Chapter 7
Mechanism of Lightning Flashes

7.1 Initiation of Lightning Flashes Inside a Cloud

7.1.1 Conditions Necessary for Initiation of Lightning Flashes

As we discussed in Chap. 2, the initiation of an electric discharge requires the electric field in the air to increase beyond a critical electric field, which depends on the air density. At sea level this critical electric field is approximately 3×10^6 V/m. The critical electric field necessary for electrical breakdown decreases with atmospheric density, and at a height of approximately 5 km the value of this field is approximately 1.5×10^6 V/m. It is important to note that these values of the electric fields are applicable in clear air devoid of particles. However, the presence of small particles in air can decrease the background electric field necessary for electrical breakdown due to field enhancement. For example, a spherical particle in a background electric field of strength E gives rise to an electric field that varies as $3E\cos\theta$ on its surface (Fig. 7.1). Thus, the maximum electric field on the surface of the sphere is $3E$. If the particle has a pointed shape, then the field enhancement will be higher. It is important to recognize that to create an electrical breakdown, it is not sufficient for the electric field to reach the critical value at a point. The electric field should increase above the critical value over a critical region so that the electron avalanche process can be initiated. A thundercloud contains a variety of small particles, such as water droplets, ice crystals, and graupel, and their presence will reduce the background electric field necessary for electrical breakdown to a value on the order of 500 kV/m. However, only rarely are such high electric fields observed inside thunderclouds. Measurements conducted inside thunderclouds consistently show typical electric field values of the order of 100–150 kV/m [1]. These values are significantly below the values necessary for electrical breakdown. The question is how the electric fields necessary for an electrical breakdown are

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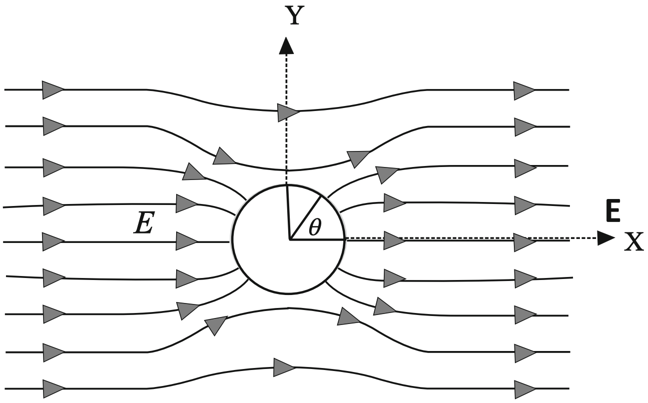


Fig. 7.1 Electric field configuration around a conducting sphere in a uniform electric field. Note the concentration of electric field lines at the two ends of the sphere facing the electric field. This concentration of field lines gives rise to an enhancement of the electric field by a factor of 3 at points where the x-axis (the direction of the electric field) cuts the sphere (Figure created by author)

achieved inside thunderclouds and what the significance is of an overall electric field of approximately 100–150 kV/m in the breakdown process.

7.1.2 Classical Explanation

In the classical explanation, it is assumed that the electric field necessary for the initiation of a discharge is created by the dynamics of the charged particles. This could represent the collision of several charged particles, which momentarily increases the electric field to achieve breakdown. During collisions several particles can act as a single object with an elongated shape, increasing the field enhancement beyond the value necessary for electrical breakdown. Or the field enhancement could be due to the sudden compression of a volume of charged particles resulting from turbulence, thereby increasing the volume charge density and leading to an increase in the electric field. The reason for not observing such high field regions in experiments could be due to the local nature of the high field regions and the transitory nature of the high electric field.

Once electrical breakdown is initiated in a small region, it gives rise to electrical streamer discharges. If the electric field exceeds approximately 250 kV/m (the critical electric field necessary for the propagation of positive streamers in reduced air density in a cloud [2]) over a region of a few meters or so, the discharges may culminate in generating a leader discharge. Once a leader is initiated, it needs approximately 100 kV/m of background electric field in the initial stages of its propagation [3]. As the leader becomes longer, the electric field necessary for its propagation decreases. Thus, a leader may propagate inside a cloud without much hindrance because of the background field of 100–150 kV/m available inside the cloud. If the field inside the cloud is below this value, it impedes the propagation of leaders in the cloud, even if they were generated inside high field regions, thereby preventing the initiation of lightning discharges.

7.1.3 Electron Runaway Breakdown Mechanism

The other mechanism proposed for the initiation of lightning flashes is known as the *electron runaway mechanism* [4]. Let us consider this mechanism in detail. A free electron located in a gaseous medium when exposed to an electric field experiences a force equal to $-eE$, where E is the applied electric field and e is the electronic charge. Under the influence of this force and governed by the Lorentz force (Chap. 3) and Newton's second law, the electron continues to accelerate. As the electron accelerates through the gaseous medium, it collides with atoms and molecules, and this causes the electron to lose energy. Thus, this interaction of the electron with atoms and molecules generates a frictional (or drag) force that opposes the force exerted on the electron by the electric field. For a given electron energy, the drag force decreases linearly with decreasing density. Let us denote by F_D the energy lost by an electron moving a unit length because of this frictional force. The unit of this parameter is eV/m. Figure 7.2 shows how this frictional force (in eV/cm) varies as a function of the energy of the electron at standard

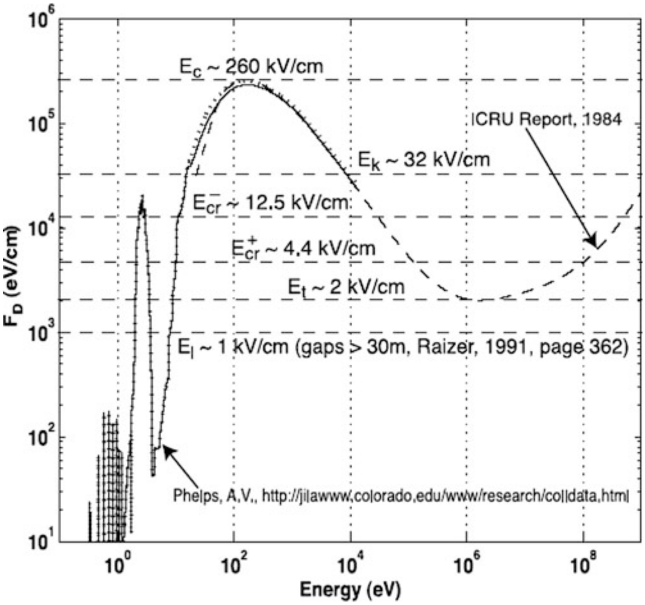


Fig. 7.2 Magnitude of so-called *drag force* as a function of electron energy. The diagram corresponds to normal atmospheric density (Adapted from Moss et al. [5])

atmospheric density. As mentioned earlier, the value of F_D scales inversely with the atmospheric density. For example, the values of F_D corresponding to half the atmospheric density (corresponding to cloud height) can be obtained by dividing the values of F_D given in Fig. 7.2 by 2. Note that the maximum value of this frictional force is (neglecting the maximum around 30 eV), approximately 2.5×10^5 eV/cm, corresponds to an electron energy of approximately 100 eV. After reaching a peak at this electron energy, the frictional force decreases with increasing electron energy and reaches a minimum when the electron energy is approximately 10^6 eV. It is interesting to note that the frictional force can be expressed as an electric field that opposes the acceleration of the electron caused by the applied field. For example, the peak frictional force experienced by an electron having an energy of 100 eV can be translated to an opposing electric field at a magnitude of approximately 250 kV/cm. If the magnitude of the background electric field that accelerates the electron is larger than the opposing electric field, the gain in the energy of the electron per unit length will be larger than the losses and the electron continues to gain energy and becomes a runaway electron. As shown in Fig. 7.2, once the electron exceeds the threshold energy of approximately 100 eV, the external electric field necessary to push the electron to runaway status decreases with increasing energy. For example, a 10^6 eV electron located inside the cloud continues to gain energy and becomes a runaway in a background electric field of approximately 100 kV/m (recall that the atmospheric density at a given cloud height is approximately half the value at ground level and therefore the values given in Fig. 7.2 should be divided by 2). Thus, a relativistic electron having an energy on the order of 10^6 eV generated by a cosmic ray in a background field of approximately 100 kV/m in a cloud continues to gain energy, and during collisions it generates one or more electrons having an energy greater than or equal to 10^6 eV. These electrons also accelerate in this field and generate more electrons. This gives rise to an avalanche of runaway electrons. These runaway electrons not only produce other runaway electrons; they also give rise to a large number of slow moving electrons (thermal electrons). In the runaway breakdown hypothesis, it is assumed that this charge separation and redistribution caused by the runaway electron avalanches changes the electric field in the cloud in such a way that it generates the conditions suitable for electrical breakdown in the cloud.

7.2 Mechanism of Lightning Flash

Once an electrical breakdown is initiated as a result of either of the aforementioned mechanisms, it gives rise to streamer discharges, and these streamer discharges in turn give rise to a leader discharge. Once a leader is created, it propagates in the background electric field, leading to either a cloud flash or a ground flash.

Unfortunately, the cloud flash remains hidden inside the cloud, and its mechanism cannot be studied by direct photography. On the other hand, since part of the ground flash occurs below the cloud, its mechanism can be inferred by studying the physical events of a ground flash that takes place below the cloud base [6].

However, note that the cloud base can be located at a height of 1–2 km, whereas the initiation of a lightning flash may take place at a height of approximately 7 km. Thus, a major portion of the lightning channel of a ground flash remains hidden inside the cloud.

Before describing the mechanism of ground and cloud flashes, let us first describe the mechanism by which a leader discharge, initiated inside a cloud without the aid of conducting bodies that can supply charges to the electrical discharges, propagates in the background electric field that exists inside the cloud.

7.2.1 Bidirectional Propagation of a Leader

As we discussed in Chap. 2, a leader is an electrical discharge that generates a conducting channel in air. In the case of leaders generated from grounded objects, the current necessary for the propagation of the leader is supplied from ground. However, the situation is different in the case of leaders initiated in clouds. Since there are no conducting or grounded objects to supply the charges and currents necessary for the propagation of the leader, the only mode of propagation available for the leader is to propagate as a bidirectional leader [7]. The mechanism is as follows. Once a neutral conducting channel is placed in a background electric field (the electric field inside the cloud), charges of opposite polarity are concentrated at the two ends of the conducting channel. This concentration of electric charge increases the electric field at the ends, and this in turn gives rise to streamer discharges of opposite polarity from the two ends of the conducting channel. As streamer discharges of one polarity propagate forward, the charges of opposite polarity being accumulated in the conductor are utilized by the streamer discharges of opposite polarity moving out from the other end. By concentrating their current into the streamer stem and causing it to conduct, these streamer discharges (Chap. 2) add to the length of the leader channel. Thus, the leader extends from both directions (Fig. 7.3). The total charge on the leader remains zero while positive charges are concentrated on one end and negative charges on the other. This mode of propagation of the leader is called *bidirectional leader propagation*. All lightning leaders that originate in space without the advantage of a conducting grounded

Fig. 7.3 Bidirectional propagation of a leader. Initiation of a leader inside a cloud gives rise to two leader branches, one charged positively and the other negatively, and moving in opposite directions along the field lines of the background electric field. The net charge on the leader channel is zero. In other words, the positively charged leader branch provides the negative charge for the development of the negatively charged branch, and vice versa (Figure created by author)

body propagate in this mode. The initiation of the leader may take place according to the mechanisms describes earlier. Once initiated, the proto leader channel acts as a conductor placed in a uniform electric field, and if the background electric field is strong enough, the bidirectional mode of propagation takes over.

It has been observed experimentally that the positive end of a bidirectional leader propagates more or less in a continuous manner, whereas the negative end moves in intermittent steps. The reason for the intermittent nature of the negative tip of the leader is explained in Chap. 2.

Theoretical studies and inferences made from interferometric studies (Chap. 13) show that from time to time the tip of a positive leader branch of a bidirectional leader could be cut off from the origin of a bidirectional leader, and this shutting off of the current path connecting the positive leader tip to the flash origin can give rise to discharges called *recoil leaders* [8]. In the next section, we consider how a recoil leader is created.

7.2.2 Concept of Recoil Leaders

Though the mechanism of recoil leaders is not clearly understood, some proposals based on experimental observations have been made. The mechanism by which recoil leaders are created is shown in Fig. 7.4. Consider the positive part of a bidirectional leader channel growing upward. As the tip of the positive section of the leader propagates, the conductivity of the channel at a point behind the tip could decrease to such a level that the flow of current to (or from) the tip is cut off

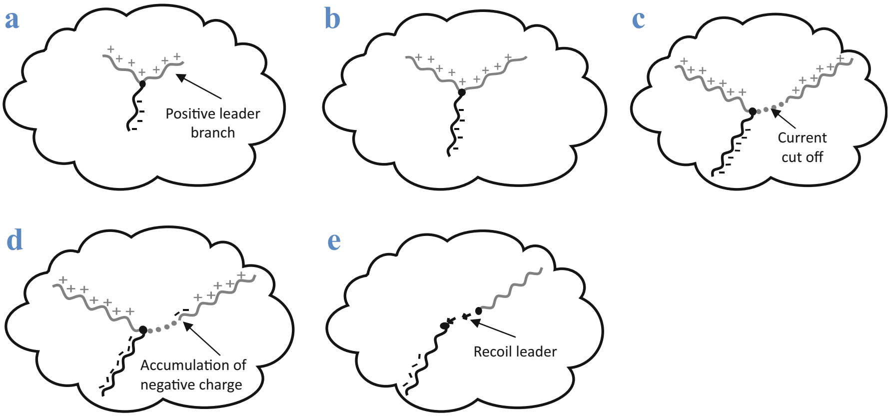


Fig. 7.4 Mechanism through which recoil leaders are created. (**a, b**) A bi-directional leader with two positive branches are created inside the cloud and one of the positive polarity branchs of the leader channel gets cut off (i.e., the channel decays) at the origin. (**c**) As this positive leader branch continues to propagate, negative charges are accumulated at the end of the positive leader channel at the cutoff point. (**d**) When the negative charge accumulated at the channel end reaches a critical value (i.e. the electric field exceeds the breakdown electric field), a negative leader will start from the negatively charged end of the channel and propagate through the cutoff gap, reestablishing the conducting path. (**e**) This negative leader is called a *recoil leader* (Figure created by author)

(as shown in Fig. 7.4). As the positive tip of the leader continues to propagate upward, a negative charge accumulates at the cutoff point. As the negative charge accumulates at the cutoff point, the electric field at the cutoff point increases. When this electric field reaches a critical value, a negative leader that travels toward the point of origin of the bidirectional leader channel is initiated. This discharge is called a recoil leader (Fig. 7.4c). Recoil leaders play a significant role in the development of lightning flashes.

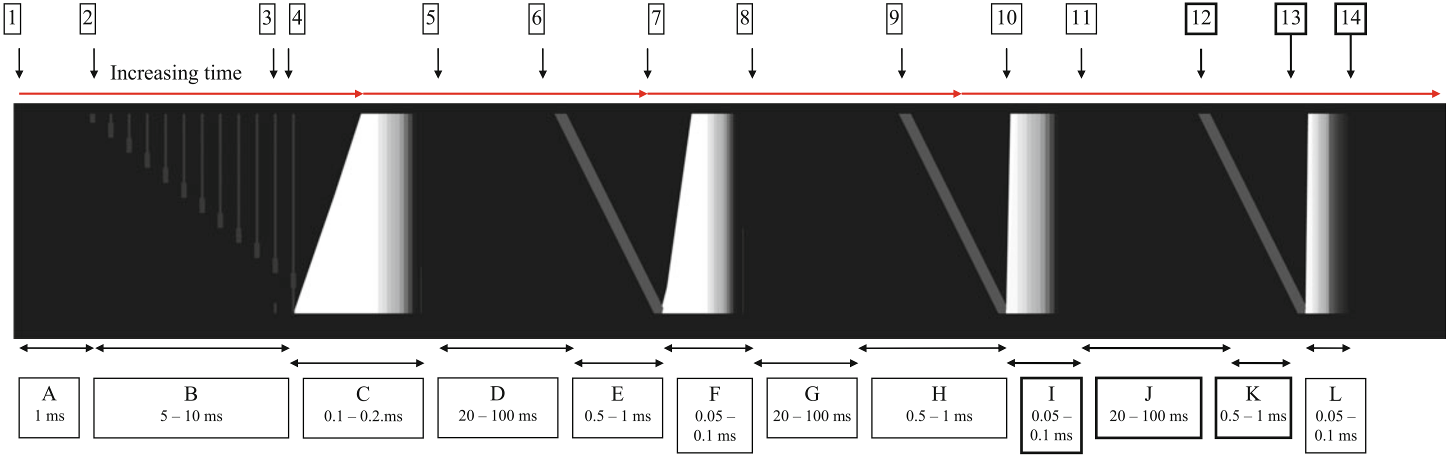
7.2.3 *Mechanism of Ground Flashes*

The processes taking place during a ground flash can be divided into many parts. Let us consider them individually in order of their occurrence. Most features of flashes that take place below clouds were identified in the first half of the last century using streak cameras containing rotating lenses, i.e., a Boys camera [6]. The mechanisms of events taking place inside clouds were inferred from the electric and magnetic fields generated by lightning flashes. From the latter quarter of the last century on, more details of the mechanism of lightning flashes have been obtained using fast video photography and interferometric techniques [8–10].

Figure 7.5 shows an idealized sketch of a possible streak camera photograph of a ground flash. In a streak camera photograph, one can observe stepped leaders, first return strokes, connecting leaders, dart leaders, subsequent return strokes, continuing currents (not shown in Fig. 7.5), and *M*-components (not shown in Fig. 7.5). Such photographs provide no clues as to how lightning flashes are initiated inside clouds and how the preliminary breakdown inside clouds leads to a stepped leader. Moreover, the way in which dart leaders and *M*-components are initiated by recoil streamers and *K*-changes remains hidden inside clouds. Let us now consider these events one at a time.

7.2.3.1 Preliminary Breakdown

A ground lightning flash is usually initiated at the lower edge of a negative charge center, and there is evidence to support the suggestion that this breakdown process is aided by the electric field enhancement caused by a positive charge pocket located below the negative charge center [11]. Thus, the first breakdown event may take place between the negative charge center and the positive charge pocket (Fig. 7.6). This initial electrical breakdown is called the *preliminary breakdown*, which, as can be inferred from the electromagnetic fields generated by this process (Chap. 9), consists of a multitude of discharges taking place either in the same channel or in multiple channels. This gives rise to a burst of electromagnetic radiation. This is the first event that signals the initiation of a ground flash, and it can be identified easily in the records of remotely measured electric fields. This process cannot be observed directly because it happens inside clouds. However, one might be able to detect the scattered light emitted by this process at the base of clouds.



What happens at different times?

1 - Electrical breakdown takes place between the negative charge and positive charge pocket at the base of the cloud.
2 - A stepped leader is initiated.
3 - A connecting leader is initiated from ground.
4 - The connecting leader meets the downcoming stepped leader and the first return stroke is initiated.
5 - The first return stroke ends.
6 - A first dart leader is initiated from cloud.
7 - The dart leader reaches ground and a second return stroke is initiated.
8 - second return stroke ends.
9,10,11,12,13,14 - dart leader return stroke process is repeated twice more.

What happens over different time intervals?

A - A stepped leader is initiated inside the cloud
B - A stepped leader travels towards ground. Each time a step is made the whole channel momentarily luminates.
C - The return stroke travels up. The channel is very bright below the front of the return stroke. This luminous section of the channel increases with time. After the return stroke front reaches the cloud, the current decays in the channel as does the luminosity.
D - No current flows in the channel.
E - A dart leader is initiated in the cloud which propagates towards the ground. At any instant dart leader appears as a bright ‘dart’ several tens of meters in length.
F - The second return stroke travels towards the cloud.
G,H,I,J,K - The dart leader return stroke process is repeated twice more.
(Typical duration of each event is given in thousandths of a second; abbreviated as ms)

Fig. 7.5 A time-resolved picture of a lightning flash may appear like this on a photographic plate. Time increases to the right (Figure created by author)

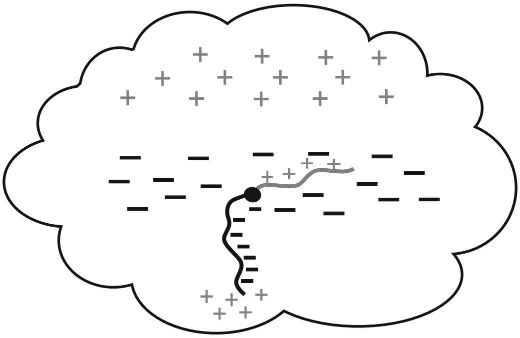


Fig. 7.6 The preliminary breakdown in a ground flash may take place between the negative charge center and the positive charge pocket. This gives rise to a negative leader branch propagating toward the ground and a positive leader branch propagating into the charge center under the influence of the background electric field produced by the negative charge center (Figure created by author)

7.2.3.2 Stepped Leader

The preliminary breakdown gives rise to a bidirectional leader inside the cloud. The positive part of the channel moves (mostly along a horizontal direction) into the negative charge center, and the negative end of the channel starts moving away from the negative charge center and toward ground. Typical for the negative end of a bidirectional leader, it moves in steps toward ground. This negative leader traveling toward the ground in a stepped manner is called a *stepped leader*. Figure 7.7 shows an idealized sketch of a stepped leader moving toward ground.

In a photographic record, the stepped leader appears to propagate toward ground in intermittent steps [6]. The length of each step is approximately 10–100 m, and the time interval between steps is approximately 10–100 μs. During the stepping process the step is illuminated for a few microseconds. The new step usually starts at the end of the previous step (see Chap. 2 for a description of the stepping process).

The stepped leader consists of a hot channel or core that is created during each step, surrounded by the charge associated with streamer discharges that led to the formation of the leader step. Experimental data show that the temperature of the core of a newly created leader channel is approximately 20,000 K [12]. One would expect this temperature to decrease with time, but since the current associated with new leader steps created ahead of this channel section passes through it, the temperature of the section does not decrease below approximately 10,000 K as the stepped leader moves forward. The core of the stepped leader is approximately a few centimeters in diameter. The leader transports a negative charge from the cloud toward ground, and in any given channel section this charge is stored both in the core and in a region around the core called the corona sheath. The charge on the corona sheath is partly due to the charge on the streamer discharges that led to the creation of the leader step and partly due to the corona charges that leak out from the central core, which is at a very high potential (Chap. 2). The diameter of the corona sheath can be a few to a few tens of meters, depending on the amount of

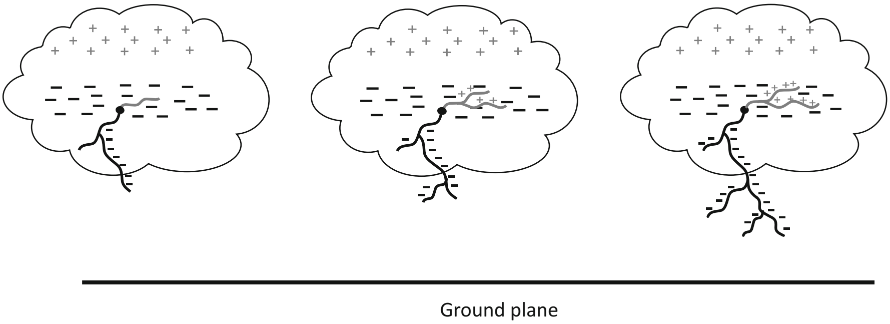


Fig. 7.7 Idealized sketch of a stepped leader moving toward ground. As the negatively charged branch of the leader channel travels toward ground, the positive counterpart of the bidirectional leader moves into the negative charge center, depositing a positive charge in there. Effectively, the process removes the negative charge from the negative charge center and deposits it on the negative branch of the leader channel. The downward moving leader may give rise to several branches as it travels toward ground (Figure created by author)

charge on the leader channel. The larger the charge, the larger the diameter of the corona sheath. A typical stepped leader may have a corona radius of approximately 10 m. The current flowing during the formation of the step can be a few kilo Amperes. There is a continuous current flow along the leader channel from the tip toward the cloud, and this current can be approximately 100 A. The stepped leader stores an electrical charge on it, and a typical stepped leader may contain approximately 0.001 C of charge in each 1 m of the channel close to its tip. This linear charge density may not be uniform on the stepped leader channel. As we will see subsequently, the amount of charge on the stepped leader channel and its distribution along the length of the leader channel is controlled by the potential of the cloud.

With respect to stepped leaders, two speeds are of interest: the speed of formation of the steps and the average downward speed of the stepped leader. Experimental data show that the speed of step formation can be up to approximately 10^8 m/s [13]. Since there is a pause during steps, the average downward speed of the stepped leader is approximately 3×10^5 m/s [10].

On its way toward ground a stepped leader may give rise to several branches. These branches, being negative discharges, also exhibit a stepping behavior.

7.2.3.3 Connecting Leader

As the stepped leader approaches ground, the electric field at ground level increases steadily. When the stepped leader reaches a height of approximately a few hundred meters or less from ground, the electric field at the tip of grounded structures increases to such a level that leader discharges are initiated from them (Fig. 7.8). These discharges, called *connecting leaders*, travel toward the downward moving stepped leader. The length of the connecting leader can be several tens of meters,

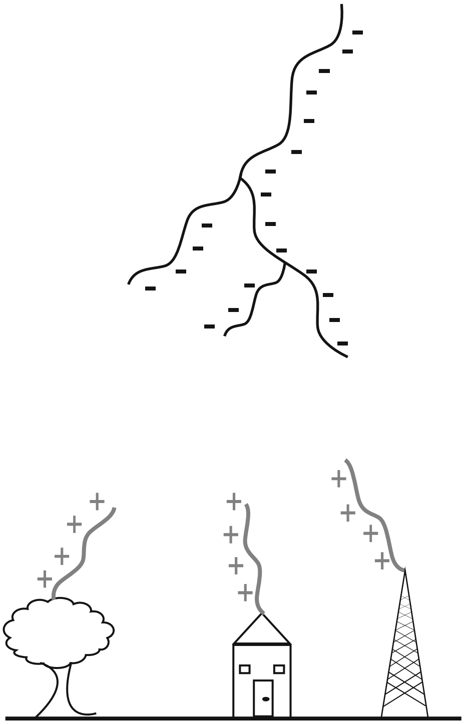


Fig. 7.8 Under the influence of the electric field of the downward moving negative stepped leader, structures at ground level launch positive connecting leaders that attempt to connect with the downward moving stepped leader (Figure created by author)

and its final length depends on several parameters. For a given stepped leader the connecting leader grows longer when the height of the structure from which it issued increases. The reason is that the taller the structure, the higher the electric field at its tip produced by the stepped leader. This is due to the field enhancement caused by the accumulation of positive charge on the structure. Thus, a connecting leader is initiated from a taller structure when the stepped leader is at a greater height from the structure than in the case of a shorter structure. Consequently, a taller structure gives rise to long connecting leaders. For a given structure, the length of the connecting leader increases with increasing charge on the stepped leader. The reason is that a stepped leader with a higher charge can create conditions suitable for the initiation of a connecting leader from the structure when the stepped leader is at a higher height. Thus, connecting leaders generated by either tall structures or stepped leaders with a large charge are longer than connecting leaders generated by either short structures or stepped leaders transporting a small amount of charge.

A connecting leader caused by the electric field of a stepped leader carries a positive charge on it. The average speed of a connecting leader is approximately 10^5–10^6 m/s [14].

Many structures at ground level can issue connecting leaders as the stepped leader approaches ground. The length of the connecting leader may depend on (a) the geometry of the structure, (b) the lateral distance of the stepped leader from the structure, or (c) the ability of the structure to supply the current necessary for the propagation of the connecting leader. Connecting leaders can also be issued from different points of the same structure. Connecting leaders issued from different structures or from different points of the same structure compete with each other to make a connection to the stepped leader.

7.2.3.4 Striking Distance

As the stepped leader approaches ground, the connecting leaders issued from different structures or from different points on the same structure accelerate toward it to make the final connection. However, very soon one of the connecting leaders takes the lead and starts approaching the downward moving stepped leader. As the distance between the tips of the two leaders (i.e., the leading connecting leader and the stepped leader) decreases, the electric field between them increases. When the separation between them reaches a critical distance, the average electric field between the tips of two leaders increases beyond the electric field necessary for streamer propagation (Chap. 2). The propagation of streamers in the intervening region leads to imminent electrical breakdown between the two leader tips, and a connection between them becomes imminent. This condition is called the *final jump condition*, and the distance between the tip of the downward moving stepped leader and the point of origin of the connecting leader at the instant of the final jump condition is called the *striking distance* (Fig. 7.9). Note that the striking distance should increase with increasing charge on the stepped leader channel and should also increase with the height of the structure. The reason for this is that both these conditions promote long connecting leaders (Chaps. 14 and 18).

It is important to note that other definitions have been given to the striking distance. For example, it was defined as the height of the tip of the stepped leader when a connecting leader is generated [15]. But since many connecting leaders are issued from grounded structures, this definition cannot be used to define the striking distance ambiguously.

The preceding sections describe the action of a connecting leader that successfully bridges the gap between a structure (or ground) and a stepped leader. The moment the connection is made between the successful connecting leader and the stepped leader, the resulting return stroke (see the next section) reduces the background electric field significantly, and the other connecting leaders stop their advance because of a lack of electric field to support their propagation.

In the preceding discussion, we tacitly avoided the description of the movement of the connecting leader and the stepped leader at times close to the final jump. For example, what is the direction of propagation of the leaders and to what extent are they influenced by the presence of the other? It is correct to say that both leaders move in the general direction of the highest electric field. Some scientists assume that both the stepped leader and the connecting leader move toward each other at times close to the final jump, whereas others assume that it is the connecting leader that moves toward the stepped leader while the path of the latter is little influenced by the connecting leader. This remains an open question at present in the lightning research community.

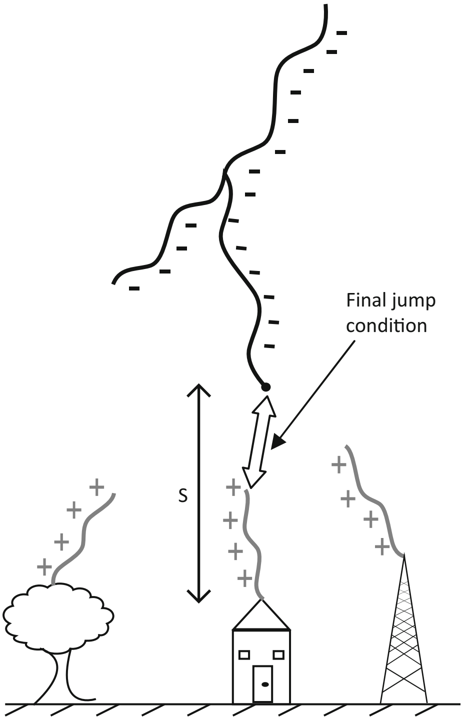


Fig. 7.9 Definition of striking distance. As the connecting leader generated by a grounded structure approaches the downward moving stepped leader, the electric field in the gap between the tips of two leaders continues to increase. When the electric field in the gap reaches a value of approximately 500 kV/m, streamer discharges start moving into the gap, making the final contact imminent. This situation is called a *final jump condition*. The distance to the tip of the stepped leader from the tip of the structure that initiated the connecting leader is the striking distance. In the figure the striking distance is denoted by *S* (Figure created by author)

7.2.3.5 Return Stroke

As explained previously, a connecting leader may successfully bridge the gap between ground and the downward moving stepped leader. The object that initiated the successful connecting leader is the one that will be struck by lightning. Once the connection is made between the stepped leader and ground, a wave of near-ground potential travels along the leader channel toward the cloud, and the associated luminosity event that travels upward at a speed close to that of light in free space is called a *return stroke*. Let us see what happens during this process. The discussion given below is pertinent to a negative return stroke but the physical process is identical but of opposite polarity in positive return strokes. The stepped leader channel is at a potential very close to the cloud potential. For a typical lightning flash this could be approximately 50 MV (Chap. 14). To maintain this potential, it must carry a negative charge along the channel. Now, the ground is at zero potential, and the tip of the connecting leader is also at a potential close to that of the ground. When a connection is made between the connecting leader and the stepped leader, the potential of the first element on the stepped leader that is being "touched" by the connecting leader (i.e., the tip of the stepped leader) changes from the cloud potential to ground potential. As a result, the charge located at that channel element that was necessary to maintain that element at the cloud potential is released, and this charge flows to ground along the connecting leader. Consequently, the potential at the next element on the leader channel that was adjacent to the grounded element also changes and the charge located on it is also released. In this manner a wave of ground potential travels upward and releases the charge bound on the leader channel by the cloud potential. The released charge travels to ground along the stepped leader channel. This flow of charge toward ground generates a large current in the channel, causing it to glow brilliantly as it is being heated. As the charges located at higher and higher levels along the stepped leader join in the dash toward ground, this high current region and the accompanying luminosity move up along the channel. This process of sweeping the electric charge stored on a stepped leader channel to ground is called a *return stroke* (Fig. 7.10).

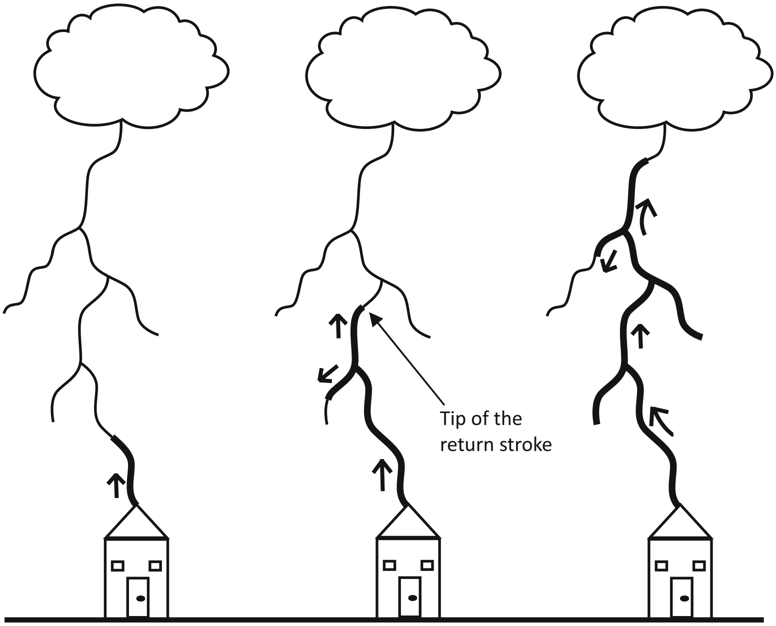


Fig. 7.10 When the downward moving stepped leader meets a connecting leader or a grounded structure (in the figure, the connecting leader is not shown for clarity), a potential discontinuity propagates upward along the stepped leader channel. This upward moving potential discontinuity is called the *return stroke*. The return stroke also moves along the branches of the stepped leader channel. In the case of negative return strokes, electrons move downward along the return stroke channel and the direction of positive current flow associated with the return strokes is as shown in the diagram. An alternative way to visualize the return stroke is to assume that it moves positive charge from ground and deposit it on the leader channel neutralizing the negative charge of the leader (Figure created by author)

In a return stroke initiated by a stepped leader (containing a negative charge), electrons move downward as the return stroke travels upward, much like a tube of sand that has just been opened at the bottom: the action moves up while the sand particles fall down. The speed of upward growth of a return stroke is approximately 10^8 m/s [16]. The rapid flow of electric charge out of the channel and into the striking point generates a large current. The average peak current can be as high as 30,000 A, with individual strikes reaching 80,000 A or more [17]. The total charge brought to ground during a return stroke is approximately 5 C (more details on the properties of return-stroke currents can be found in Chap. 8).

The rapid generation of heat during a return stroke raises the temperature of the air in the discharge channel to approximately 30,000 K in a few microseconds [18]. This temperature is approximately six times higher than that of the surface of the Sun. This almost instantaneous heating of the air in the return-stroke channel causes it to expand with such force that it generates a shock wave in the air. We experience the remnants of this shock wave as thunder.

Usually, a stepped leader consists of several branches, and only one of the branches of a stepped leader reaches the ground first. What happens to the other branches that were making their way through the air toward ground? When the upward moving return-stroke front reaches a branch point in the stepped leader channel, it forms two fronts, one moving along the original direction (i.e., along the main channel) and the other along the branch (Fig. 7.10). When the return stroke moves along a branch (which may still be trying to reach ground), the charges in it stop their abortive attempt to create a path to ground and follow the hot channel of the return stroke to ground. Because the branch is deprived of its electric charge, it cannot develop any further. This current flow from the branch into the main channel gives rise to a sudden increase in the current flow in the main channel. The increase in current flow gives rise to an increase in brightness of the main channel. The increase in the brightness of the main channel that happens when the return-stroke front encounters a branch is called a *branch component*.

The thin bright channel that can be observed by the naked eye during a ground lightning flash is a manifestation of a return stroke. The eye is not fast enough to resolve either the propagation of the return stroke or the short time interval between the passage of the stepped leader and the return stroke. To the naked eye it appears that the whole channel becomes bright simultaneously.

In the previous section it was mentioned that a leader channel consists of a thin core surrounded by a region consisting of defunct streamer discharge channels carrying a charge i.e., a corona sheath. A return stroke travels along the central core of a leader channel. It is this channel whose potential is transferred from cloud potential to ground potential during a return stroke. This change in potential of the central core generates a high electric field on its surface, giving rise to positive streamers. These positive streamers carrying a positive charge move into the corona sheath and neutralize the negative charge on it (Fig. 7.11). As the positive streamers originating from the central core move into the corona sheath, they leave behind a negative charge on the central core. Once released into the central core, the negative charge flows to ground along the return-stroke channel. The net effect is the transfer of negative charge from the corona sheath along the return-stroke channel to ground.

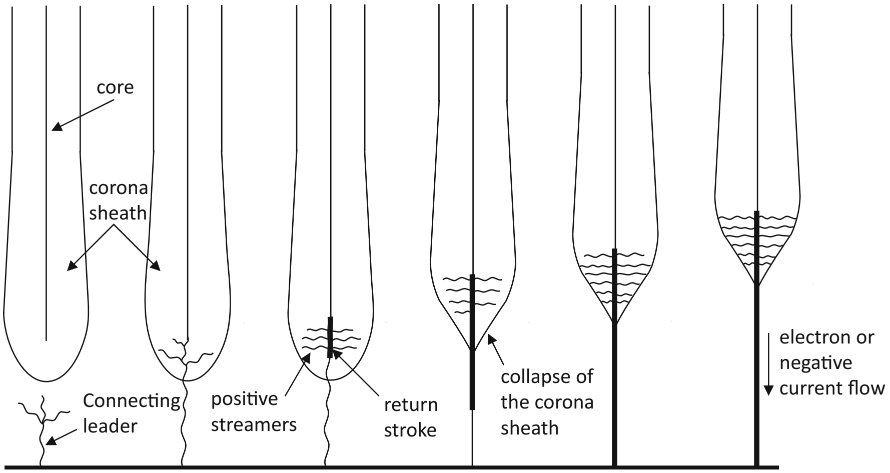


Fig. 7.11 Detailed mechanism of return strokes. A return stroke is initiated when the connecting leader, after penetrating the corona sheath of the stepped leader, meets the hot core of the stepped leader. Initially, the return stroke propagates in two directions, one front toward ground and the other front toward the cloud. As the return stroke passes through the stepped leader channel, it extends positive streamers and neutralizes the negative charge on the corona sheath (i.e., collapse of corona sheath). This process of neutralization proceeds upward, while the electrons released by the neutralization process generate a (negative) current that travels downward (i.e., the positive current travels upward) (Figure created by the author)

One interesting question is whether the return-stroke channel ends up being neutral or charged at the end of the return-stroke process. Actually, whether the channel is charged or not depends on the background electric field present at the moment of the leader propagation. Since the return-stroke channel is near zero potential and is located in the background electric field of the cloud, electric charges are induced in this channel. More charges are induced at higher sections and fewer at lower sections. Thus, in principle, the return-stroke channel ends up being positively charged following the return stroke. The positive charge density is zero close to the ground and increases with increasing height. In other words, the return stroke not only removes negative charge from the stepped leader channel but also deposits a positive charge on it.

It is important to note that positive charges do not move a significant distance during the return stroke. Thus, all charge transfer processes, i.e., removal of negative charge from the leader channel and charging of the return-stroke channel with a positive charge, take place by the removal of electrons from the leader channel.

The active lifetime of a return stroke is approximately a few hundred microseconds. After this time the channel ceases to glow, but it remains hot at a few thousand degrees for several tens of milliseconds. Sometimes, this is the end of the lightning flash, but in many cases events take a more dramatic turn.

7.2.3.6 Recoil Leaders

The arrival of the first return-stroke front at the point of origin of a lightning flash inside the cloud leads to a change in potential in the vicinity of this point. This change in potential may initiate a positive discharge that travels away from the end of the return-stroke channel into the charge center. Recall that as the negative stepped leader was traveling downward toward ground, its positive counterpart was traveling into the negative charge center. From time to time, recoil leaders travel along branches of this positive leader channel toward the flash origin. On occasion, these discharges may die out before they make contact with the cloud end of the return-stroke channel. Such events are called *K changes*. If these discharges make contact with the previous return-stroke channel, which is still hot and therefore a preferable path for an electrical discharge to ground, it will lead to an electrical discharge that travels toward ground. These electrical discharges are called *dart leaders*.

7.2.3.7 Dart Leaders and Dart Stepped Leaders

If the return-stroke channel happens to be in a *partially conducting stage with no current flow* during the arrival of a recoil leader to the flash origin, it may initiate a dart leader that travels along the still hot but defunct return-stroke channel toward ground (Fig. 7.12). Similarly to a stepped leader, it transports a negative charge toward the ground, but unlike a negative stepped leader, its tip travels continuously instead of making steps. The reason for the absence of steps in the dart leader is that the hot, defunct return-stroke channel makes it much easier to create an electrical breakdown at the tip of the dart leader, and the physical process that is needed for a leader to travel in virgin air becomes unnecessary. In a time-resolved photograph, a dart leader appears as a dart that travels toward ground. It has this appearance because most of the electrical activity that gives rise to the generation of light takes place over a few meters of the tip of the dart leader. The length of this bright dart is approximately 10–70 m. Recall that there is a channel connecting this dart to the cloud, and, though not visible, a current flows along this channel as the dart moves forward. Usually, the majority of dart leaders do not create any branches. However, occasionally, a dart leader immediately following the first return stroke may give rise to a few branches. The current associated with the dart leader is approximately 1 kA, and its speed of propagation is approximately 10^7 m/s [19]. As mentioned previously, the dart leader carries a negative charge, and the charge density at the ground end of a typical dart leader is approximately 0.0001–0.00015 C/m [20] (see also Chap. 14).

In some instances, as the dart leader progresses toward ground, it may encounter, especially close to ground, a defunct return-stroke channel section whose ionization has decayed to such an extent that it cannot support the continuous propagation of the dart leader. In this case, the dart leader may start to propagate toward ground as a stepped leader. Such a leader is called a *dart-stepped leader*. Sometimes the lower part of the channel has decayed to such an extent that the dart leader stops *before actually reaching the* ground. These are termed *attempted leaders*.

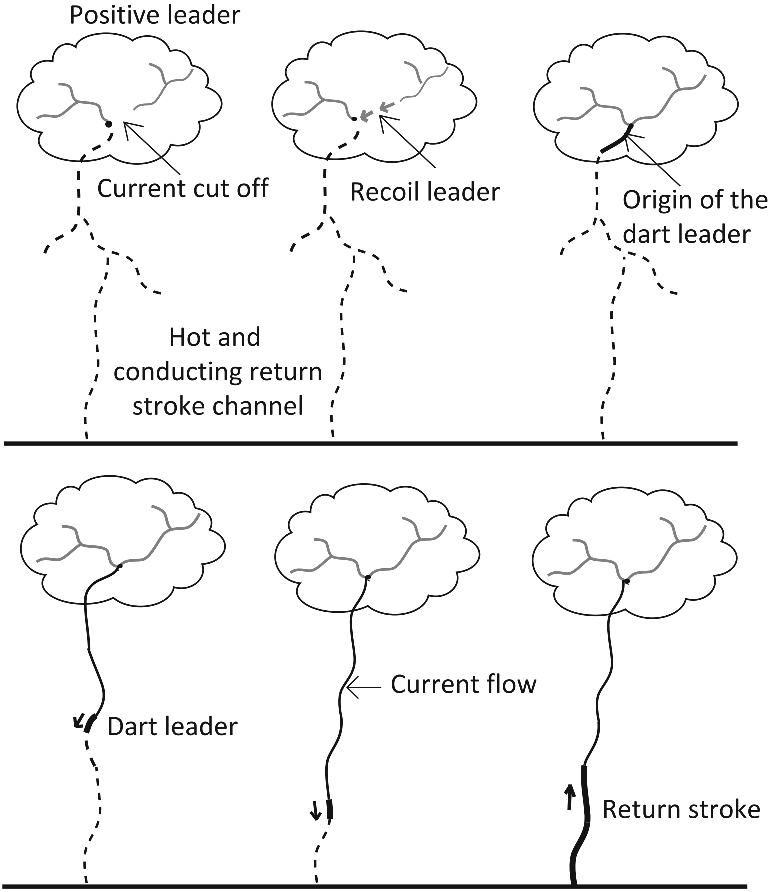


Fig. 7.12 A dart leader originates when a recoil leader generated by a positive branch of a leader meets the hot and conductive (but no current flow) return-stroke channel at the point of origin of the lightning flash. The encounter gives rise to a dart leader that propagates toward ground. Only the region close to the head of the dart leader (a few meters) is bright, even though a current is flowing along the whole channel behind the head of the dart leader. Because of this, the dart leader appears as a bright dart (hence the name) that travels from cloud to ground. The dart leader charges the channel with a negative charge. When the dart leader reaches the ground, a return stroke is initiated (Figure created by author)

7.2.3.8 Subsequent Return Strokes

When the dart leader reaches the ground, another return stroke, called a *subsequent return stroke*, is initiated. Recall that the potential of a dart leader is much greater than the ground potential (though not as high as the potential of the stepped leader because the removal of the charge during the first return stroke reduces the could potential), and the subsequent return stroke is a discharge that transports the ground potential along the channel. The mechanism of charge transfer is identical to that of the first return stroke. However, its speed of upward propagation can be somewhat higher than that of the first return stroke. Since the charge transported by a dart leader is less than that of a stepped leader, the current generated by subsequent return strokes are usually less than that of the first strokes. Typically, the peak current of a subsequent return stroke is approximately 12 kA (see Chap. 8 for more details on subsequent return-stroke currents). When the subsequent return-stroke front reaches the cloud, activity similar to that which occurred after the arrival of the first return stroke at the cloud's end may take place. This activity may cause another dart leader to travel along the subsequent return-stroke channel, leading to another subsequent stroke.

In the literature on lightning, the electrical activity in a cloud that takes place between return strokes are collectively known as *junction processes* or *J processes*. Note also that branch components occur mainly in the first return strokes and occasionally in the first subsequent stroke (i.e., the one immediately following the first return stroke). This is because, in general, dart leaders do not give rise to branches. A typical ground flash may last for approximately 0.2–0.3 s, with a mean number of strokes of between 3 and 4.

7.2.3.9 Continuing Currents

In certain instances when the return-stroke front reaches the flash origin, the electrical activity in the cloud may continue to feed the return-stroke channel with a low-level current for a long duration. These currents are called *continuing currents*. Continuing currents may last anywhere from 10 ms to hundreds of milliseconds, and the current flowing along the channel may have magnitudes in the range of several tens to hundreds of amperes [21, 22]. In many cases, continuing currents are initiated by subsequent strokes, and on average the percentage of lightning flashes that support continuing currents is approximately 30–50 % [23].

7.2.3.10 M-Components

If the return-stroke channel happens to be carrying a continuing current at the time of arrival of a recoil leader to the flash origin, the encounter results in a discharge that travels toward the ground along the channel supporting the continuing current (Fig. 7.13). These discharges are called *M-components*. When M-components reach the ground, no return strokes are initiated, but recent analyses of the electric fields generated by M-components show that the current wave associated with them may reflect from the ground [24].

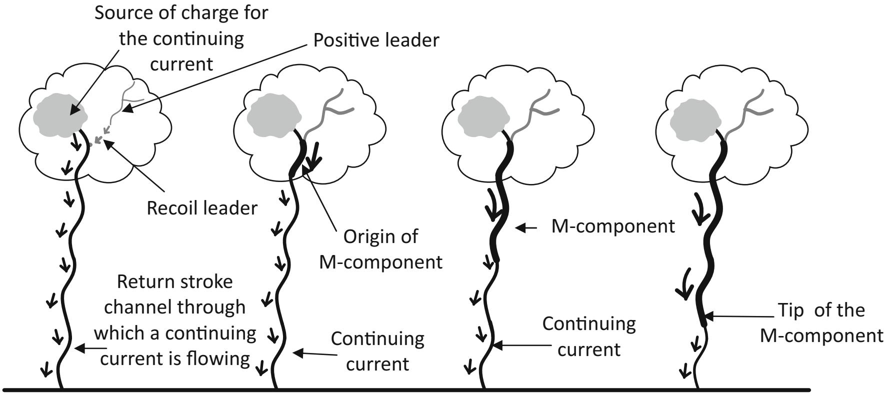


Fig. 7.13 M-components are created in return-stroke channels through which a continuing current is flowing. A recoil leader generated by a branch of a positive leader with a current cutoff makes a connection with the return-stroke channel through which a continuing current flows. The interaction gives rise to an enhancement of the current flow in the channel, and this disturbance (or the current pulse) travels toward ground along the return-stroke channel. This is called an *M-component*. Research has shown that when an M-component reaches the ground, the current pulse associated with the M-component is reflected at ground end with a reflection coefficient equal to approximately one (Figure created by author)

7.2.4 Mechanism of Cloud Flashes

Cloud flashes normally occur between the main negative and upper positive charge of a cloud. Most of the information available today on the mechanism of cloud flashes is based on electric field measurements. More recently, scientists have made important discoveries utilizing very high-frequency (VHF) radio imaging techniques [8, 9, 25]. The following description of a cloud flash is based on these observations (Fig. 7.14).

A cloud flash commences with a movement of negative discharges from the negative charge center toward the positive one in a more or less vertical direction. The vertical channel develops within the first 10–20 ms from the beginning of the flash. This channel is a few kilometers in length and developed at a speed of approximately 1.5×10^5 m/s. Even after the formation of the vertical channel, it is possible to detect an increase in the electrostatic field, which is indicative of a negative charge transfer to the upper levels along the vertical channel.

The main activity following the formation of a vertical channel is the horizontal extension of channels in the upper level (i.e., channels in the positive charge center). These horizontal extensions of the upper-level channels are correlated to brief electrical breakdowns at the lower levels, followed by discharges propagating from the lower level to the upper level along the vertical channel. Thus, upper-level breakdown events are probably initiated by electric field changes caused by the transfer of charges from lower levels. For approximately 20–140 ms of a cloud flash, repeated breakdowns occur between the lower and upper levels along the

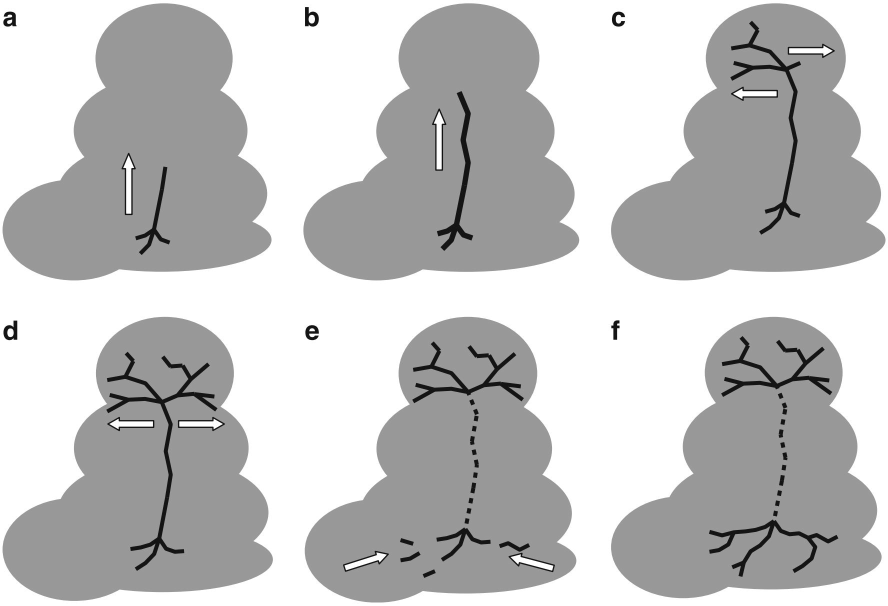


Fig. 7.14 Mechanism of a cloud flash. The cloud flash commences with a movement of negative discharges from the negative charge center toward the positive one in a more or less vertical direction. This is the initial stage (**a**, **b**). This stage is followed by an active stage in which horizontal extension of the upper-level channels takes place while charge is being transported from the lower level to the upper level along the vertical channel (**c, d**). In the latter part of this active stage, significant extensions of the lower-level channels take place, but the extensions take place retrogressively (**e**). In the final stage, the conductivity of the vertical channel decreases and the upper-level channels are cut off from the low-level channels (**f**). The *arrows* indicate the general direction of the discharge development (Figure created by author)

vertical channel. These discharges transport negative charges to the upper levels. Breakdown events of this type can be categorized as *K changes*. In general, the vertical channels through which these discharges propagate generate no radiation in the radio frequency range, indicating that they (i.e., the vertical channels) are conducting. This is so because, in general, conducting channels do not generate radio frequencies as discharges propagate along them. Occasionally, however, a discharge makes the vertical channel visible at radio frequencies, and then propagation can be observed at a speed of approximately (5–7) $\times 10^6$ m/s, which is typical of K changes. This active stage of discharge may continue for up to approximately 200 ms.

In the latter part of this active stage (140–200 ms), significant extensions of the lower-level channels (i.e., channels in the negative charge center) take place, but they occur retrogressively. That is, successive discharges, or K changes, often start just beyond the outer extremities of the existing channels and then move into and along these channels, thereby extending them further. These K changes transport negative charges from successively longer distances to the origin of the flash, and sometimes even to the upper level of the cloud flash, as inferred from radio frequency emissions from the vertical channel. Sometimes, these K changes give rise to discharges that start at the origin of the flash and move away from it toward the origin of the K changes. Such discharges can be interpreted as positive recoil events that transport positive charges away from the flash origin and toward the point of initiation of the K change.

In the final part of the discharge, the vertical channel and the upper-level channels are cut off from the lower-level channels. This is probably caused by a decrease in the conductivity of the vertical channel.

7.2.5 Mechanism of Upward Initiated Lightning Flashes

The basic features of an upward initiated lightning flash are shown in Fig. 7.15. Consider a tall structure similar to that of a telecommunications mast. Consider a situation when this tower is located under a growing thundercloud. As the charging process inside the cloud intensifies, the electric field strength below the cloud increases. Because of the geometry of the tower, this background electric field strength increases by several tenfold or even several hundredfold at the tip of the tower. If this electric field exceeds a critical value over a critical distance, it will give rise to a positive leader (similar to a connecting leader) that travels toward the cloud (see Chap. 2 for details concerning the initiation of positive leaders). When it reaches the cloud, it makes a connection with the charge centers, and a current similar to a continuing current starts to flow along this channel to ground. Once this continuing current ceases, dart leaders may travel along the channel, initiating return strokes. The only difference between this lightning flash and a normal lightning flash is the absence of a stepped leader and the first return stroke and the presence of a continuing current at the beginning of the flash. The processes taking place during the dart leader–return stroke sequences are identical to those of normal lightning flashes.

7.2.6 Mechanism of Positive Ground Flashes and Their Main Difference with Negative Ground Flashes

Positive ground flashes transport positive charges from cloud to ground. A positive flash usually originates at a point close to the positive charge center. As in the case of a negative ground flash, the leader is bidirectional, but in this case the negative leader end travels toward the positive charge center while the positive leader end travels toward ground. Usually, positive ground flashes originate from positive charge centers displaced laterally from the negative charge center as a result of wind shear [26]. This makes it possible for a positive leader to propagate unhindered by the negative charge center, which otherwise would have interacted with the positive leader to generate a cloud flash. As is typical for leaders carrying a positive charge,

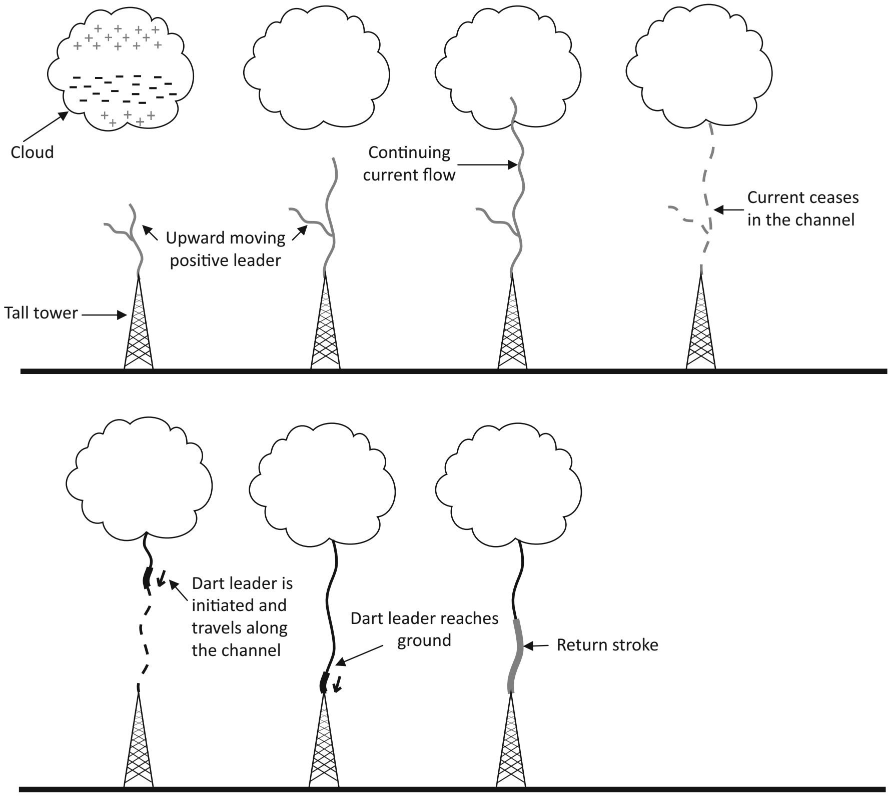


Fig. 7.15 Mechanism of upward initiated lightning flashes. Under the influence of the electric field created by a thundercloud, a leader (the polarity depends on the electric field, but let us assume it to be a positive leader) is generated from a tall structure. It travels upward (sometimes creating branches that are directed upward) toward the cloud. Once it reaches the cloud, a continuing current may start to flow along the channel to ground. After several to many tens of milliseconds the continuing current ceases. At this stage, because of the action of a recoil leader, a dart leader is created in the channel. This dart leader travels toward ground, and when it reaches the ground, a return stroke is initiated. This dart leader–return stroke process may be repeated several times in the channel (Figure created by author)

the positive leader travels more or less continuously toward ground, but the channel luminosity may change from time to time during its propagation. For this reason the term *stepped leader* is reserved for the first leaders associated with negative ground flashes. A positive leader may generate large amounts of very faint branches as it travels toward ground, and from time to time bright recoil leaders travel along these branches toward the main channel [27]. The luminosity variation observed during the propagation of a positive leader may be a result of this action of recoil leaders (Sect. 7.2.2). As the leader approaches the ground, a negative connecting leader is issued from a grounded structure, and this leader may show stepping behavior typical of negative leaders. When a negative connecting leader meets the downward moving positive leader, a return stroke is issued, and the mechanism of the return stroke is identical to that of a negative return stroke.

Experimental data show that positive lightning flashes seldom support subsequent return strokes. Most flashes contain only one return stroke. Positive return strokes may harbor very large peak currents (on the order of 200 kA) and the duration of positive currents could be much longer (several milliseconds) than those of negative return strokes (Chap. 8). The reason for the single-stroke nature of positive lightning flashes could be that the cloud-probing leader of positive flashes is a negative one, and, unlike positive leaders, negative leaders are not hindered by current cutoff (which leads to recoil leaders). Thus the current continues to flow during the return stroke until the charge reservoir is depleted.

7.3 Nomenclature of Ground Lightning Flashes

Lightning ground flashes can be divided into two types based on the point of initiation. If the point of initiation of a lightning ground flash is in a cloud, then it is categorized as a downward flash. If it initiates by a structure at ground level, it is called an upward lightning flash. Depending on the polarity of the charge brought to ground, both types can be further subdivided into positive and negative polarities. These categories are illustrated in Fig. 7.16. Typical parameters of negative ground flashes are summarized in Table 7.1.

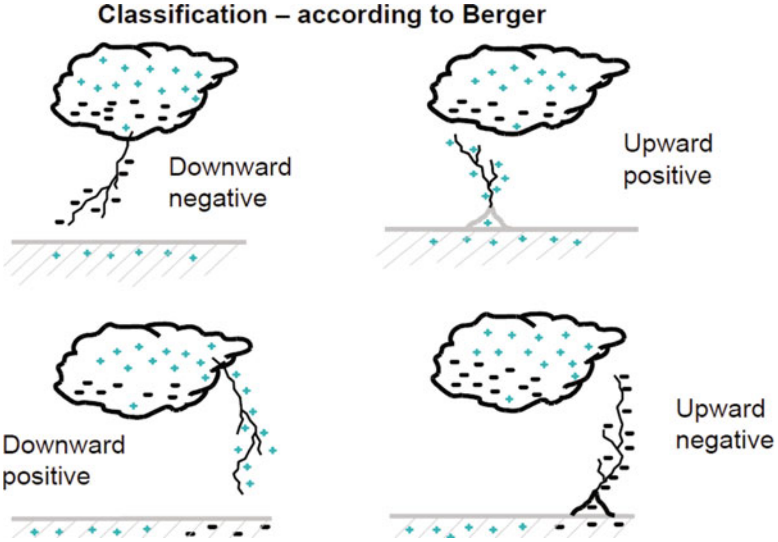


Fig. 7.16 Four categories of lightning ground flashes (Adapted from Berger [28]). Whether the lightning flash is termed up or down is determined by the direction of the leader; the polarity is determined by the charge on the leader channel

Table 7.1 Typical parameters of lightning flashes

Parameter	Typical value or range
Duration of lightning flash	200–300 ms
Number of return strokes per flash	3–4
Time interval between strokes	40–60 ms
Percentage of flashes with single strokes	20 %
Speed of stepped leaders	3×10^5 m/s
Length of steps of stepped leaders	10–100 m
Time interval between steps of stepped leaders	10–100 μs
The charge per unit length on the stepped leader (close to ground end)	0.001 C/m
Peak current in first return stroke	30 kA
Rise time of current of first return strokes	5 μs
Rate of change of current of first return strokes	10–20 kA/μs
Charge associated with first return stroke	5 C
Speed of dart leaders	10^7 m/s
Length of dart of dart leader	10–70 m
Charge on dart leader	1 C
Peak current of subsequent strokes	12 kA
Rise time of current of subsequent strokes	0.5 μs
Rate of change of current of subsequent strokes	50–100 kA/μs
Charge associated with subsequent strokes	1 C
Percentage of flashes with continuing currents	30–50 %
Duration of continuing currents	100 ms
Amplitude of continuing currents	100–200 A
Peak current of M-components	100–200 A
Rise time of M-component current	400 μs
Duration of M-component current	2 ms

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