Chapter 2
Basic Physics of Electrical Discharges

2.1 Introduction

The main constituents of air in the Earth's atmosphere are nitrogen (78 %), oxygen (20 %), noble gases (1 %), carbon dioxide (0.97 %), water vapor (0.03 %), and other trace gases. Because of the ionization of air by the high-energy radiation of cosmic rays and radioactive gases generated from the Earth, each cubic centimeter of air at ground level contains approximately ten free electrons. In general, air is a good insulator and it can retains its insulating properties until the electric field to which it is exposed to exceeds approximately 3×10^6 V/m at standard atmospheric conditions (i.e., $T = 293$ K and $P = 1$ atm). When the electric field exceeds this critical value, air is converted very rapidly into a conducting medium, making it possible for electrical currents to flow through it in the form of sparks. Let us now consider the basic processes that make possible the conversion of air from an insulator into a conductor and the different types of discharge that take place in air under various conditions.

2.2 Beginning of an Electrical Discharge – Electron Avalanche

As mentioned previously, because of cosmic radiation, there are approximately ten free electrons at any given time in a cubic centimeter of air at ground level. These free electrons are generated continuously. As they are generated they remain free for only a very short time (on the order of tens of nanoseconds) because they become attached to oxygen molecules in the air. When an electric field is applied in air, all ions and free electrons experience a force due to the electric field. Because of their small mass, the electrons accelerate rapidly, gaining energy. As they accelerate, they collide with other atoms and molecules, and part of the energy

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gained is transferred to these atoms and molecules. Of course, during this process some electrons are captured by oxygen atoms. If the electric field is kept constant, then the electrons soon reach a constant speed; this speed is called the *drift speed*. For a given type of charged particle, the drift speed is a function of the electric field. The drift speed increases as the applied electric field increases. As the electric field increases, the energy gained by the electrons increases, and a stage is reached where the electrons gain so much energy that they start ejecting other electrons from atoms during collisions. For example, to eject an electron from an oxygen atom, one needs approximately 13 eV. Let us start with one electron that has enough energy to knock another electron out of an atom. During a collision with another atom this electron generates another electron. Now both electrons start accelerating in the electric field. When they gain sufficient energy from the field, they give rise to two more electrons, bringing the total number of electrons to four. As illustrated in Fig. 2.1, the continuation of this process leads to a stream of electrons moving in the opposite direction of the electric field (electrons, because of their negative electric charge, move in a direction opposite to the direction of the electric field). While this process of electron accumulation is going on, the process of electron attachment, mainly to oxygen molecules in the air, is also taking place. The process of attachment can be considered as a process that impedes the increase of free electrons in the air because it gives rise to slow moving negative ions that are incapable of ionization as electrons.

Now let us describe the foregoing process mathematically. Assume that a free electron is generated at a given point and starts moving in the background electric field, generating more electrons (Fig. 2.1). The electric field is directed along the

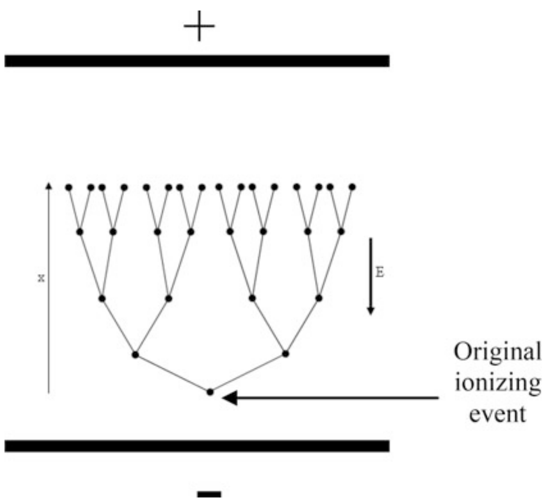

Fig. 2.1 Formation of an electron avalanche. An electron moving in a background electric field gains enough energy to release another electron from an atom during collision. This event is marked as the original ionizing event in the figure. These two electrons accelerate in the background electric field and give rise to two more electrons through collisional ionization. The process repeats itself, giving rise to a cumulative increase in the number of electrons. In the diagram, the locations of electrons are displaced laterally for clarity (Figure created by author)

negative x-axis. First the electron gains the energy necessary to ionize, and following ionization, there are two electrons. These two electrons now move in the electric field, gaining energy, and once they ionize, they generate four electrons. This shows that the electrons must move a certain distance, say λ, in the electric field before they gain enough energy to ionize. Consequently, when an electron travels a unit distance along the electric field, it gives rise to $1/\lambda$ free electrons. Let us represent this number by the symbol α. Since each new electron created takes part in the ionization process, the number of electrons n present when the first electron travels a distance x is (note that it is not equal to αx!)

$$n = e^{\alpha x}. \tag{2.1}$$

Observe that, according to this equation, the number of electrons increases exponentially with distance. This rapid increase in the number of electrons is called an *electron avalanche*. But this is not the whole story. We must consider the effect of the attachment of electrons to oxygen molecules. Let us denote by η the number of attachments that takes place per unit length traveled by an electron. Then the total number of electrons reaching distance x is given by

$$n = e^{(\alpha - \eta)x}. \tag{2.2}$$

This equation describes completely the growth of electrons in an electron avalanche. This is the first or basic element of an electrical discharge. Now, before proceeding further, we must understand the parameters that control the value of α and η. Experiments and theory show that they are both determined by the electric field (E) and the gas density (δ). Actually, they depend on the ratio of the electric field to the gas density, that is, on E/δ. The value of α increases with increasing E/δ, and η decreases with it. Now, a closer look at the equation shows that the number of electrons increases with distance only when $\alpha > \eta$. For small values of E/δ, $\alpha < \eta$, and the avalanche does not grow. However, for large values of E/δ, $\alpha > \eta$, and the avalanche grows cumulatively, increasing the number of electrons with distance. The critical value of E/δ where the transition takes place is equal to 1.04×10^{-19} Vm^2. For atmospheric density at sea level (2.7×10^{25} molecules/m^3) the value of the electric field corresponding to it is 2.8×10^6 V/m. In practical applications it is common to assume that this critical value is 3.0×10^6 V/m. This is why the electric field in atmospheric air should increase beyond this value for an electrical breakdown to take place. This also shows that with decreasing density, a smaller electric field is needed to cause a breakdown. For example, the critical electric field, E, necessary for an electrical breakdown of air of density δ is given by

$$E = E_o \frac{\delta}{\delta_o}, \tag{2.3}$$

where δ_o is the density of air at sea level under standard atmospheric conditions and E_o is the corresponding critical electric field necessary for an electrical breakdown under the same conditions. Since the density of air in the Earth's atmosphere decreases with height, z, as $\delta = \delta_o e^{-z/\lambda_p}$, with $\lambda_p \approx 7.64 \times 10^3$, the critical electric field necessary to cause an electrical breakdown in the atmosphere decreases with height as

$$E = E_o e^{-z/\lambda_p}. \tag{2.4}$$

2.3 Electrical Discharges Consist Only of Electron Avalanches

Consider a lightning conductor or any other object in the electric field of a thundercloud. When a conducting object is placed in a background electric field, the electric field at the sharp points on the object becomes many times larger than the background electric field because of the separation of electric charge along the object. The longer the conductor or the sharper the pointed tip is, the larger the electric field will be at the tip. Because of this field enhancement of the conductor, the electric field is very high close to the tip of the conductor and decreases rapidly as one moves away from the tip (Fig. 2.2). If the background electric field is large enough, it is possible that over a certain region around the tip of the conductor the electric field will exceed the critical electric field necessary for electrical breakdown. Thus, any free electron generated in this volume gives rise to electron avalanches. As a consequence, the localized space where the electric field exceeds the breakdown value is filled with electron avalanches. In Fig. 2.2 this boundary is located at a distance of 0.1 m (marked x_c in the diagram) from the tip of the conductor. The avalanches do not extend further into the field region, where the electric field is smaller than 3×10^6 V/m, because in this region the coefficient of attachment η is higher than the coefficient of ionization α, leading to their decay.

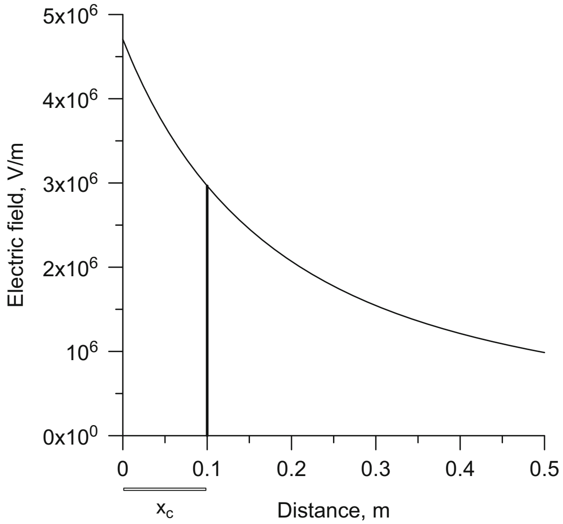

Fig. 2.2 The electric field in front of a 0.2-m-thick, 20-m-long grounded conductor immersed in a background electric field of 10^5 V/m. In the diagram, x_c is the distance from the tip of the conductor within which the electric field exceeds the breakdown electric field in air at standard atmospheric pressure (Figure created by author)

This is the most basic form of electrical discharge that can occur in nature, and it is called a *corona discharge*. Inside the discharge volume, the ionization and deionization of atoms cause light emissions, and in the dark this region can be perceived as a glowing region. When this happens below a thundercloud as a result of the thundercloud electric field, it is called *St. Elmo's fire*. It was observed at the tip of the masts of boats during thundery weather, and sailors interpreted it as a sign from the patron saint of the sailors, St. Elmo.

Now, in the corona discharge described above, the volume of the discharge is limited by the confinement of the high electric field region to a small volume. What happens if the high electric field extends over a much larger space in the air? Does the electron avalanche continue to grow with the number of electrons at its head, reaching an extremely high number? We consider this question in the next section.

2.4 Streamer Discharges – Avalanche to Streamer Transition

The analysis given in Sect. 2.2 shows that as the avalanche increases in length (i.e., increase x in Eq. 2.1), the charge accumulated at the head of the avalanche increases. As a result, the electric field produced by this charge located at the head of the avalanche also increases as the avalanche moves forward. If the background electric field continues to support the growth of the avalanche, a situation arises in which the electric field produced by the charge located at the avalanche head overwhelms the critical electric field necessary for electrical breakdown in the medium. At this stage the electric field produced by the charges located at the avalanche head, i.e., the space charge electric field, starts influencing the ionization processes taking place in the vicinity of the avalanche head. When this stage is reached, the avalanche is converted into a streamer discharge. The exact mechanism of the formation of a streamer discharge from an avalanche depends on the polarity of the source that generates the background electric field. First, consider a source at positive polarity. That is, the electric field generated by the source is such that the electrons are attracted to it. The source could be a charged hail particle in a background electric field of a thundercloud, a Franklin rod exposed to the background electric field of a thundercloud, or a high-voltage electrode. For clarity we refer to it as the *anode*.

If the electric field in front of the anode is high enough, a photoelectron (an electron ejected from an atom by a high-energy photon) generated at a point located in front of the anode initiates an avalanche that propagates toward the anode. The process is depicted in Fig. 2.3. As the electron avalanche propagates toward the anode, an immobile (stationary with respect to the fast moving electrons) positive space charge accumulates at the avalanche head. When the avalanche reaches the anode, the electrons are absorbed into it, leaving behind the net positive space charge. Because of the recombination of positive ions and electrons, the avalanche head is a strong source of high-energy photons. These photons create other avalanches in the

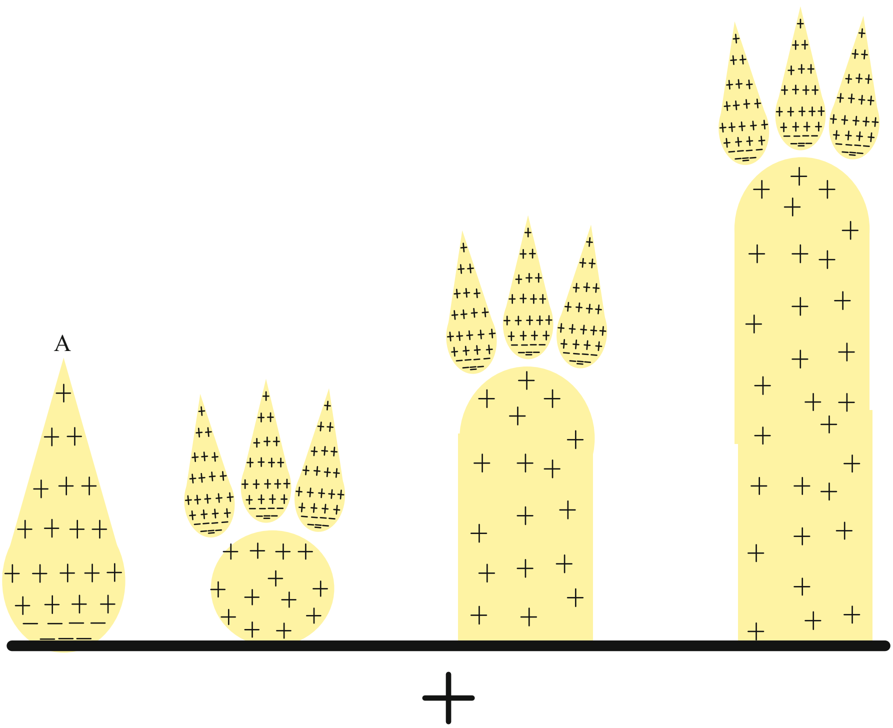

Fig. 2.3 Mechanism of positive streamers. A photoelectron generated at a point located in front of the anode (*point A*) initiates an avalanche that propagates toward the anode. When the avalanche reaches the anode, the electrons are absorbed into it, leaving behind the net positive space charge. If the number of positive ions in the avalanche head is larger than a critical value, secondary avalanches created by the photons are attracted toward the positive space charge. The positive space charge is neutralized by the electrons in the secondary avalanches, creating a weakly conducting channel. Consequently, a part of the anode potential is transferred to the channel, making it positively charged and increasing the electric field at the tip. The high electric field at the tip attracts more electron avalanches to it, and the channel grows as a consequence (Figure created by author)

vicinity of the positive space charge. If the number of positive ions in the avalanche head is larger than a critical value, then the electric field created by the space charge becomes comparable to or overwhelms the critical electric field necessary for breakdown. As a result, the secondary avalanches created by the photons are attracted to the positive space charge. The electrons in the secondary avalanches are neutralized by the positive space charge of the primary avalanche, leaving behind a new positive space charge not too far from the anode. Furthermore, the neutralization process leads to the creation of a weakly conducting channel, and part of the anode potential is transferred to this channel, making it positively charged and increasing the electric field at the tip. The high electric field at the tip of this weakly conducting channel attracts more electron avalanches to it, and the resulting neutralization process causes the weakly conducting channel to extend in a direction away from the anode. This discharge, which travels away from the anode, is called a *positive streamer*.

Now let us consider a source of negative polarity, i.e., a *cathode*. A photoelectron created close to the cathode generates an avalanche (primary avalanche) that moves away from the cathode, leaving behind positive charge close to it. The process is depicted in Fig. 2.4. When the avalanche reaches a critical size, the positive charge of the avalanche starts attracting secondary avalanches to it. As in the case of a positive streamer, the electrons in the secondary avalanches neutralize this positive charge,

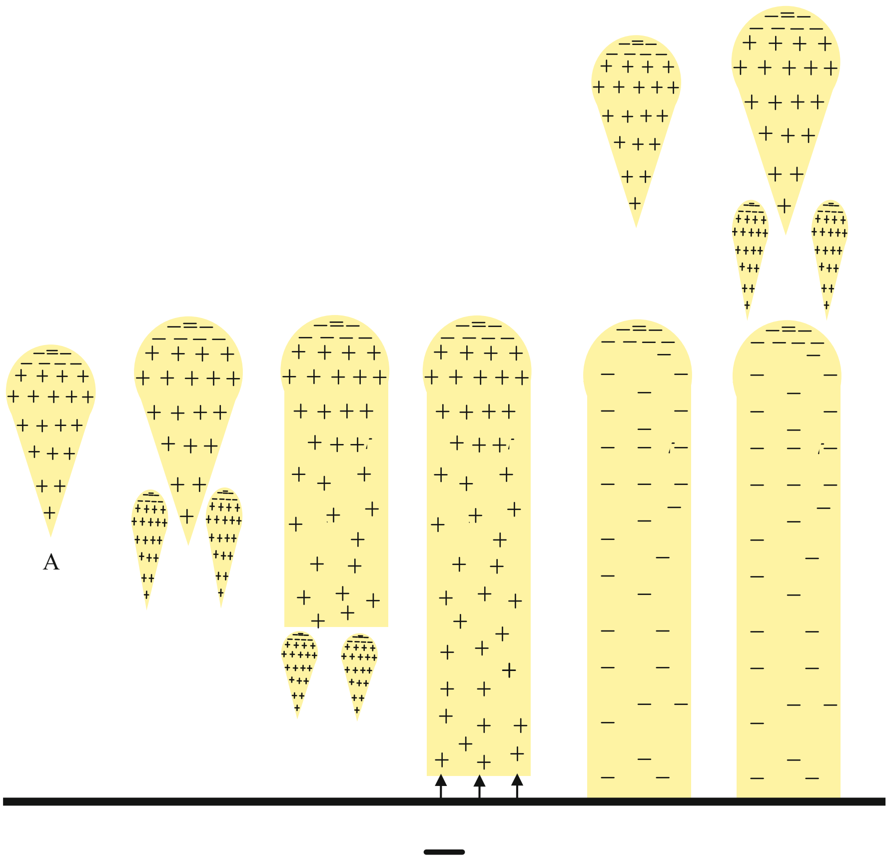

Fig. 2.4 Mechanism of negative streamers. A photoelectron generated close to the cathode (*point A*) generates an avalanche that moves away from the cathode, leaving behind a positive charge close to it. When the avalanche reaches a critical size, the positive charge of the avalanche starts attracting secondary avalanches to it. As in the case of positive streamers, the electrons in the secondary avalanches neutralize this positive charge, effectively moving it toward the cathode. When the positive charge reaches the cathode, the field enhancement associated with the proximity of positive space charge to the cathode leads to the emission of electrons from the latter. These electrons will neutralize the positive space charge, creating a weakly conducting channel that connects the negative head of the electron avalanche to the cathode. Part of the cathode potential will be transferred to the head of this weakly ionized channel (i.e., negative streamer), increasing the electric field at its head. This streamer head now acts as a virtual cathode, and the process is repeated. Repetition of this process leads to the propagation of the negative streamer away from the cathode (Figure created by author)

effectively moving it toward the cathode. When the positive charge reaches the cathode, the field enhancement associated with the proximity of positive space charge to the cathode leads to the emission of electrons from the cathode. These electrons neutralize the positive space charge, creating a weakly conducting channel that connects the negative head of the electron avalanche to the cathode. As a consequence, a part of the cathode potential is transferred to the head of this weakly ionized channel (i.e., *negative streamer*), increasing the electric field at its head. This streamer head now acts as a virtual cathode, and the process is repeated. Repetition of this process leads to the propagation of the negative streamer away from the cathode.

If the background electric field is very high, the positive space charge of the primary avalanche may reach the critical size necessary for streamer formation before reaching the anode. This may lead to the formation of a bidirectional discharge whose two ends travel toward the anode and the cathode, the former as a negative streamer and the latter as a positive streamer. Such a discharge is called a *midgap streamer* (Fig. 2.5).

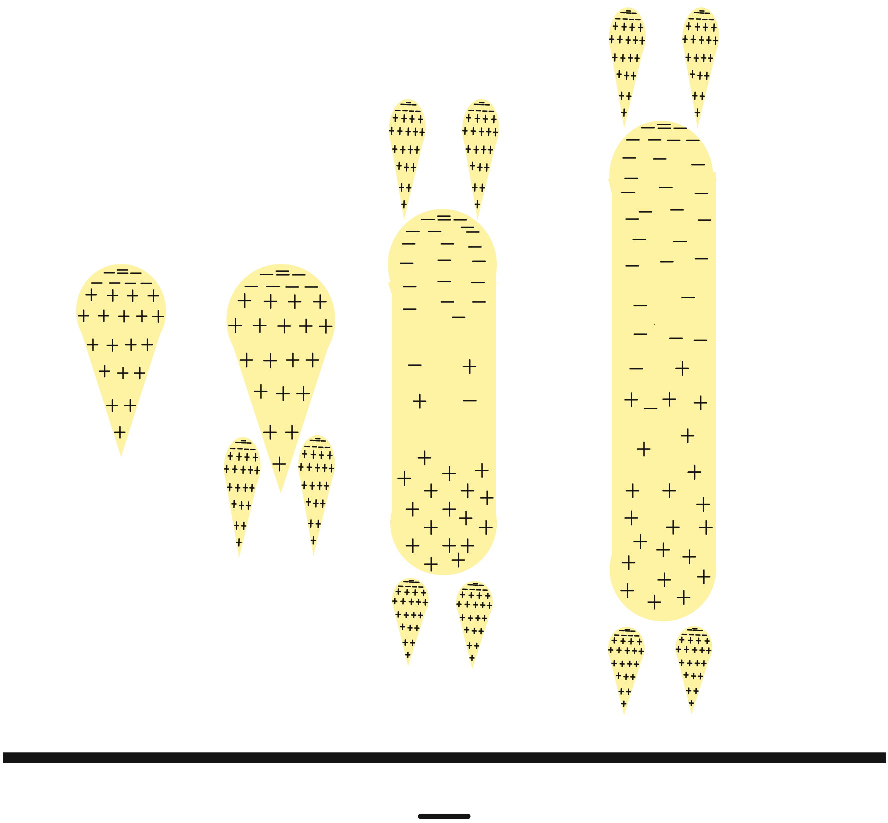

Fig. 2.5 Mechanism of midgap streamers. If the background electric field is very high, then the positive space charge of the primary avalanche may reach the critical size necessary for streamer formation before reaching the anode (compare this picture with that in Fig. 2.3). This may lead to the formation of a bidirectional discharge whose two ends travel toward the anode and the cathode, the former as a negative streamer and the latter as a positive streamer (Figure created by author)

So far we have not discussed the exact conditions under which an avalanche is converted into a streamer. As was mentioned earlier, the avalanche-to-streamer transition takes place when the number of charged particles at the avalanche head exceeds a critical value, N_c. From cloud chamber photographs of avalanches and streamers, Raether [1] estimated that an avalanche converts into a streamer when the number of positive ions in the avalanche head reaches a critical value of approximately 10^8. A similar conclusion was also reached independently by Meek [2]. On the other hand, Bazelian and Raizer [3] suggest 10^9 as a reasonable value for this transformation. Thus, the condition for the transformation of an avalanche into a streamer can be written as

$$e^{\int_0^{x_c}[\alpha(x)-\eta(x)]dx} = 10^8 - 10^9. \tag{2.5}$$

Note that in writing down the preceding equation it is assumed that the electric field is not uniform, and therefore both α and η are functions of distance. Moreover, in the preceding equation, the distance x is measured from the origin of the avalanche, and x_c is the distance from the origin of the avalanche where the background electric field goes below the critical value necessary for electrical breakdown. In the electric field shown in Fig. 2.2, the region where the foregoing integration should be performed is marked x_c.

The advancement of the streamer in a given background electric field is based on the distortion of the electric field at the streamer head and the enhanced production of energetic photons from the streamer head. These energetic photons create secondary electrons in front of the streamer head, and the secondary electrons give rise to secondary avalanches that move, in the case of positive streamers, toward the streamer head. Once initiated, the streamers have been observed to travel in background electric fields that are not large enough to support avalanche formation. Secondary avalanche formation in a streamer is confined to a very small region around the streamer head where the electric field exceeds 2.8×10^6 V/m, which is the minimum electric field required for cumulative ionization in air (or the formation of avalanches) under standard atmospheric conditions. This region is called the *active region*. The dimension of the active region is approximately 200 μm, and the streamer radius was found to be on the order of 10–50 μm [4, 5]. This value, however, may correspond to short streamers. Since electron multiplication in the active region is supported by the space charge electric field of the streamer head, the streamer can propagate in electric fields that are much smaller than the critical electric field necessary for cumulative electron ionization. In air, the background electric field necessary for positive streamer propagation lies in a range of $4.5–6 \times 10^5$ V/m [6–8]. For negative streamers it lies in a range of $1–2 \times 10^6$ V/m. Any variation in the electron loss processes, such as electron attachment and gas density, can change this electric field. For example, when air is saturated with water vapor, the critical electric field necessary for positive streamer propagation grows from 4.7×10^5 V/m at a humidity of 3 g/m^3 to 5.6×10^5 V/m at a humidity of 18 g/cm^3 [8–10]. The critical electric field necessary for streamer propagation decreases approximately linearly with decreasing air density [3, 10].

In background electric fields close to the critical value necessary for streamer propagation, streamer speed is approximately 10^5 m/s. However, the streamer speed increases with increasing background electric field. Another interesting physical parameter pertinent to streamers is the potential gradient along the streamer channel. No direct measurements are currently available on the potential gradient of streamer channels. Experiments conducted with long sparks show that the average potential gradient of an electrode gap when the positive streamer bridges the gap between the two electrodes is approximately 5×10^5 V/m [11]. This indicates that the potential gradient of positive streamer channels in air at atmospheric pressure is close to this value. Note that this value is approximately the same as the critical electric field necessary for the propagation of positive streamers.

2.5 Corona Discharges Consisting of Both Avalanches and Streamer Discharges

Let us consider again a lightning rod placed in the background electric field of a thundercloud or a stepped leader (described in Chap. 7) coming down from a thundercloud. Assume that at any given instant the electric field exceeds the breakdown electric field in a certain region around the conductor. Let us assume that this high field region extends to a distance of r_0 in front of the conductor tip. Consider a free electron created at the edge of this region, that is, at a distance of r_0 from the conductor. This electron gives rise to an electron avalanche that travels toward the tip of the lightning conductor. As it travels toward the tip of the conductor, the number of electrons at the head of the avalanche increases. When the electrons reach the conductor, they are absorbed into it, leaving behind a blob of positive space charge in front of the conductor. If the background electric field is large enough or the distance to the outer boundary is large enough, this space charge gives rise to a streamer (as explained in the previous section) that starts propagating away from the tip of the conductor. Actually, when this condition is reached, many of the avalanches traveling toward the lightning conductor give rise to streamers, and there is a burst of streamers that start propagating away from the tip of the conductor. These streamers do not stop at the boundary defined by the radius r_0 because the critical electric field they need for their propagation is smaller than the electric field at radius r_0. Thus, they continue to propagate into the low field region where the electric field is less than the breakdown electric field. Actually, they propagate until they completely exhaust the available potential difference. The way to estimate the distance the streamers travel, i.e., the length of the streamers, is described in the next section.

In the situation described previously, both avalanches and streamer discharges are found in the high field region surrounding the conductor. Now, it is possible to understand what happens at the tip of a lightning conductor (or any other structure for that matter) when the background electric field continues to increase with time as happens, for example, just before a lightning strike. As the electric field continues to increase, first electron avalanches are created in the vicinity of the conductor tip. As the electric field increases further, the discharge process changes, and streamers are created. These streamers travel a greater distance than the boundary of the region of space where the electric field is confined to 3×10^6 V/m. In the literature, this process is called *streamer inception* from the tip of the lightning rod. Now, let us see how to evaluate the extension of the streamer region and the charge generated by streamers.

2.6 Extension and Charge of Streamer Discharge

Earlier it was mentioned that streamers propagate until they completely exhaust the available potential difference for propagation. The potential difference in front of a grounded lightning conductor in the presence of a uniform background electric field is shown in Fig. 2.6. The potential is zero at the tip of the conductor and increases as the point of observation moves away from the tip of the conductor. Initially it increases rapidly but then levels off as the electric field becomes smaller. Of course, it will not become constant because there is a background electric field. Now, recall that as a streamer moves in this background potential, it maintains a constant potential difference of 5×10^5 V per meter of its length. Thus, it moves to a point located at a distance, say d, such that the potential at that point is $d \times 5.0 \times 10^5$ V. In the distance–voltage diagram, the extension of the streamer can be obtained by drawing a straight line with a gradient equal to 5×10^5 V/m and locating the point where this straight line crosses the potential curve. This procedure is illustrated in

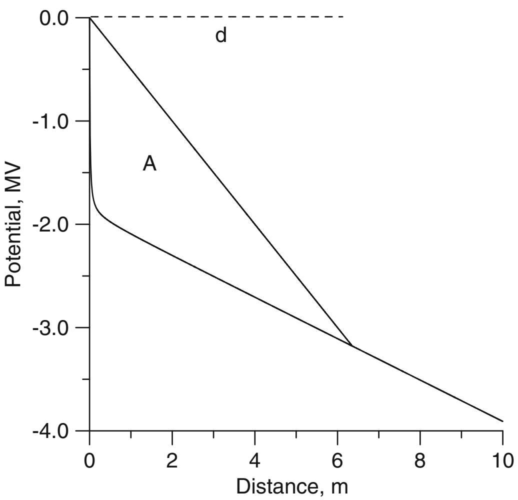

Fig. 2.6 The potential in front of a 0.02-m-thick, 10-m-long grounded conductor immersed in a background electric field of 2×10^5 V/m. In the diagram, d is the distance from the tip of the conductor up to which the streamers generated from the tip of the conductor extend. The *straight line* corresponds to a line with a potential gradient of 5×10^5 V/m (Figure created by author)

Fig. 2.6, and the distance up to which the streamers extend is marked d. If the background potential is known, then one can investigate how far the streamers will travel from the conductor using this procedure. Now, as we will see subsequently, we also wish to evaluate the amount of charge being deposited by the streamers. Analysis shows that this charge is proportional to the area between the potential curve and the straight line with a gradient of 5×10^5 V/m. This area is marked A in Fig. 2.6. Thus, the charge in the streamer region can be written as

$$Q = KA, \tag{2.6}$$

where K is a constant that depends on the spatial variation of the electric field through which the streamers are propagating. In the case of lightning-related problems, it was shown by Becerra and Cooray [12] that a suitable value for this constant is approximately $(3-4) \times 10^{-11}$ C/Vm. Now, let us see what happens as the electric field continues to increase with time.

2.7 Leader Discharge

If we look carefully at the streamer bursts generated by conductors raised to a high potential or by conductors at zero potential but placed in a background electric field, we see that, like branches coming out from a tree stem, the streamer burst emanates from a small bright region attached to the conductor. This region is called the *stem of the streamers* (Fig. 2.7). Now, as the streamers move out from the conductor, the current associated with these streamers is forced to move through the stem of the

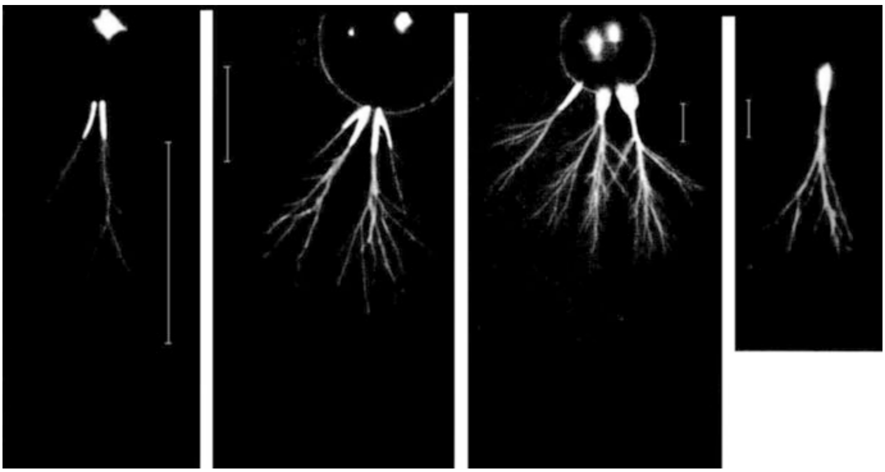

Fig. 2.7 The bright regions close to the electrode are the stem of streamer channels. Note that several streamer channels could originate from a single stem. Thus, the current generated by all these streamers goes through the stem (Figure courtesy of Division for Electricity, Uppsala University, Sweden)

streamer burst. This causes the streamer stem to heat up. Theory and experiment show that if the charge in the streamer burst is greater than approximately 1 μC, then the stem is heated to a temperature exceeding 1,600 K.

In the streamer phase of the electric discharge, many free electrons are lost because of attachment to electronegative (having an tendency to become attached to electrons) oxygen in air. Furthermore, a considerable amount of energy gained by electrons from the electric field is used in exciting molecular vibrations (especially of nitrogen molecules). Since electrons can transfer only a small fraction of their energy to atoms during elastic collisions (one can show this very easily using Newtonian mechanics and the fact that atoms are much heavier than electrons), electrons have a higher temperature than atoms. That is, the gas and the electrons are not in thermal equilibrium. As the gas temperature in the streamer stem rises to approximately 1,600–2,000 K, rapid detachment of the electrons from oxygen negative ions takes place, and this supplies the discharge with a copious amount of electrons, thereby enhancing the ionization [13]. Moreover, as the temperature rises, the time required to convert the energy stored in the molecules as vibrational energy into thermal or translational energy (i.e., kinetic energy) decreases and the vibrational energy converts back into translational energy, thereby accelerating the heating process. As the ionization process continues, the electron density in the channel continues to increase. When the electron density increases to approximately 10^{17} cm^{-3}, a new process starts in the discharge channel. This is the strong interaction of electrons with each other and with positive ions through long-range Coulomb forces [13]. This leads to a rapid transfer of the energy of electrons to positive ions, causing the electron temperature to decrease while the ion temperature increases. The positive ions, having the same mass as the neutrals, transfer their energy very quickly, in a time on the order of 10^{-8} s, to neutral atoms. This results in a rapid heating of the gas. At this stage the energy of the ions and neutral atoms becomes so large that they also start ionizing during collisions. This form of ionization is called *thermal ionization*. Once thermal ionization sets in, the electron density in the channel increases rapidly, leading to an increase in the conductivity of the streamer stem. This process is called *thermalization*. During thermalization, as the electron temperature decreases (because the electrons transfer a large fraction of their energy to ions and neutrals), the gas temperature increases, and very quickly all the components of the discharge, namely electrons, ions, and neutrals, achieve the same temperature and the discharge reaches a local thermodynamic equilibrium. The result is the conversion of the streamer stem into a hot conducting channel. This hot channel is called a *leader* or *leader discharge*.

2.8 Propagation of Leader Discharge

When a small channel section (i.e. streamer stem) attached to a grounded conductor (in the case of a lightning rod) is heated to a high temperature, the channel section becomes highly conducting, and as a consequence, its potential becomes approximately that of the grounded conductor (i.e., ground potential). This change in the potential causes an increase in the electric field at the tip of this conducting section (or the leader channel). This increase in the electric field at the tip of the leader channel gives rise to a streamer burst now emanating from a stem attached to the tip of the leader. As before, the current flowing in the streamer burst heats this new streamer stem, converting it into a hot channel, thereby extending the hot channel section or the leader. In this manner, the leader discharge, with the aid of streamer discharges, propagates away from the conductor (Fig. 2.8). As we will see in Chap. 7, a ground flash is initiated by a discharge that travels from cloud to ground. This discharge is called a *stepped leader*. The stepped leader carries a negative charge to ground, and as the leader extends toward the ground, the electric field at ground increases. When a leader is generated from a lightning conductor because of the influence of the increasing electric field caused by the stepped leader, it is called a *connecting leader*. Initially, the speed of the connecting leader is on the order of 10^4 m/s but increases as it extends toward the negative stepped leader. Theory shows that the amount of charge necessary to heat a unit length of leader channel,

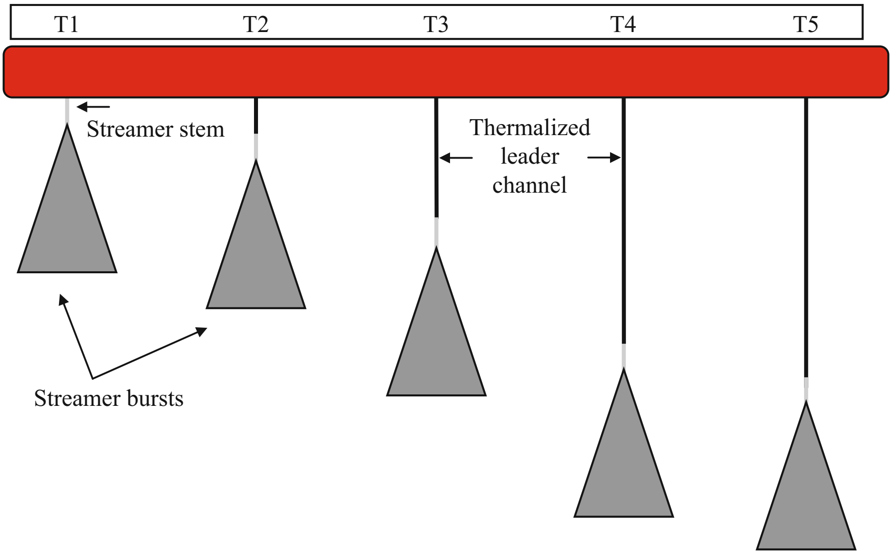

Fig. 2.8 Mechanism of positive leaders. When the electric field at the surface and in the vicinity of the anode increases to a value large enough to convert avalanches into streamers, a burst of streamers is generated from the anode (*T1*). Many of these streamers have their origin in a common channel called the *streamer stem*. The combined current of all streamers flowing through the stem causes this common region to heat up, and as a result, the stem is transformed into a hot and conducting channel called the *leader* (*T2*). Because of its high conductivity, most of the voltage of the anode is transferred to the head of the leader channel, resulting in a high electric field there. This high electric field now leads to the production of streamer discharges from a common stem located at the head of the leader channel (*T2*). With the aid of cumulative streamer currents the new stem is gradually transformed into a newly created leader section with the streamer process now repeating at the new leader head (*T3*, *T4*, *T5*) (Figure created by author)

say q_l, is approximately 60 μC. Thus a streamer burst associated with a charge Q will extend the leader by an amount equal to Q/q_l. However, theory also shows that this value depends additionally on the speed of the leader, and it increases as the speed of the connecting leader increases [12].

The preceding description is for a discharge that results in response to the electric field generated by the downward moving stepped leader carrying negative charge to ground. The electric field at the tip of the lightning conductor is such that it moves positive charges away from the tip and negative charges toward the tip. This means that in all stages of the discharge (i.e., avalanche, streamer, and leader) electrons travel toward the conductor, while positive charges are moved away from the conductor. This is defined as a *positive polarity discharge* because the charge deposited in the streamer bursts and on the leader channel is positive. Experimental data show that positive leaders travel more or less continuously. On the other hand, experimental data additionally show that negative leaders do not travel continuously but in steps. The reason for this is explained in a section to follow.

2.9 Potential of Leader Channel

The leader channel maintains a certain potential gradient along its channel, and for this reason the potential at the head of the leader is different from the potential at the point of initiation of the leader. Moreover, the potential gradient along the leader channel is not constant. It is smaller in the older sections of the leader channel and larger in newly created sections. The development of the potential gradient along the leader channel can be derived iteratively using the theory developed by Gallimberti [13]. Assume that at any time the current flowing through a section of the leader channel, the electric field in that channel section, and the radius of that channel section are known. Let us represent them by $I(t)$, $E(t)$, and $a(t)$. Then the radius of the leader channel at a time $t + \Delta t$ is given by

$$\pi \cdot a^2(t + \Delta t) = \pi \cdot a^2(t) + \frac{\gamma - 1}{\gamma \cdot p_0} E(t) \cdot I(t) \cdot \Delta t. \tag{2.7}$$

The electric field in the leader channel at that time is given by

$$E(t + \Delta t) = \frac{a^2(t)}{a^2(t + \Delta t)} E(t). \tag{2.8}$$

In the preceding equations, γ is the ratio of specific heats at constant volume and constant pressure, and p_0 is the atmospheric pressure. In writing down the preceding equations it was assumed that the current in the leader channel remained more or less the same when the time changed from t to $t + \Delta t$. Starting from an initial value for the radius of the leader channel and the electric field in the channel one can use the preceding equations to study the development of the potential gradient of the leader channel. It is common practice to assume that the initial radius of the leader channel is approximately 50–100 μm and the initial potential gradient approximately 500 kV/m. In practical applications the leader channel is divided into a large number of small sections, and the development of the potential gradient in each section is calculated using the preceding set of equations. Of course, the calculation assumes that the current flowing along the leader channel as a function of time is known.

The calculation of the leader potential gradient can be simplified if, instead of calculating the time evolution of the leader potential gradient in each segment as previously, one uses the expression derived by Rizk [14] for the potential of the tip of the leader channel, which is given by

$$U_{\mathrm{tip}} = lE_\infty + x_o E_\infty \ \ln\left[\frac{E_{\mathrm{str}}}{E_\infty} - \frac{E_{\mathrm{str}} - E_\infty}{E_\infty} \mathrm{e}^{-\{l/x_0\}}\right].$$

In the preceding equation, l is the total leader length, E_∞ is the final quasistationary leader gradient, and x_0 is a constant parameter. The values of parameters to be used are $E_\infty = 3 \times 10^4$ V/m, $E_{\mathrm{str}} = 4.5 \times 10^5$ V/m (potential gradient of streamer channels), and $x_0 = 0.75$ m.

2.10 Mechanism of Stepped Leader

The development of the negative leader discharge is slightly more complicated. It also maintains its propagation with the aid of negative streamers generated from its head. As in the case of positive leaders, a negative leader also originates with a streamer burst issued from the high-voltage electrode, i.e., the cathode in this case. However, the mechanism of its propagation is different from that of positive leaders. Let us consider the events taking place immediately after the generation of a streamer burst from the head of the negative leader. The same set of events take place immediately after the generation of a streamer burst from the cathode with the hot streamer stem acting as the negative leader head during the creation of the negative leader. A simplified schematic diagram giving the main features of propagation of a negative leader is shown in Fig. 2.9. Once a negative streamer burst is generated from the leader head, a unique feature called a *pilot system*, which does not exist in positive leaders, is created. The pilot system consists of a bright spot called a *space stem*, from which streamers of both polarities develop in opposite directions. The location of the space stem is usually at the edge of the negative streamer system. The action of these streamers heats the space stem and converts it into a hot channel. This is called a *space leader*. The positive streamers from the space leader propagate toward the head of the negative leader, and the negative streamers generated from the other end of the space leader propagate in the opposite direction. Indeed, the positive streamers of the space stem propagate in the region previously covered by negative streamers. The space leader lengthens at a higher speed toward the cathode (3×10^4 m/s) than toward the anode (10^4 m/s). As the space leader approaches the main leader, the velocity of both increases exponentially. The connection of the two leaders is accompanied by a simultaneous

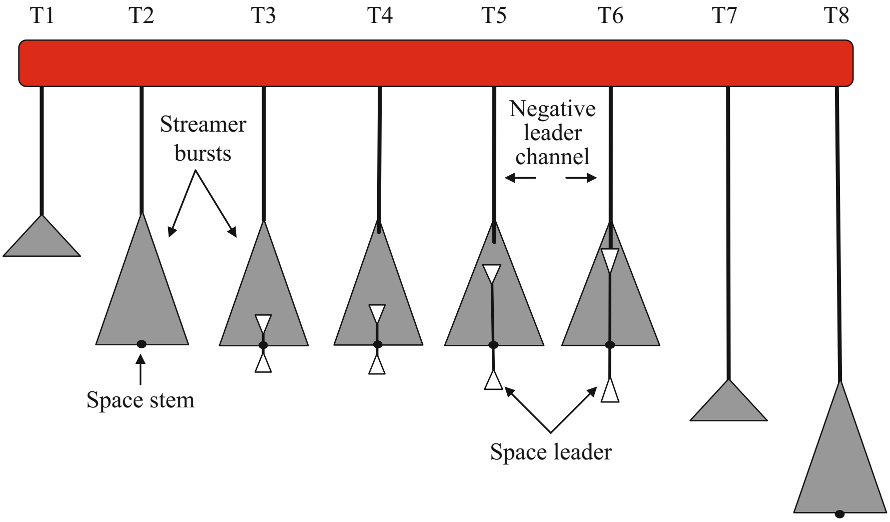

Fig. 2.9 Propagation of negative leaders. Once a negative streamer burst is generated from the leader head, a unique feature, called a *pilot system*, that does not exist in the positive leaders manifests in the system. The pilot system consists of a bright spot called a *space stem*, from which streamers of both polarities develop in opposite directions (*T2–T3*). The space stem is usually located at the edge of the negative streamer system. The action of these streamers heats the space stem and converts it into a hot channel. This is called a *space leader*. The space leader advances in both directions (the speed of extension of the positive end is generally higher than that of the negative end) through the cumulative action of positive streamers (generated from the side facing the negative leader) and negative streamers (generated from the opposite side) (*T4–T6*). The connection of the two leaders is accompanied by a simultaneous illumination of the whole channel starting from the meeting point (*T7*). During this process the space leader acquires the potential of the negative leader, and the negative end of the space leader becomes the new tip of the negative leader. During the formation of the step a new streamer burst is generated from the new leader head and the process is repeated (*T8*). Note that while the space leader travels toward the negative leader, the latter itself may continue to grow in length, as shown in the diagram. (The processes associated with the origin of the leader, which are almost identical to that of positive leaders, are not shown in the diagram.) (Figure created by author)

illumination of the channel of the space leader starting from the meeting point. During this process the space leader acquires the potential of the negative leader, and the negative end of the space leader becomes the new tip of the negative leader. In photographs, the negative leader appears to extend itself abruptly in a leader step. The change in the potential of the previous space leader generates an intense burst of negative corona streamers from its negative end, which has now become the new head of the negative leader. Now a new space stem appears at the edge of the new streamer system, and the process repeats itself. Recent evidence shows that, as in the case of laboratory sparks, repeated interaction of the negative leader with the space leader is the reason for the stepwise elongation of the negative leaders, as observed in negative stepped leaders in lightning flashes [15]. Models that describe the propagation of negative leaders taking into account the space leaders were published by Mazur et al. [16] and Arevalo and Cooray [17].

2.11 Low-Pressure Electrical Discharges

As described previously, an avalanche-to-streamer transition requires that the avalanche grow to approximately 10^8 electrons and the space charge in the avalanche tip create an electric field that is capable of attracting electron avalanches toward it. As the atmospheric pressure (or the density) decreases, the avalanche must grow to an ever greater length before it can accumulate enough space charge at its head to modify the background electric field. The reason for this is that, in comparison to an avalanche at atmospheric pressure, a larger gas volume is needed to create a given amount of charge at low pressure. Thus, with decreasing pressure, the charge density associated with a given amount of space charge decreases. This could be the case in low-pressure discharges taking place in the upper atmosphere (i.e., sprites and elves) during thunderstorms. In these discharges, the length of streamers like discharges may exceed hundreds of meters to kilometers [18]. Another interesting feature of these low-pressure discharges is the absence of the thermalization process. As mentioned earlier, the thermalization requires increasing the electron density beyond a certain limit (i.e., approximately 10^{17} cm^{-3}). In low-pressure discharges the density of molecules and atoms is such that the electron densities never reach the critical values necessary for thermalization. In these discharges, the electron temperature remains very high while the gas temperature remains close to ambient. The ionization by electron impacts is the dominant mechanism of ionization in these discharges. These discharges are also known as *Townsend discharges*.

2.12 A Summary of Mechanism of Lightning Flashes

A full description of the mechanism of lightning flashes is provided in Chap. 7. However, to introduce the reader to the nomenclature associated with the study of lightning flashes, this brief description is presented here. The following description is adapted from [19].

A thundercloud generally contains two main charge centers, one positive and the other negative, and a small positive charge pocket located at the base of the cloud. A ground flash occurs between the charge centers of the cloud and the ground, and the result is a transfer of charge from cloud to ground. When a ground flash brings positive charge down to Earth, it is called a *positive ground flash*; when it brings negative charge it is called a *negative ground flash*.

Electromagnetic field measurements show that a ground flash is initiated by an electrical breakdown process in the cloud called the *preliminary breakdown*. This process leads to the creation of a column of charge called the *stepped leader*, which travels from cloud to ground in a stepped manner. Some researchers use the term *preliminary breakdown* to refer to both the initial electrical activity inside the cloud and the subsequent stepped leader stage.

On its way to ground a stepped leader may give rise to several branches. 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 or fewer meters from ground, the electric field at the tip of grounded structures increases to such a level that electrical discharges are initiated from them. These discharges, called *connecting leaders*, travel toward the downward moving stepped leader. One of the connecting leaders may successfully bridge the gap between the 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 channel toward the cloud and the associated luminosity event that travels upward at a speed close to that of light is called the *return stroke*.

Whenever the upward moving return-stroke front encounters a branch, there is an immediate increase in the luminosity of the channel; such events are called *branch components*. Although the current associated with the return stroke tends to last for a few hundred microseconds, in certain instances the return-stroke current may not go to zero within this time but continue to flow at a low level for a few tens to a few hundreds of milliseconds. Such long-duration currents are called *continuing currents*.

The arrival of the first return-stroke front at the cloud end of the return-stroke channel leads to a change of 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. Occasionally, a negative recoil streamer may be initiated at the outer extremity of this positive discharge channel and propagate along it toward the end of the return-stroke channel. Sometimes, discharges originate at a point several kilometers away from the end of the return-stroke channel and travel toward it. On some occasions these discharges may die out before they make contact with the end of the return-stroke channel. Such events are called *K changes*. If these discharges make contact with the previous return-stroke channel, the events that follow may depend on the physical state of the return-stroke channel. If the return stroke channel happens to be carrying a continuing current at the time of the encounter, it results in a discharge that travels to ground. These are called *M-components*. When M-components reach 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. If the return-stroke channel happens to be in a partially conducting stage with no current flow during the encounter, it may initiate a dart leader that travels toward the ground. 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*. In other instances, the dart leader may encounter a 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 the ground as a stepped leader. Such a leader is called a *dart-stepped leader*. If these leaders travel all the way to ground, then another return stroke, called the *subsequent return stroke*, is initiated. In general, dart leaders travel along the residual channel of the first return strokes, but it is not uncommon for the dart leader to take a different path than the first stroke. In this case, it ceases to be a dart leader and travel toward the ground as a stepped leader. The point at which this leader terminates may be different from that of the original first leader. The separation between such subsequent channels was observed to be approximately a few kilometers on average.

Electrical activity similar to that which occurs after the first return strokes may also take place after subsequent return strokes. Note, however, that branch components occur mainly in the first return strokes and occasionally in the first subsequent stroke. This is the case because, in general, dart leaders do not give rise to branches. In the literature on lightning, the electrical activity in the cloud that takes place between the strokes and after the final stroke are called, collectively, *junction processes* or *J processes*.

The previously given description is based on observations of negative ground flashes. The mechanism of positive ground flashes is qualitatively similar to that of negative flashes, with differences in the details. In addition to these typical ground flashes, lightning flashes can also be initiated by tall structures. These are called *upward initiated lightning flashes*.

Cloud flashes normally occur between the main negative and upper positive charge of the cloud. The result is a partial neutralization of the charge centers. Cloud flashes do not contain return strokes, but they do contain discharge processes identical to the *K* changes described earlier.

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