten gigajoules). Lightning energy is approximately equal to the energy required to operate five 100-W light bulbs continuously for one month. Note that not all the lightning energy is available at the strike point, only 10^{-2}-10^{-3} of the total energy, since most of the energy is spent for producing thunder, hot air, light, and radio waves.

Given above is only basic information about downward negative lightning. In the following, referring to Fig. 8, we present a more complete sequence of processes involved in a typical downward negative lightning flash.

The source of lightning is usually a cumulonimbus (see Section I above), whose idealized charge structure is shown in Fig. 8 as three vertically stacked regions labeled "P" and "LP" for main positive and lower positive charge regions, respectively, and "N" for main negative charge region. The stepped leader is preceded by an in-cloud process called the preliminary or initial breakdown. It may be a discharge bridging the main negative and the lower positive charge regions, as shown in Fig. 8. The initial breakdown serves to provide conditions for the formation of the stepped leader. The latter is a negatively charged plasma channel extending toward the ground at an average speed of 2×10^5 m/s in a series of discrete steps. Each step produces a current pulse that originates at the tip of the downward-extending leader channel and propagates upward, like a mini return stroke, as schematically shown in Fig. 9. Krider et al. [8] inferred that the peak step current is at least 2–8 kA close to the ground and the minimum charge involved in the formation of a step is 1–4 mC. From high-speed time-resolved photographs, each step is typically 1 μs in duration and tens of meters in length, with the time interval between steps being 20 to 50 μs. The stepped leader serves to form a conducting path or channel between the cloud charge region and ground. Several coulombs of negative charge are distributed along this path, including downward branches. The leader may be viewed as a process removing negative charge from the cloud charge region and depositing this charge onto the downward extending channel. The stepped-leader duration is typically some tens of milliseconds, the total charge is about 5 coulombs, and the average leader current is some hundreds of amperes.

As the leader approaches ground, the electric field at the ground surface, particularly at objects or relief features protruding above the surrounding terrain, increases until it exceeds the critical value for the initiation of one or more upward connecting leaders. It is usually assumed that the initiation of an upward connecting leader (UCL)

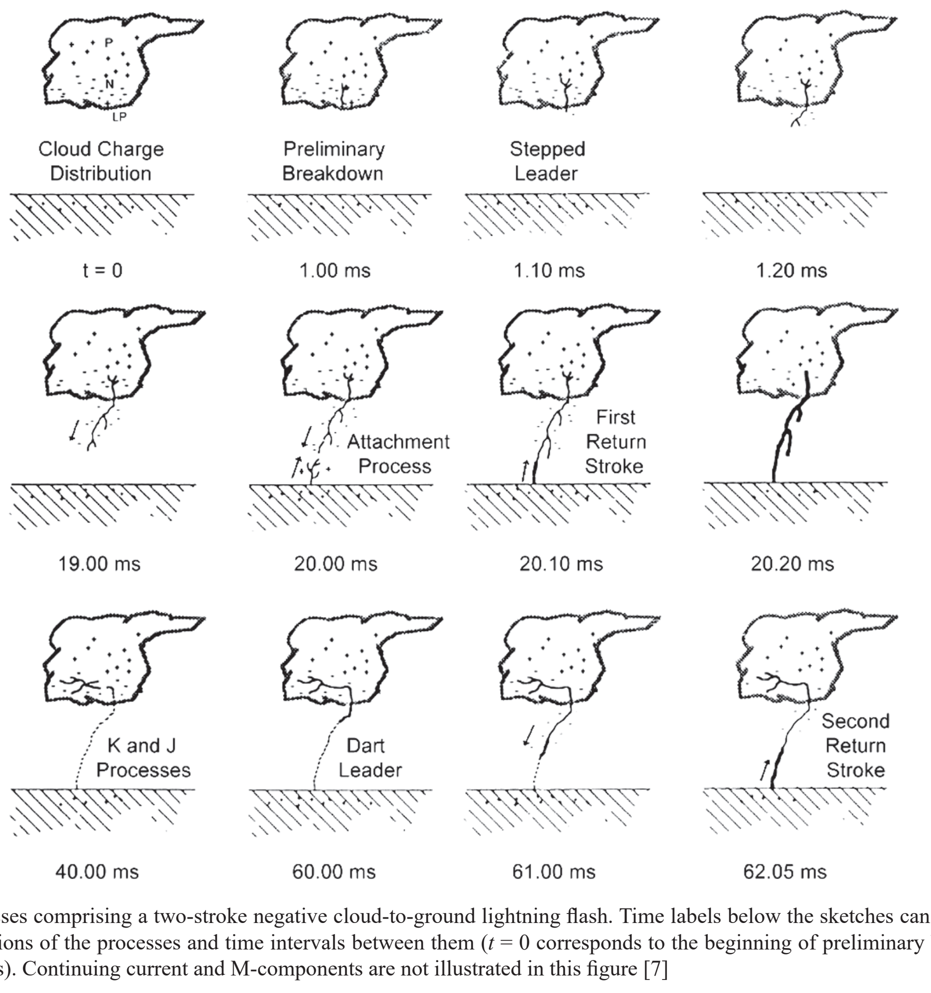


Fig. 8. Various processes comprising a two-stroke negative cloud-to-ground lightning flash. Time labels below the sketches can be used to roughly estimate typical durations of the processes and time intervals between them (*t* = 0 corresponds to the beginning of preliminary breakdown process which ends at *t* = 1 ms). Continuing current and M-components are not illustrated in this figure [7]

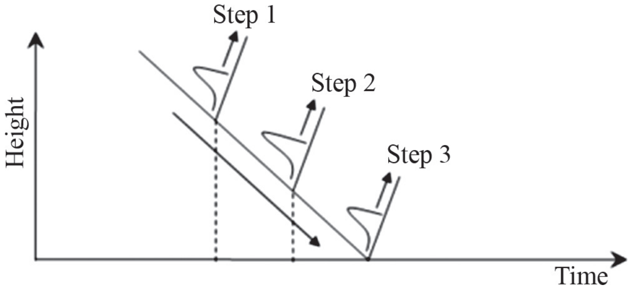


Fig. 9. Schematic representation of the downward leader stepping process. Negatively-sloped arrow indicates the overall downward extension of the leader channel. Three consecutive steps giving rise to current (and light) pulses are shown. Each step-current pulse originates at the tip of the downward-extending channel and propagates upward (as indicated by a positively-sloped arrow), like a mini return stroke [9]

from ground in response to the descending stepped leader marks the beginning of the attachment process. The attachment process includes the so-called breakthrough phase that is assumed to begin when the relatively low conductivity streamer zones ahead of the two propagating leader tips meet to form a common streamer zone. The subsequent accelerated extension of the two relatively high conductivity plasma channels toward each other takes place inside the common streamer zone (see Rakov and Tran [10]) and references there in). The attachment process ends when contact is made between the hot channels of the downward and upward moving leaders, probably some tens of meters above ground (more above a tall structure), where the first return stroke begins (see Fig. 10 where the attachment process for a subsequent stroke is shown). The return stroke serves to neutralize the leader charge or, equivalently, to transport the negative charges stored on the leader channel to the ground. It is worth noting that the return-stroke process may not neutralize all the leader charge and is likely to deposit some excess positive charge onto the upper part of the leader channel and into the cloud charge source region. The speed of the return stroke, averaged over the visible channel, is typically between one-third and one-half of the speed of light. There is no consensus about whether or how the first return-stroke speed changes over the lower 100 m or so, but over the entire channel, the speed decreases with increasing height, dropping abruptly after passing each major branch. At the same time, a transient enhancement of the channel luminosity below the branch point, termed a branch component, is often observed.

When the first return stroke, including any associated in-cloud discharge activity (discussed later), ceases the flash may end. In this case, the lightning is called a single-stroke flash. However, more often the residual first-stroke channel is traversed by a leader that appears to move continuously, a dart leader. During the time interval between the end of the first return stroke and the initiation of a dart leader, J (for junction) and K processes occur in the cloud. K processes can be viewed as transients occurring during the slower J process. The J processes amount to a redistribution of cloud charge on a tens of milliseconds time scale in response to the preceding return stroke. There is controversy as to whether these processes, which apparently act to extend the return-stroke channel further into the cloud, are necessarily related to the initiation of a following dart leader. The J process is often viewed as a relatively slow positive leader extending from the flash origin into the negative charge region, with the K process being a relatively fast “recoil process” that begins at the tip of the positive leader or in a decayed positive leader branch and propagates toward the flash origin. Both the J processes and the K processes in cloud-to-ground discharges serve to transport additional negative charge into and along the existing channel (or its remnants), although not all the way to the ground. In this respect, K processes may be viewed as attempted dart leaders. The processes that occur after the only stroke in single-stroke flashes and after the last stroke in multiple-stroke flashes are sometimes termed F (for final) processes. These are similar, if not identical, to J processes.

The dart leader progresses downward at a typical speed of 10^7 m/s, typically ignores the first stroke branches, and

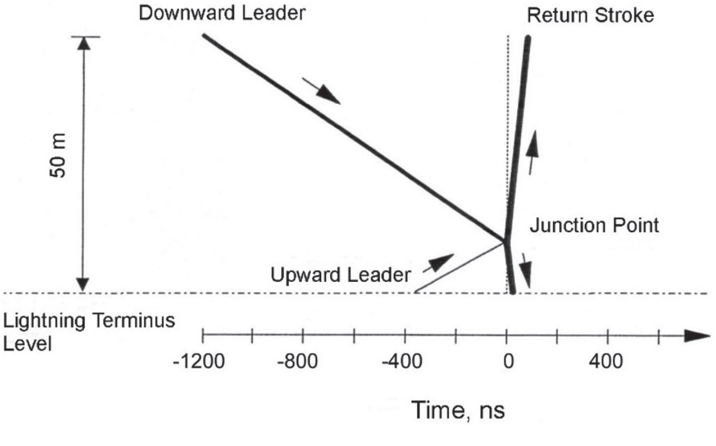


Fig. 10. Schematic representation of the attachment process followed by the bidirectional return-stroke process observed in a rocket-triggered lightning stroke. Strokes of Rocket-triggered lightning are similar to subsequent strokes in natural lightning [11]

deposits along the channel a total charge of the order of 1 C. The dart-leader current peak is about 1 kA. Some leaders exhibit stepping near ground while propagating along the path traversed by the preceding return stroke; these leaders being termed dart-stepped leaders. Additionally, some dart or dart-stepped leaders deflect from the previous return-stroke path, become stepped leaders, and form a new termination on the ground.

Wang et al. [11], using the digital optical imaging system ALPS with 3.6-m spatial and 100-ns time resolution, observed the attachment process in one rocket-triggered-lightning stroke (see Section V of this chapter). A sketch of the time-resolved image for that event is shown in Fig. 10, in which the return stroke begins at $t = 0$. Note that the return stroke was initially a bidirectional process that involved both upward- and downward-moving waves which originated from the junction point of the downward negative dart leader and the upward positive connecting leader.

The impulsive component of the current in a subsequent return stroke is often followed by a continuing current which has a magnitude of tens to hundreds of amperes and a duration up to hundreds of milliseconds (median duration is 6 ms). Continuing currents with a duration in excess of 40 ms are traditionally termed long continuing currents. Between 30% and 50% of all negative cloud-to-ground flashes contain long continuing currents. The source for continuing current is the cloud charge, as opposed to the charge distributed along the leader channel, the latter charge contributing to at least the initial few hundred microseconds of the return-stroke current observed at ground. Continuing current typically exhibits a number of superimposed surges that rise to peak and fall off to the background current level in some hundreds of microseconds, with the peak being generally in the hundreds of amperes range but occasionally in the kiloamperes range. These current surges are associated with enhancements in the relatively faint luminosity of the continuing-current channel and are called M components. Note that continuing current and M-component processes are not shown in Fig. 8.

The time interval between successive return strokes in a flash is usually several tens of milliseconds, although it can be as large as many hundreds of milliseconds if a long continuing current is involved and as small as one millisecond or less. Note that interstroke intervals are usually measured between the peaks of current or electromagnetic field pulses. The total duration of a flash is typically some hundreds of milliseconds, and the total charge lowered to ground is some tens of coulombs. The average number of strokes per flash is 3 to 5. The overwhelming majority (typically about 80%) of negative cloud-to-ground flashes contain more than one stroke.

One-third to one-half of all lightning discharges to earth, both single- and multiple-stroke flashes, strike ground at more than one point with the spatial separation between the channel terminations being up to many kilometers. The average number of channels per flash is 1.5 to 1.7. In most cases, multiple ground terminations within a given flash are associated not with an individual multi-grounded leader but rather with the deflection of a subsequent leader from the previously formed channel.

The salient properties of downward negative lightning discharges are summarized in Table 1.

Lightning initiation in thunderclouds remains a mystery. Indeed, maximum electric fields typically measured in thunderclouds (see Table 3.2 [12] and references therein) are $1–2\times10^5$ V/m (the highest measured value is 4×10^5 V/m), which is lower than the expected conventional breakdown field, of the order of 10^6 V/m. Two general mechanisms of lightning initiation have been suggested. One relies on the emission of positive streamers from hydrometeors when the electric field exceeds $2.5–9.5\times10^5$ V/m, and the other involves high-energy cosmic ray particles and the so-called runaway breakdown that occurs in a critical field, calculated to be about 10^5 V/m at an altitude of 6 km. Either of these two mechanisms permits, in principle, creation of an ionized region (“lightning seed”) in the cloud that is capable of locally enhancing the electric field at its extremities. Such field enhancement is likely to be the main process leading to the formation (via conventional breakdown) of a hot, self-propagating lightning channel.

Rocket-Triggered Lightning. An understanding of the physical properties and deleterious effects of lightning is critical to the adequate protection of power and communication lines, aircraft, spacecraft, and other objects and systems. Many aspects of lightning are not yet well understood and are in need of research that often requires the termination of lightning channel on an instrumented object or in the immediate vicinity of various sensors. The probability for a natural lightning to strike a given point on the earth's surface or an object of interest is very low, even in areas of relatively high lightning activity. Simulation of the lightning channel in a high-voltage laboratory has limited application, since it does not allow the reproduction of many lightning features important for lightning protection and it does not allow the testing of large distributed systems such as overhead power lines. One promising tool for studying both the direct and the induced effects of lightning is an artificially initiated (or triggered) lightning discharge from a natural thundercloud to a designated point on ground. The most effective technique for artificial lightning initiation is the so-called rocket-and-wire technique. It allows generation of full-scale lightning discharges with currents up to tens of kiloamperes and potentials of the order of 10 MV. Energy tapped by these discharges is naturally accumulated in the cloud that would otherwise produce natural lightning. In most respects, the rocket-and-wire triggered lightning (often referred to as rocket-triggered or just triggered lightning) is a controllable analog of natural lightning.

The rocket-and-wire technique involves the launching of a small rocket extending a thin wire (either grounded

Table 1

Characterization of negative cloud-to-ground lightning [12]

Parameter	Typical Value[a]
Stepped leader	
Step length, m	50
Time interval between steps, μs	20–50
Step current, kA	>1
Step charge, mC	>1
Average propagation speed, m s^{-1}	2×10^{5}
Overall duration, ms	35
Average current, A	100–200
Total charge, C	5
Electric potential, MV	~ 50
Channel temperature, K	~ 10,000
First return stroke[b]	
Peak current, kA	30
Maximum current rate of rise, kA μs^{-1}	10–20
Current risetime (10–90 percent), μs	5
Current duration to half-peak value, μs	70–80
Charge transfer, C	5
Propagation speed, m s^{-1}	(1-2)×10^{8}
Channel radius, cm	~ 1–2
Channel temperature, K	~ 30,000
Dart leader	
Speed, m s^{-1}	(1-2)×10^{7}
Duration, ms	1–2
Charge, C	1
Current, kA	1
Electric potential, MV	~ 15
Channel temperature, K	~ 20,000
Dart-stepped leader	
Step length, m	10
Time interval between steps, μs	5–10
Average propagation speed, m s^{-1}	(1-2)×10^{6}
Subsequent return stroke[b]	
Peak current, kA	10-15
Maximum current rate of rise, kA μs^{-1}	100
10-90 percent current rate of rise, kA μs^{-1}	30–50
Current risetime (10–90 percent), μs	0.3–0.6
Current duration to half-peak value, μs	30–40
Charge transfer, C	1
Propagation speed, m s^{-1}	(1-2)×10^{8}
Channel radius, cm	~ 1–2
Channel temperature, K	~ 30,000
Continuing current (longer than 40 ms or so)[c]	
Magnitude, A	100–200
Duration, ms	~ 100
Charge transfer, C	10–20
M component [b]	
Peak current, A	100–200
Current risetime (10–90 percent), μs	300–500
Charge transfer, C	0.1–0.2
Overall flash	
Duration, ms	200–300
Number of strokes per flash [d]	3–5
Interstroke interval, ms	60
Charge transfer, C	20
Energy, J	109–1010

[a] Typical values are based on a comprehensive literature search and unpublished experimental data acquired by the University of Florida Lightning Research Group.

[b] All current characteristics for return strokes and M components are based on measurements at the lightning channel base.

[c] About 30 to 50 percent of lightning flashes contain continuing currents longer than 40 ms or so.

[d] About 15 to 20 percent of lightning flashes are composed of a single stroke.

or ungrounded) into the gap between the ground and a charged cloud overhead. In the former case, the triggered lightning is referred to as classical and in the latter case as altitude triggered one. The sequence of processes (except for the transition from leader to return stroke stage that is referred to as the attachment process) in classical triggered lightning is schematically shown in Fig. 11. When the rocket, ascending at about 150–200 m/s, is about 200–300 m high, the field enhancement near the rocket tip launches a positively charged leader that propagates upward toward the cloud. This upward positive leader vaporizes the trailing wire, bridges the gap between the cloud and the ground, and establishes an initial continuous current with a duration of some hundreds of milliseconds that transports negative charge from the cloud charge source region to the triggering facility. After the cessation of the initial continuous current, one or more downward dart-leader/upward return-stroke sequences may traverse the same path to the triggering facility. The dart leaders and the following return strokes in triggered lightning are similar to dart-leader/return-stroke sequences in natural lightning, although the initial processes in natural downward and rocket-triggered lightning are distinctly different.

First lightning triggering was done in the 1960s over water (inspired by lightning unintentionally initiated by a plume of water resulting from an underwater explosion; see Fig. 1 of Brook et al. [14] and since the early 1970s has been performed over land. To date, over 1,500 lightning discharges have been triggered by researchers in different countries (United States, France, Japan, China, and Brazil) using the rocket-and-wire technique, with over 450 of them at Camp Blanding, Florida. Presently, there are four facilities, two in China (Binzhou and Conghua) and two in the United States (Florida and New Mexico), where triggered-lightning experiments can be performed. Photographs of two classical rocket-and-wire triggered lightning flashes are shown in Fig. 12. Examples of some results of triggered-lightning experiments are shown in Fig. 13 and 14.

Fig. 13 shows a photograph of surface arcing during a triggered-lightning flash from experiments at Fort McClellan, Alabama. The soil was red clay and a 0.3 or 1.3-m steel vertical rod was used for grounding of the rocket launcher. The surface arcing appears to be random in direction and often leaves little if any evidence on the ground. Even within the same flash, individual strokes can produce arcs developing in different directions. In one case, it was possible to estimate the current carried by one arc branch which contacted the instrumentation. That current was approximately 1 kA, or 5% of the total current peak in that stroke. The observed horizontal extent of surface arcs was up to 20 m, which was the limit of the photographic coverage during the Fort McClellan experiments. These results suggest that the uniform ionization of soil, usually postulated in studies of the behavior of grounding electrodes subjected to lightning surges, may be not an adequate assumption.

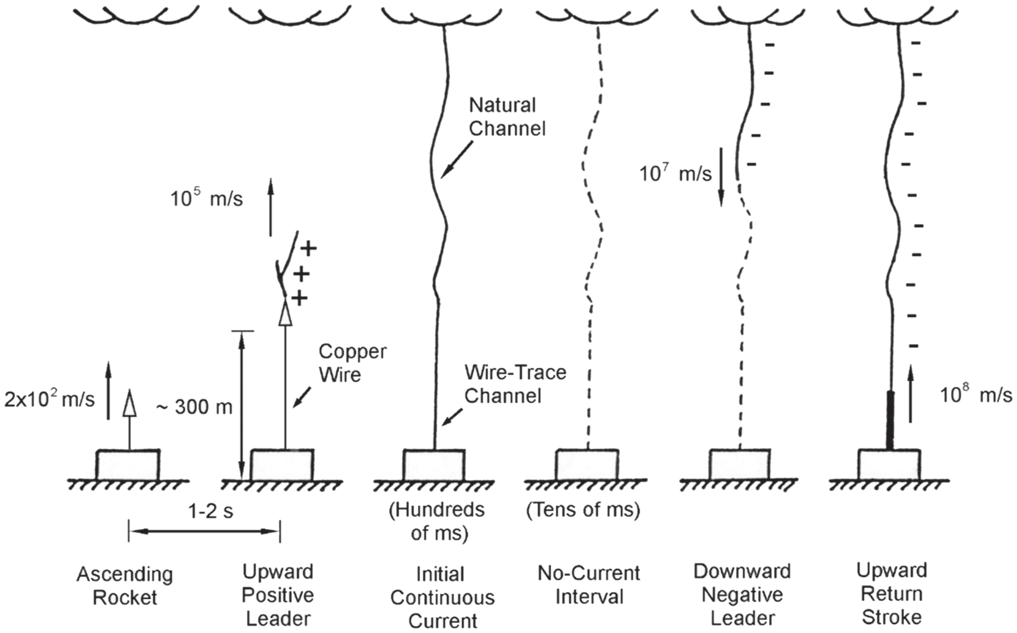


Fig. 11. Sequence of events (except for the attachment process) in classical rocket-triggered lightning. The upward positive leader and initial continuous current constitute the initial stage of a classical rocket-triggered flash [13]

Fig. 12. Photographs of lightning flashes triggered using the rocket-and-wire technique at Camp Blanding, Florida. Top – a distant view of a strike to the test runway; bottom – a close-up view of a strike to the test power system

In 1993, an experiment, sponsored by Electric Power Research Institute (EPRI), was conducted at Camp Blanding by Power Technologies, Inc. to study the effects of lightning on underground power cables. In this experiment three 15 kV coaxial cables with polyethylene insulation between the center conductor and the outer concentric shield (neutral) were buried 5 m apart at a depth of 1 m, and lightning current was injected into the ground at different positions with respect to these cables. The cables differed only in the level of insulation from the surrounding soil. One of the cables (Cable *A*) had an insulting jacket and was placed in PVC conduit (pipe), another one (Cable *B*) had an insulating jacket and was directly buried, and the third one (Cable *C*) had no jacket and was directly buried. About 20 lightning flashes were triggered directly above the cables which were unenergized.

The underground power cables were excavated by the University of Florida researchers in 1994. The damage found ranged from minor punctures of the cable jacket to extensive puncturing of the jacket and melting of nearly all the concentric neutral strands near the lightning attachment point. Some damage to the cable insulation was also observed. In the case of the PVC conduit cable installation, the side wall of the conduit was melted, distorted and blown open, and the lightning channel had attached to the cable inside and damaged its insulation. Photographs of the damaged parts of the cables are shown in Fig. 14. Note fulgurites (glassy tubes formed when lightning current flows through sandy soil) in Fig. 14,*a* and *b*. The presence of fulgurites indicates that the lightning channel continues to extend below the ground surface, in addition to developing

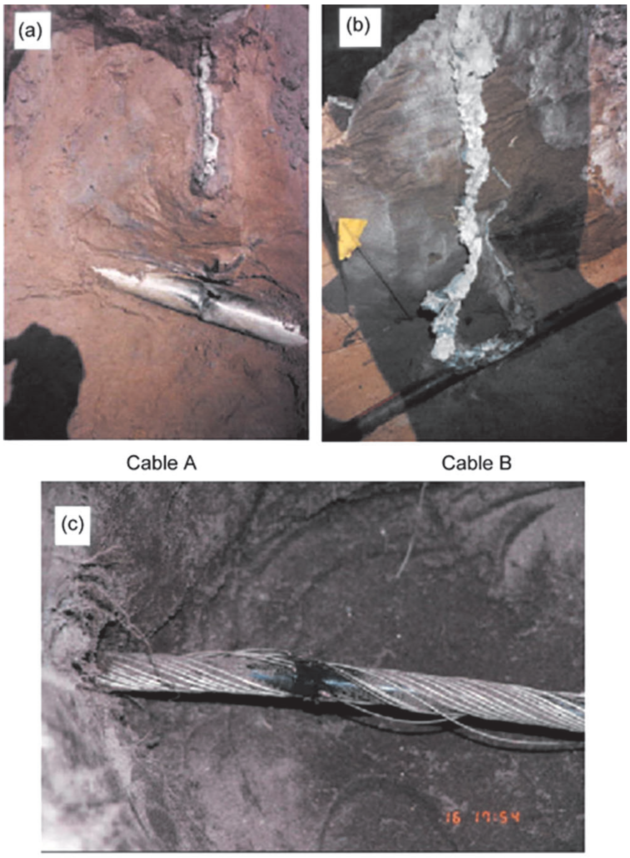
Fig. 13. Photograph of surface arcing associated with the second stroke (current peak of 30 kA) of flash 9312 triggered at Fort McClellan, Alabama. Lightning channel is outside the field of view. One of the surface arcs approached the right edge of the photograph, a distance of 10 m from the rocket launcher [15]

along the ground surface in the form of surface arcs (see Fig. 13). Overall, these experiments showed that buried cables attract lightning striking ground within a distance of 10 m or so from the cable and that three layers of insulation (insulating jacket, PVC pipe, and air inside the PVC pipe; see Fig. 14,*a*) plus 1-m layer of soil do not make cables "invisible" to lightning.

Further information on rocket-triggered lightning can be found in works of Horii and Nakano [16], Rakov and Uman [12, ch. 7], Dwyer and Uman [17], and Qie and Zhang [18]. The results of rocket-triggered-lightning experiments have provided considerable insight into natural lightning processes that would not have been possible from studies of natural lightning due to its random occurrence in space and time. Among such findings are detailed observations of lightning propagation and attachment to ground, discovery that all types of negative lightning leaders produce X-rays, identification of the M-component mode of charge transfer to ground, direct measurements of NO_x production by an isolated lightning channel section, estimation of lightning input energy, and many others. The first terrestrial gamma-ray flash (TGF) observed at ground level was associated with triggered lightning. Triggered-lightning experiments have contributed significantly to testing the validity of various lightning models and to providing ground-truth data for testing the performance characteristics of lightning locating systems. Triggered lightning is a very useful tool for studying the interaction of lightning with various objects and systems and testing lightning protection schemes.

Summary. An understanding of the physical properties and deleterious effects of lightning is critical to the adequate protection of power and communication lines, aircraft, spacecraft, and other objects and systems. The characteristic of Thunderclouds is given and their Charge structure is considered. Basic terminology has been introduced, and different types of lightning have been described. For the most common negative cloud-to-ground lightning, main lightning processes have been identified and the existing hypotheses of lightning initiation in thunderclouds have been reviewed.

In the next issue of the journal the second part of the article will describe the current and electromagnetic signatures of lightning, as well as consider methods for measuring electric and magnetic fields of lightning.



Cable A

Cable B

Cable C

Fig. 14. Lightning damage to underground power cables: *a* – coaxial cable in an insulating jacket inside a PVC conduit (pipe); note the section of vertical fulgurite in the upper part of the picture (the lower portion of this fulgurite was destroyed during excavation) and the hole melted through the PVC conduit, *b* – coaxial cable in an insulating jacket, directly buried; note the fulgurite attached to the cable, *c* – coaxial cable whose neutral (shield) was in contact with earth; note that many strands of the neutral are melted through. Photos in (*a*) and (*b*) were taken by V.A. Rakov and in (*c*) by P.P. Barker

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Молния, Наука. Часть 1: Современный взгляд

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Молния может быть определена как переходный, многоамперный (обычно десятки кА) электрический разряд в воздухе, длина которого измеряется в км. Как и любой разряд в воздухе, канал молнии состоит из ионизированного газа, т. е. плазмы, пиковая температура которой обычно составляет 30 000 К, что примерно в пять раз выше температуры поверхности Солнца. Молния присутствовала на Земле задолго до того, как возникла человеческая жизнь, и, возможно, даже сыграла решающую роль в эволюции жизни на нашей планете. Глобальная скорость вспышки молнии составляет от нескольких десятков до 100 км/с. Ежегодно в Соединенных Штатах происходит около 25 млн молниевых разрядов от облаков до земли и ожидается, что это число увеличится примерно на 50% из-за глобального потепления в течение XXI в. Молния инициирует многие лесные пожары, и более 30% всех отказов линий электропередачи связаны с молнией. Каждый коммерческий самолет поражается молнией в среднем раз в год. Удар молнии в незащищенный объект или систему может быть катастрофическим. В первой части статьи дается обзор грозовых облаков и их зарядовой структуры, вводится базовая терминология молний, описываются различные типы молний (в том числе так называемые ракетные молнии). Для наиболее распространенных негативных молний типа «облако-земля» определены основные молниевые процессы и рассмотрены существующие гипотезы инициирования молний в грозовых облаках.

Ключевые слова: *молния, грозовые облака, структура заряда, ракетные молнии, отрицательные молнии типа «облако-земля», молниевые процессы*

[25.12.2020]