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MÉCANISMES PHYSIQUES DU NUAGE D'ORAGE ET DE L'ÉCLAIR

THE PHYSICS OF THUNDERCLOUD AND LIGHTNING DISCHARGE

Physical processes during development of lightning flashes

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Note presented by Guy Laval.

Abstract The objective of this paper is to review our present understanding of the physical processes in lightning flashes during their development within or outside a cloud, following lightning initiation. This represents the 'big picture' of lightning development, in the scale of the cloud dimensions themselves. Since the acceptance of the bi-directional, zero-net-charge leader concept, significant changes have occurred in our understanding of the key physical processes of which a lightning flash is comprised, and in the analytical relationship between the electrical structure of a cloud and lightning parameters. These changes are discussed with an emphasis on the unifying nature of the bi-directional leader concept. ***To cite this article: V. Mazur, C. R. Physique 3 (2002) 1393–1409.***

Mécanismes généraux de développement de l'éclair

Résumé Cet article présente les connaissances actuelles des processus physiques régissant le développement de l'éclair à l'intérieur ou à l'extérieur du nuage, après la phase d'initiation. Il s'agit de proposer une vision d'ensemble du processus, à l'échelle du nuage lui-même. Depuis que le concept de leader bi-directionnel non chargé est complètement admis, notre compréhension des principaux mécanismes de l'éclair a évolué de façon significative et il est possible d'appréhender de façon analytique les relations entre la structure électrique du nuage d'orage et les paramètres caractéristiques de l'éclair. Ces nouvelles approches sont discutées en insistant sur le caractère unificateur du concept de leader bi-directionnel. ***Pour citer cet article : V. Mazur, C. R. Physique 3 (2002) 1393–1409.***

1. Introduction

The bi-directional, zero-net-charge leader concept of lightning development has become the major key in interpreting the variety of physical processes that takes place in both natural and artificial (triggered) lightning. Recognition of this concept by the lightning research community has been a lengthy process that has taken, depending on various estimates, from ten to fifty years. The concept was introduced by Heinz Kasemir [1] (also in [2]), and was verified much later with measurements of aircraft-triggered lightning [3]. The essence of this concept is: lightning initiation in the electrified cloud occurs as a bi-directional, bi-polar, zero-net-charge leader and electrodeless discharge. Such an initiation process takes

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place in intracloud, cloud-to-ground, aircraft-triggered, and so-called ‘tipsy’ rocket-triggered flashes (with conductive wire isolated from the ground). With the acceptance of this leader concept, some significant changes have occurred in our understanding of the essential physical processes in lightning flashes. We review these changes here, and also bring attention to the remaining puzzles in the ‘big picture’ of lightning development.

2. The nature of recoil streamers and the composition of a lightning flash

In the past, recoil streamers were interpreted as equivalents of ‘mini-return strokes’ carrying negative charges in intracloud (IC) flashes or during the intracloud development of cloud-to-ground (CG) flashes, when some (undefined) leaders reached pockets of opposite-sign space charge. This characterization of recoil streamers (also called K-changes) was obtained from E-field measurements, e.g., [4–6], and was largely due to the similarity of their step-like E-field changes to those of return strokes in CG flashes. However, the nature of recoil streamers and their role in the sequence of lightning processes remained confusing.

The present interpretation of recoil streamers is that they are negative leaders, i.e., self-propagating discharges, moving along previously developed trails of the positively charged parts of bi-directional and zero-net charge leaders. As negative leaders, they should be more properly called recoil *leaders* rather than recoil streamers. (Streamers are cold corona filaments of the length of a few meters, while leaders are hot plasma channels and are self-propagating.) Dart leaders in CG flashes are recoil leaders that reach the ground. The conditions under which initiation of recoil leaders occur continue to be not fully understood (see the hypothesis addressing this issue in Section 6).

We are able to unfold the mysteries of the dynamics of lightning development in the cloud scale, with recoil leaders as part of these dynamics, by applying the bi-directional leader concept to the interpretation of maps of lightning radiation sources. Mapping of lightning radiation sources is obtained either with the Difference of Time-of-Arrival (DTOA) or with Interferometric techniques, e.g., [7–9].

It is important to emphasize that these two lightning radiation mapping techniques operate in the VHF-UHF frequency band, and locate radiation sources which have been produced primarily by negative breakdown processes. The exception is the powerful positive breakdown that takes place at the upper tip of the return stroke channel in negative CG flashes after the ground potential wave reaches the tip. Radiation associated with positive breakdown during the development of positive leaders is different in its nature from that of negative breakdown; it has also been shown to have a much weaker intensity than that of negative leaders [10]. Neither of the mapping systems detects positive leaders in positive CG flashes [11], positive leaders during intracloud development of negative CG flashes, or positive leaders in rocket-triggered flashes [12]. This is why radiation maps of lightning obtained with the DTOA and interferometric systems generally depict lightning development associated only with negative leaders. Traces of positive leaders are found, however, because negative recoil leaders traverse them toward the lightning’s origin. Thus, by identifying the types of negative leaders, we can identify the polarity of the space charge region in which leader propagation occurs: initial negative leaders propagate in positive space charge regions, while recoil negative leaders (that retrace positive leaders) propagate in negative ones. The word ‘initial’ identifies breakdown and propagation in virgin air, contrary to recoil leaders that develop along previously ionized channels.

The composition of the lightning process in different types of flashes is presented in the following sections.

2.1. Intracloud flashes

Figs. 1, 3, 4, and 6 show examples of lightning mapping obtained with the DTOA technique [9] for several types of IC and CG flashes. A radiation map of a typical IC flash (Fig. 1) exhibits a two-layer structure with a vertical bridge produced by negative leaders that started at 7.8 km altitude, ascended and

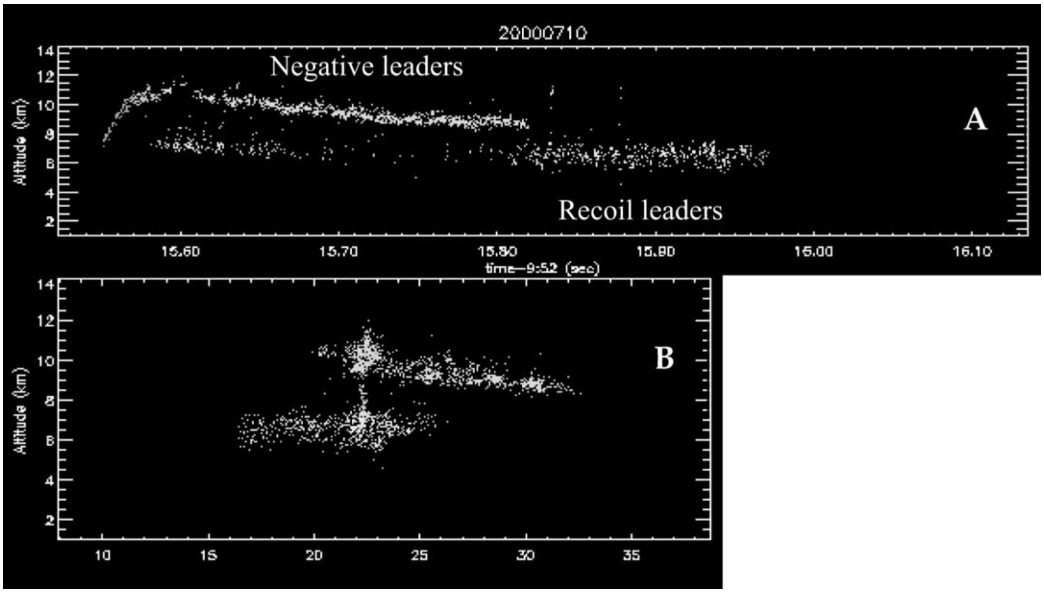

Figure 1. Lightning radiation map of an IC flash (courtesy Ron Thomas, New Mexico Institute of Mining and Technology [NMIMT]). The A and B panels depict the altitude (km)–time (s) and altitude (km)–range (km) progression of radiation sources, respectively. The recoil leaders (lower layer) have a much greater dispersion and lesser density of sources than the initial negative leaders (upper layer).

then stratified between 9–11 km (the upper layer), and recoil leaders that stratified in the 6–7 km region (the lower layer). The lightning radiation map in Fig. 1 is indicative of the classical tripole-charge structure in a thundercloud, with an upper positive space charge region at an altitude of 9–11 km, a lower negative space charge region at an altitude of 6–7 km, and the low positive charge region at the cloud base.

Negative leaders in the IC flash, as shown in Fig. 1, dominate the initial and ‘very active’ stage of the discharge (called from now on the initial stage), but cease during the subsequent, so-called junction stage (definitions of these stages are in [13]). Recoil leaders briefly appear 30 ms after lightning initiation, but become dominant during the junction stage of the discharge, starting at 270 ms after initiation. The negative leader radiation on the map appears as a dense pattern of sources noticeably different from that of the recoil leader radiation, which is highly dispersed and less well organized.

The conceptual sketch in Fig. 2 provides the interpretation of the lightning radiation map in Fig. 1.

The initial stage of IC flashes corresponds to the bi-directional development of the bi-polar leader with the negative leader on one end of the bi-polar lightning ‘tree’ and the positive leader on the other, progressing in opposite directions (periods t_1 to t_4 in Fig. 2). The junction stage of the flash (period t_5 in Fig. 2) corresponds also to the bi-directional development, which takes place, however, only in the positive part of the bi-polar lightning tree (from the point of lightning origin outward), this time with positive leaders and negative recoil leaders progressing in opposite directions. During both stages of the flash, the mapping system detects only the radiation of initial negative leaders and negative recoil leaders, but not that of positive leaders.

There is an obvious asymmetry in the emerging picture of lightning development during the two stages. While bi-directional development at both ends of the lightning tree takes place during the initial stage, no new negative leaders develop at the negative end of the tree during the junction stage. This suggests that the negative end of the tree is ‘dead’ during the entire junction stage. The current cutoff in the bi-directional leader channel occurred either in the beginning of the junction stage, or sometimes earlier, during the initial stage. It is possible that in the latter case both ends of the lightning tree progressed for a long while as

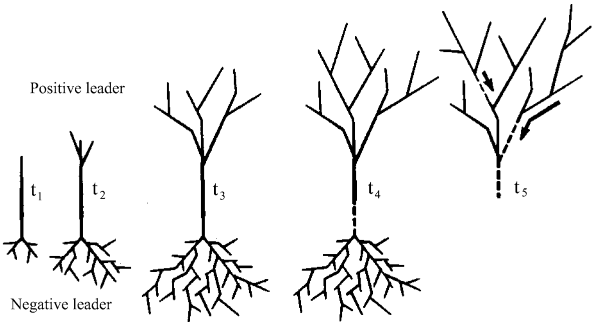

Figure 2. Development of a bi-directional lightning ‘tree’ in a typical IC flash made of positive leaders above and negative leaders below. Depicted are the structures corresponding to radiation sources at a given time period. t_1 shows initiation of a bi-polar and bi-directional leader; t_2–t_4 shows branching and progression of the bi-directional leader during the initial stage of the flash; t_4 shows current cutoff in trunk channel connecting positive and negative parts of lightning tree; t_5 shows progression of the positive leader, with intermittent occurrence of negative recoil leaders (arrows) during the junction stage (there is no radiation sources at the negative end of the tree during this period).

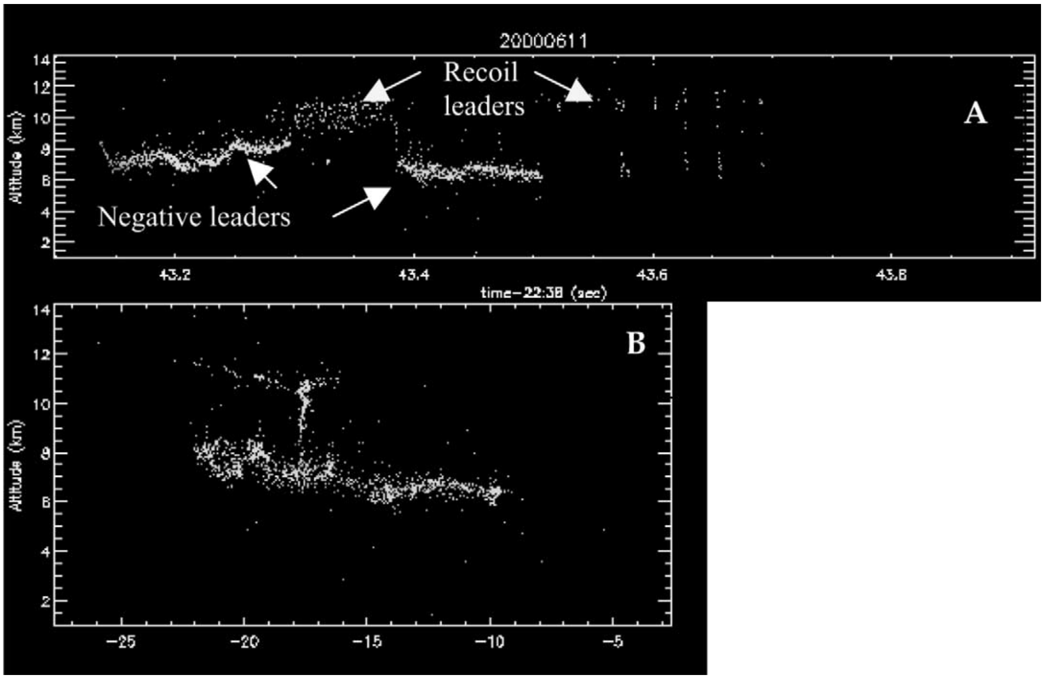

Figure 3. Lightning radiation map of an ‘inverted’ IC flash (courtesy Ron Thomas, NMIMT). The A and B panels depict the altitude (km)–time (s) and altitude (km)–range (km) progression of radiation sources, respectively. There are two consecutive cycles of the initial and junction stages of radiation in this flash, with recoil leaders at the upper layer and initial negative leaders at the lower layer.

unidirectional leaders. Thus, bi-directional leader development takes place first in the entire lightning tree (during the initial stage), but is confined later only within its positive end.

The unidirectional leader development of a mono-polar, charged leader occurs in leaders connected to the ground and after channel cutoff (e.g., in rocket-triggered flashes with grounded wire, and lightning from tall buildings), and in segments of bi-directional leaders after current cutoff.

Recent observations with the DTOA system detected IC flashes with the same bi-level radiation structure as in typical IC flashes (e.g., Fig. 1), but with the radiation sources of the recoil leaders in the layer *above* the layer containing the negative leaders. These so-called ‘inverted’ IC flashes (Fig. 3) correspond to a space charge structure with upper negative and lower positive space charges. The question remains whether this charge structure is a modified tripole with an additional negative screening charge layer at the cloud top, or an inverted dipole. The dynamics of inverted IC flashes are the same as those depicted in the conceptual sketch (Fig. 2) and as described above for a typical IC flash.

There is a characteristic timing pattern detected in radiation maps of IC flashes (see Figs. 1 and 3); namely, the periods of each type of radiation (those of initial negative leaders and recoil leaders) are clearly separated in time, i.e., when one type of radiation is present the other is absent, and vice versa. This timing pattern reflects the asymmetry in the radiation maps of IC flash development, commented on above, the asymmetry resulted from the absence of radiation from positive leaders. (There are also observations with the DTOA system of recoil leaders occurring at the same time as initial negative leaders; the possibility of several bi-directional leader processes cannot be excluded.)

2.2. Cloud-to-ground flashes

A typical multi-stroke negative CG flash (Fig. 4) exhibits cyclical development, each cycle consisting of the downward propagation of either a stepped or dart leader to ground, followed by the intracloud development of positive leaders (recognized by the presence of recoil leaders). The number of such cycles is equal to the number of return strokes. The dynamics of negative CG flash development, prior to the negative stepped leader touching the ground (see Fig. 5), are the same as in IC flashes (Fig. 2). The return stroke energizes the development of the unidirectional positive leader, which continues even after current cutoff occurs in the channel to ground (period t_5 in Fig. 5). This stage is similar to the junction stage of the IC flash, with bi-directional development of positive leaders and negative recoil leaders. In CG flashes, recoil leader radiation follows, and also coincides with intracloud positive leader development after the first and subsequent return strokes. Dart leaders are those recoil leaders that have reached the ground. The lightning radiation map of a negative CG flash (Fig. 4) shows that recoil leaders are associated with the negative space charge region that is situated between 6 and 8 km of altitude.

In cases of positive CG flashes (see Fig. 6), initial negative leader progression occurs within a positive space charge region that is associated with a melting layer (the ‘bright band’ in a vertical cross-section of radar images) located above 0 °C isotherm. Radiation from positive leaders to the ground is not detected, although the points where they touch the ground are determined (after careful examination) from the slightly more pronounced radiation path of the return strokes that carry a negative charge.

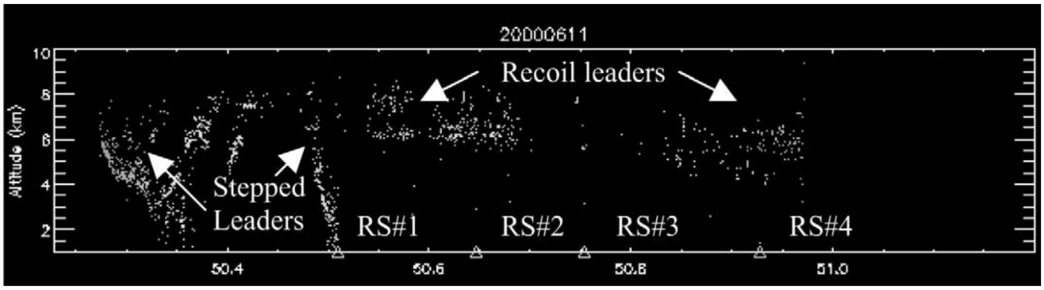

Figure 4. Lightning radiation map, altitude (km)−time (s), of a multi-stroke negative cloud-to-ground flash (courtesy Ron Thomas, NMIMT). Stepped leaders started at an altitude of 6 km, first terminating in the air and then reaching the ground at time 50.5 s. Four return strokes (RS) are marked with symbol Δ on the time axis. Negative dart leaders are virtually invisible on the radiation map because of their propagation along the weakly ionized channels of previous return strokes, rather than through virgin air, as in the case of stepped leaders.

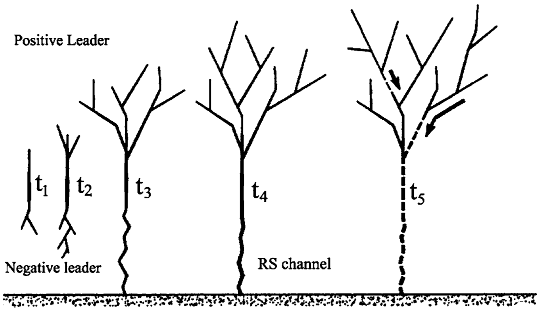

Figure 5. Development of a bi-directional, bi-polar lightning 'tree' in a negative CG flash made of positive leaders above and negative leaders below. t_1 shows initiation of a bi-polar and bi-directional leader; t_2 shows progression of the bi-directional leader; t_3 shows ground contact of the negative leader; t_4 shows return stroke, t_5 shows current cutoff and progression of the positive leader, with intermittent occurrence of negative recoil leaders (arrows) traversing toward the flash origin.

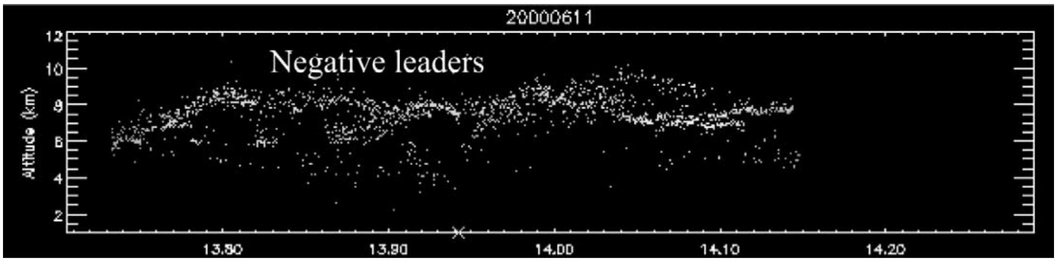

Figure 6. Lightning radiation map, altitude (km)–time (s), of a positive CG flash (courtesy Ron Thomas, NMIMT). The panel depicts altitude (km)–time (s) progression of radiation sources. The return stroke (RS) is marked with the symbol X on the time axis. The positive leader is virtually invisible on the radiation map. The negative leader started at an altitude of 6 km, then developed within the positive space charge region around 8 km of altitude.

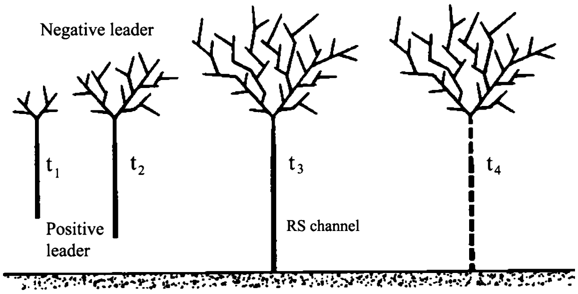

Figure 7. Development of a bi-directional lightning 'tree' in a positive CG flash made of negative leaders above and a positive leader below. t_1 shows initiation of a bi-polar and bi-directional leader; t_2 shows progression of the bi-directional leader; t_3 shows ground contact of the positive leader; t_4 shows return stroke; t_5 shows current cutoff and progression of the negative leader. There is no intermittent occurrence of negative recoil leaders during this stage.

The same concept of the bi-directional, zero-net-charge leader also describes the development of positive CG flashes until channel cutoff (see Fig. 7). The upward negative leader progression energized by the return stroke is the final stage of this flash. This brings us to the issue of the multiplicity of return strokes in positive CG flashes, or rather, the absence of such multiplicity.

Numerous successful triggering, in Japan, of upward negative leaders by rockets with a trailing grounded wire show that there are no downward positive leaders that traverse the remnants of the previously established channel to ground after leader channel cutoff, as dart or dart-stepped negative leaders do in multi-stroke negative CG flashes. In fact, during the entire multi-year duration of the rocket-triggered lightning program in winter storms in Japan, there were no cases of the triggering of a positive CG flash; only the triggering of upward negative leaders was observed [14]. This evidence strongly supports the hypothesis [15] that positive CG flashes cannot have multiple return strokes. This is consistent with the observation that positive CG flashes most often have one return stroke [16]. However, positive CG flashes,

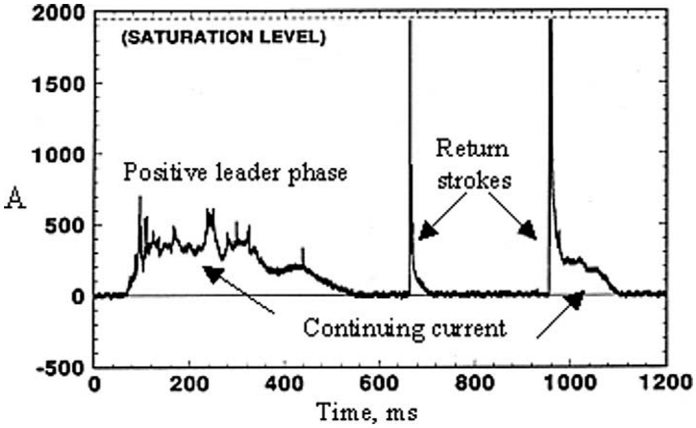

Figure 8. Current record of a rocket-triggered cloud-to-ground flash showing continuing current during the positive leader phase and after each of two return strokes [18].

with several channels to ground separated by distances of tens of km from each other have been observed and mapped with the DTOA system in summer thunderstorms in the US [17].

3. Continuing current as an indicator of a developing leader

The existence of continuing current has been consistently acknowledged in the past, and its presence has been usually detected in records of current to ground and slow electric field changes after return strokes in CG flashes, or in current records of rocket-triggered lightning and upward leaders (see Fig. 8). However, this was considered to be a separate process in lightning development; for example, Krehbiel [19] called events with continuing current 'continuing current discharges'. No clear definition of continuing current, or clear explanation of its nature existed before the acceptance of the bi-directional, zero-net-charge leader concept.

Our new understanding is that continuing current is the result of the changing distribution of induced charges on the conducting leader channel during its development in the ambient electric field inside the cloud [20] (see Section 5). Therefore, continuing current is an inseparable part of any leader process, regardless of polarity. In close proximity to the leader tip, continuing current is superimposed on the pulse current, which originates at the tip as a result of the breakdown process in the corona streamer zone ahead of the leader [21]. Both the breakdown processes, and thus the pulse current characteristics, are of a different nature in positive and negative leaders (e.g., [10]). The presence of continuing current, commonly observed either in the E-field change record, or as the continuing luminosity of a visible channel, is an indication of a developing leader in the flash. The duration of continuing current, which delineates the duration of leader development, varies from a few to hundreds of ms. Since leader development normally immediately follows each return stroke in CG flashes, so a continuing current of some duration is present after each return stroke.

4. 'Spider lightning': a mystery resolved

'Spider lightning' (see Fig. 9) has long been a well-known phenomenon frequently observed during the decaying stage of a thunderstorm, but its nature has been unveiled only recently [22]. It has been determined that spider lightning is a negative leader similar to a negative stepped leader in CG flashes. Its horizontal stratification is related to the stratified structure of space charges during the decaying stage of a storm; this is different from the charge structure that exists during the mature stage of a storm, when most negative stepped leaders occur. The demystification of spider lightning is significant, because it provides us with additional evidence for the interpretation of the 'big picture' of lightning flash development as a sequence

Figure 9. ‘Spider’ lightning: visible, horizontally stratified lightning channels propagating over large distances near cloud base during the decaying stage of a storm (courtesy National Severe Storms Laboratory archives).

of positive and negative leaders. Spider lightning may be part of both bi-directional and uni-directional leader development in IC and positive CG flashes [22].

5. The analytical relationship between the electrical structure of a cloud and lightning parameters

A consistent physical model, which describes the relationship between cloud charges and lightning, enhances our understanding of the lightning processes in the storm scale. A two-dimensional physical model described in [20] simulates the dynamics of the bi-directional leader process of a vertical, non-branching leader in the charge structure of a mature storm. The model allows us to determine the induced charges on the leader, the leader current, and the leader potential for IC and negative CG flashes, all as a function of the ambient potential distribution. The model makes clear that the truncation of the vertical development of the leader takes place when the potential at the tip of the leader becomes close in value to the ambient cloud potential (see Figs. 10A and 11A); this leads to redistribution of the induced charges (see Figs. 10B and 11B), reduction of the continuing current (see Figs. 10C and 11C), and finally, to stopping the propagation at the truncated leader tip. Similar computer-simulated models may be developed for positive CG flashes and the decaying stage of a storm.

6. Current cutoff and its role in the initiation of recoil leaders

The current cutoff process, also called the ‘channel cutoff’, is commonly observed in rocket-triggered and natural multi-stroke negative CG flashes prior to a dart leader-return stroke sequence. Malan and Schonland [23] suggested that lightning has multiple return strokes because the channel to ground becomes resistive, i.e., cut off, while the upper part of the channel continue to extend. Krehbiel et al. [19] stated: “observational evidence of channel cutoff comes from electric field measurements of close ground (negative CG) discharges, which often exhibit a fast recovery...” The confirmation of this effect is found in electric field measurements of negative leaders triggered using the classic rocket-triggering technique (Fig. 12), and of positive CG flashes in winter storms in Japan [24].

What produces current cutoff? Krehbiel et al. [19] suggested that two factors, ‘negative resistance’ of the arc, and available source current, work interactively to result in increasing resistance and drop in potential along the channel to ground, thus causing the current cutoff. (The leader and the return stroke plasma channels have much in common with arc plasma, which possesses the descending current-voltage characteristics [25].) Heckman [26] estimated that a several kilometer long lightning channel is unstable, i.e., extinguished between strokes, if it carries less than about 100 A. He concluded that as a circuit consisting of an arc connected to a current source (at the leader tips), the lightning channel is unstable if its RC time constant exceeds a characteristic cooling time. Heckman [26] suggests that a straight, or bending, or tortuous one-dimensional channel yields almost exactly the same instability criterion.

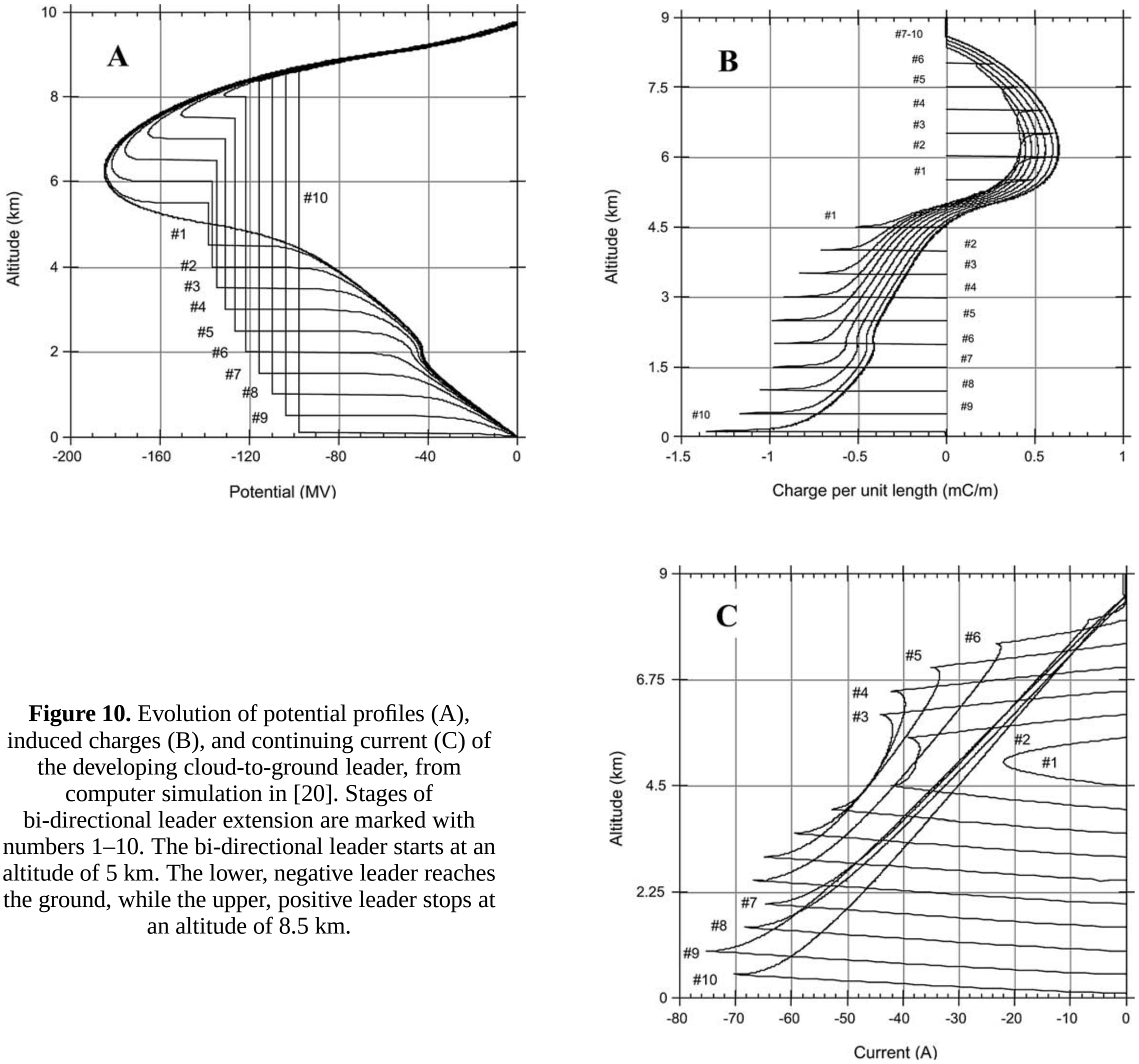

Figure 10. Evolution of potential profiles (A), induced charges (B), and continuing current (C) of the developing cloud-to-ground leader, from computer simulation in [20]. Stages of bi-directional leader extension are marked with numbers 1–10. The bi-directional leader starts at an altitude of 5 km. The lower, negative leader reaches the ground, while the upper, positive leader stops at an altitude of 8.5 km.

The current source that maintains the arc is associated with the breakdown process at the leader tip and the self-propagation of the leader channel. Mazur and Ruhnke [15] proposed a mechanism to explain decreasing current flowing from the developing branching leader to the channel to ground (see sketch in Fig. 13) that eventually leads to current cutoff when the current value drops below 100 A, according to the hypothesis by Heckman [26].

This mechanism is based on the ‘field choking’ effect on secondary corona streamers by a space charge deposited by a primary corona streamer in laboratory discharges [27]. Multiple branching of the developing leader would screen (like an umbrella) the electric field from the lower layer of branching, thus ‘choking’ or arresting the development of the lower branches. This affects cloud potential distribution near the main channel, as well as charge distribution and current value in the main channel, and reduces the current in the main channel.

It is reasonable to conclude that the phenomenon of current cutoff is a universal one that characterizes the development of any branching process. On the other hand, even a non-branching, but long, channel may become unstable by virtue of its increasing RC time-constant value. Most likely, both processes, i.e.,

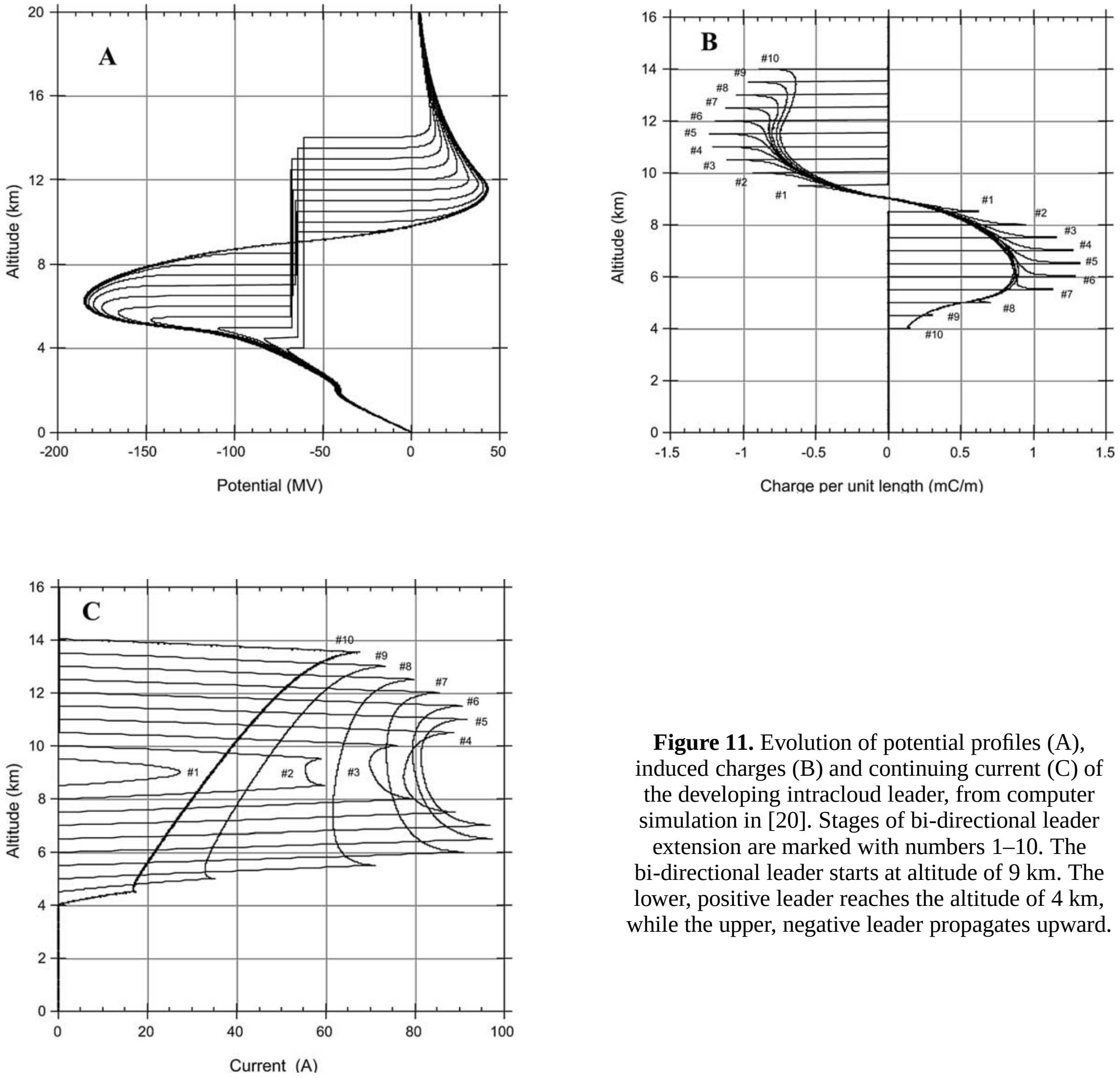

Figure 11. Evolution of potential profiles (A), induced charges (B) and continuing current (C) of the developing intracloud leader, from computer simulation in [20]. Stages of bi-directional leader extension are marked with numbers 1–10. The bi-directional leader starts at altitude of 9 km. The lower, positive leader reaches the altitude of 4 km, while the upper, negative leader propagates upward.

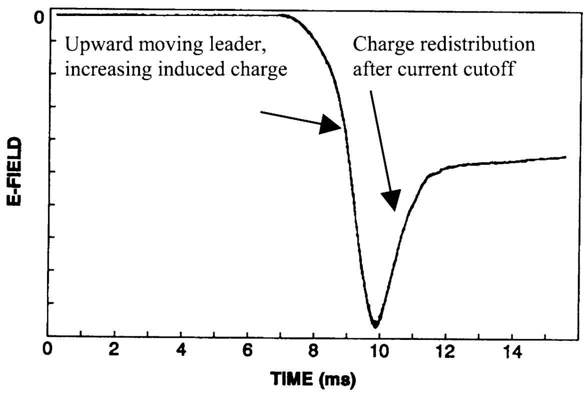

Figure 12. An example of the current cutoff effect observed in the fast reversal of E-field on the ground near a negative leader triggered by the classic rocket-triggering technique [24].

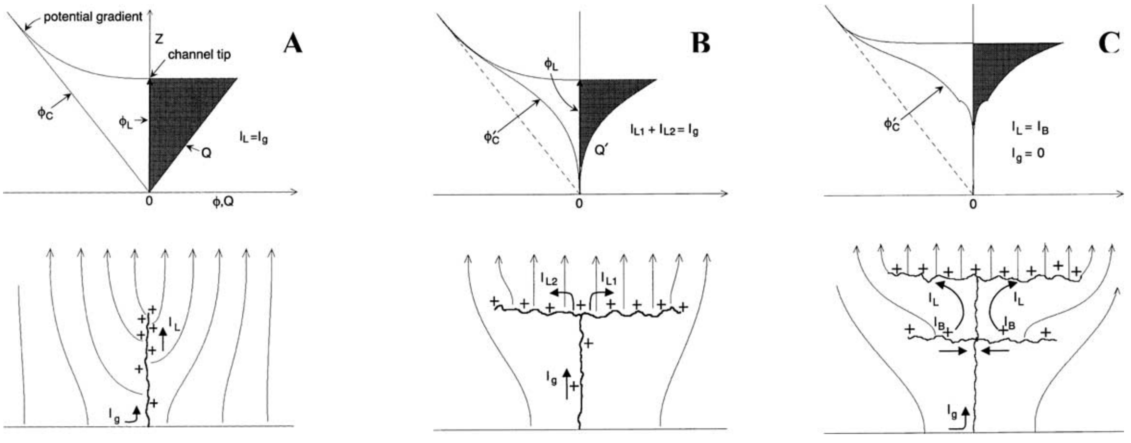

Figure 13. The concept of the screening or 'field choking' of the current in the main channel by the multiple layers of advancing branching [15]). Panels A, B, and C represent (in the upper parts of each panel) the stages of cloud potential distribution, ϕ_C, and the induced charge on the main (vertical) channel, Q; and (in the lower parts of each panel) electric field lines and currents in the main channel, I_g, and first and second layers of branching, I_L and I_B, respectively. Panel C illustrates how the current in the main channel I_g is decreasing to cutoff stage, as a result of the distribution of current generated by the upper developing branches among choked (but still conductive) lower branches and the channel to ground.

branching and elongation of the conductive arc channel, contribute to the current cutoff. Thus, it follows that the current cutoff is an essential feature of the lightning development process that occurs in channels to ground, as well as in the cloud branches of CG and IC flashes.

A question concerning the role of current cutoff in the initiation of recoil leaders in IC flashes and during the intracloud development of CG flashes should arise, because recoil leaders typically follow channel cutoff. Applying an electrostatic model of the bi-directional, zero-net-charged and mono-polar charged leaders, Mazur and Ruhnke [15] proposed a mechanism to explain recoil leader formation following current cutoff in the established leader's channel. Two processes contribute to this mechanism (see Fig. 14): (i) the conservation of charge trapped in the channel after it is cut off, and (ii) the induction of charges on the conducting channel floating in the ambient electric field. The charge trapped in the channel after its cutoff (in this case, the charge deposited by the return stroke) is stretching and, thus, decreasing in its density per unit length, due to the net elongation of the developing leader at the tip (the part of the channel above the cutoff point in Fig. 14C). While the induced charge on the bottom section of the floating conducting channel changes toward a negative value, the combined effect of the stretching of the trapped charge and induction causes the total charge at the bottom to decrease, reverse polarity, and then increase (but in the opposite polarity). The effect of this process is observed as the rapid recovery of the E-field at a ground point close to the flash (see Fig. 12). The potential of the upper, conductive, floating channel shifts toward the cloud potential, while the lower, non-conductive channel connected to the ground remains at zero potential. This difference of potentials near the cutoff point may produce an E-field sufficient to initiate electrical breakdown. It has been suggested [15] that this mechanism may be responsible for the initiation of negative recoil leaders.

Logic would dictate that this mechanism should work independently of the polarity of the floating leaders. However, while negative recoil leaders do occur after cutoff in positive leaders, and in return stroke channels of negative CG flashes, there is no observational evidence of positive recoil leaders occurring in (i) negative leaders triggered by the rocket-triggering technique, or (ii) in return stroke channels of positive CG flashes after the channel cutoff, or (iii) from the negative end of the lightning tree during the initial stage of the IC flash. To date, a physical explanation for these phenomena is still lacking.

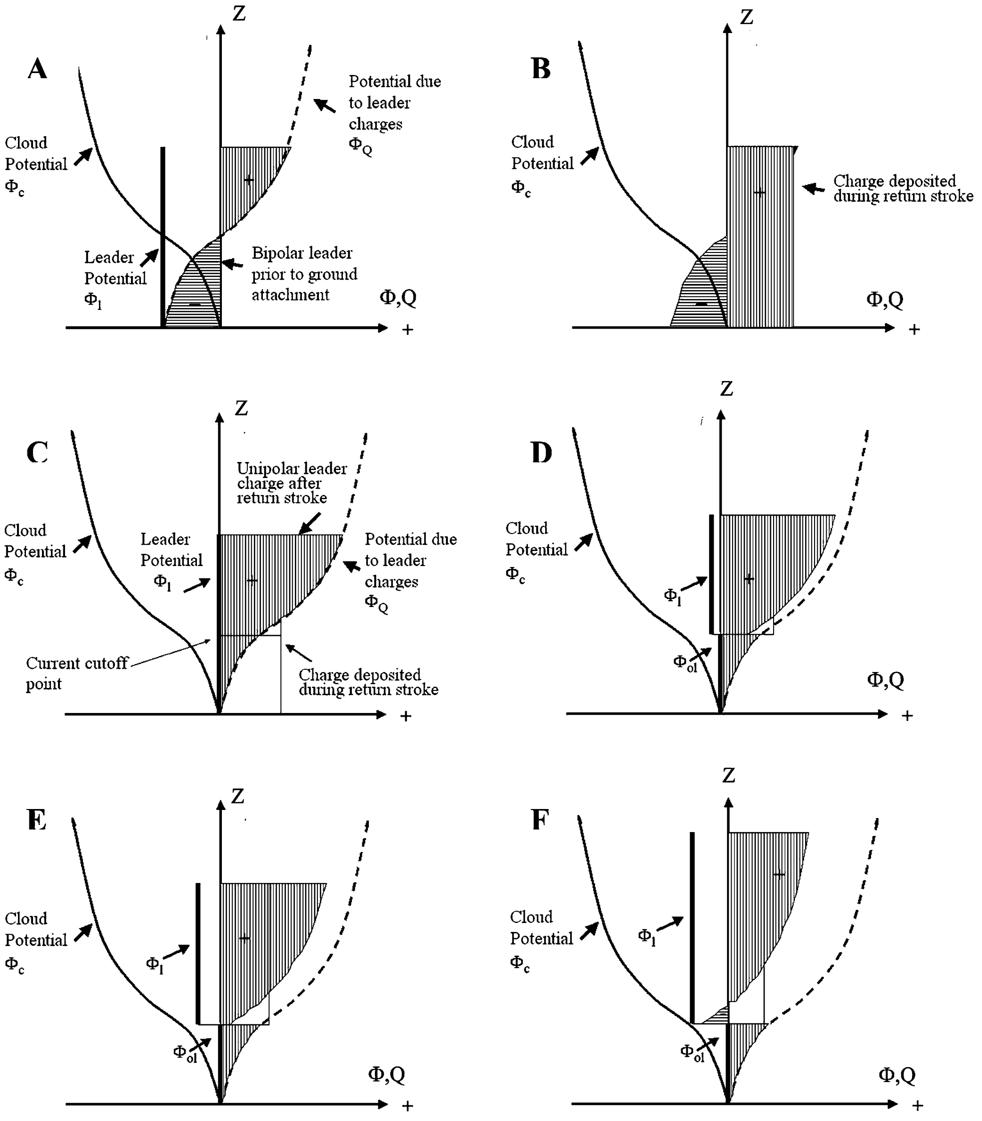

Figure 14. Evolution of charge distributions and potential functions in the leader-return stroke channel prior to, during, and after attachment to ground [15]. (Vertical and horizontal hatchings mark positive and negative induced charges, respectively). (A) downward leader just prior to touching the ground; its potential Φ_l is negative, its net charge is zero. (B) return stroke process; shifting of the potential of the leader channel from Φ_l to zero upon touching the ground is equivalent to depositing an uniform positive charge along the channel adding it to the induced charges on the leader prior to touchdown. (C) leader plus return stroke; the potential of the return stroke channel is zero, its charge distribution has the maximum at the upper tip, which leads to development of the positive leader and thus to the elongation of the channel. (D) (E) and (F) development of the floating conducting leader channel after its cutoff from the ground portion of the channel. Notice the decreasing charge density of the trapped charge (outlined by a thin line), the decreasing (then reversing sign) charge at the low end of the developing leader, and the increasing potential difference between the ground (decaying) portion of the channel (Φ_{ol}) and the floating and developing leader (Φ_l).

7. The remaining puzzle of positive cloud-to-ground flashes

The lightning processes in positive CG flashes continue to be far less investigated than those in negative CG flashes. We have only relatively small amount of comprehensive data on rocket-triggered upward negative leaders. One explanation is that the rocket-triggered lightning technique, so effective in studying the physical processes in negative CG flashes, is more difficult to implement logistically in the wintertime in Japan, where positive CG flashes, though infrequent, dominate lightning activity in winter thunderstorms.

There is also very little known about the characteristics of the downward positive leaders in positive CG flashes. The inability of the two lightning mapping techniques (DTOA and interferometric) to map positive leaders (see Section 2), and the absence of other methods to trace downward positive leaders prevents us from discovering the origin of the complex positive CG flashes that occur during the decaying stage of summer thunderstorms in the U.S. (e.g., [22]). It is encouraging that in the much less-complex and less-extended positive CG flashes in Japanese winter storms, the origin of a positive leader is found at the origin of the negative leader radiation, which is identifiable in the radiation maps [28]. This observation fits the bi-directional leader concept very well.

Among the parameters of positive CG flashes, the return stroke current values and charge transfer have been obtained from direct current measurements on tall structures, or estimated from electric field records by using models. The difference between the charge transferred by the return stroke in negative and positive CG flashes is especially significant. Brook et al. [29] and Uman [30] attributed the huge charge transfers in positive CG flashes (up to 1000 C in positive CG flashes versus up to only 10 C in negative CG flashes) to the long period and much greater values of continuing current in these than in single-stroke negative CG flashes. One may go further in the interpretation of these differences: the long duration of continuing current typical for positive CG flashes equates with the long duration and, thus, the significant length of the upward negative leader's development. For comparison, the long continuing current periods in negative CG flashes are observed typically only after some subsequent return strokes in multi-stroke flashes. The great amplitude of the continuing current indicates the considerable spatial dimensions of the negative breakdown region that results from simultaneous extensive branching in the negative leaders. (Each new branch represents an additional current source feeding the return stroke channel.) These spatial-time features of the negative leader processes in positive CG flashes are confirmed when we compare video images of return strokes in positive and negative CG flashes obtained with a high-speed and high-resolution video system (Figs. 15 and 16). The video images verify the profound difference in both the duration and the spatial extent of leader development energized by the return stroke in positive and negative CG flashes. The differential in the spatial extent is explained by the disparity in the degree of branching during the processes of positive and negative breakdown and leader development. The differential in the duration of leader development is related to the difference in the ambient potential distributions in a thunderstorm during the occurrence of flashes of each polarity.

8. Future studies

The significant progress in lightning research made during the last two decades in field observations, laboratory scale studies and related theoretical modeling and computer simulation have moved us much closer to an understanding of the physics of lightning and its development in thunderstorms. Several unresolved issues related to the 'big picture' of lightning have already been mentioned in this paper. From the standpoint of observations, efforts should be made to detect and map positive leaders that do not produce significant enough radiation to be mapped by contemporary lightning mapping systems, but which carry a charge, thus producing a noticeable signature in the electric field records. From the standpoint of physical interpretation, we should find out why recoil leaders are only of negative polarity, and positive recoil leaders have never been observed (or do not exist), in spite of seemingly similar conditions for the negative and positive breakdown at the end of the cutoff process.

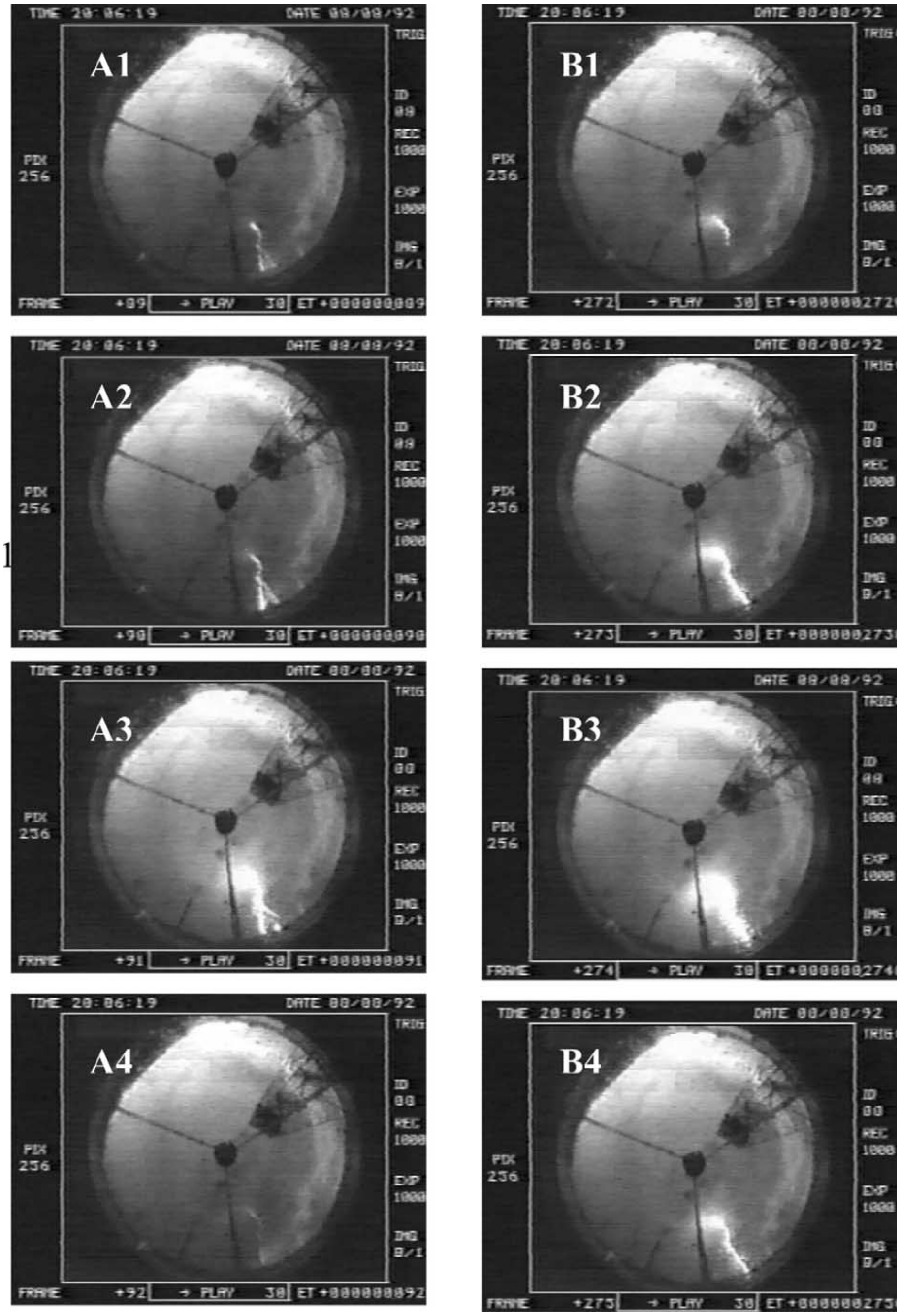

Figure 15. Series of video frames of reflections in a parabolic mirror from a multi-stroke negative CG flash obtained with a high-speed (time resolution of 1 ms) video system [31]. Series A – the stepped leader (A1, A2), the first return stroke (A3), and the continuing current (A4). Series B – a dart leader (B1, B2), the fourth return stroke (B3), and the continuing current (B4).

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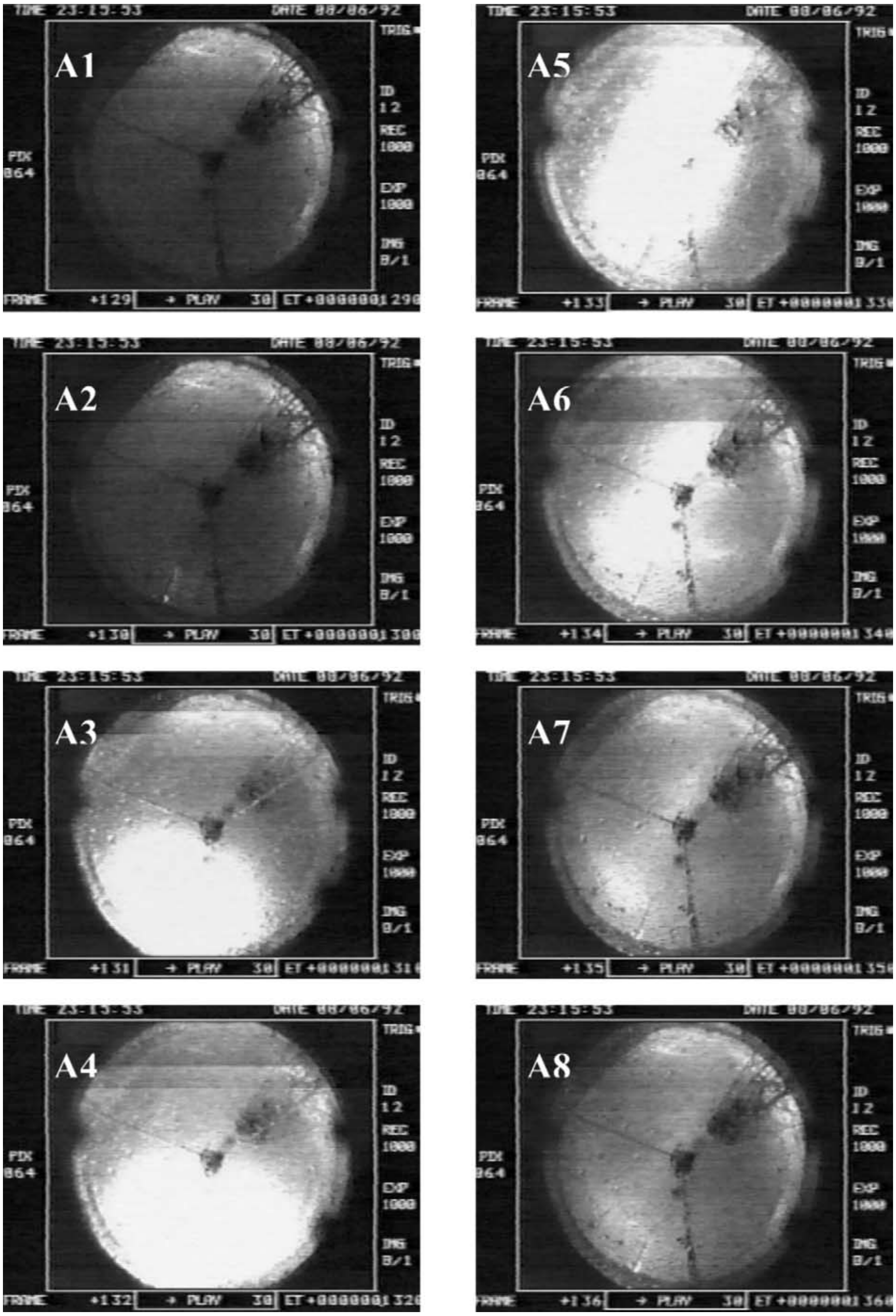

Figure 16. Series of video frames of reflections in a parabolic mirror from a positive CG flash obtained with a high-speed (time resolution of 1 ms) video system [22]. The positive leader (A2); the return stroke (A3); development of the negative leader energized by the return stroke connected with the luminous channel to ground, visible in A7–A8, that carries the continuing current (A4–A8). The video system setting was the same for images in Figs. 15 and 16.

The conventional concepts of lightning protection have been built mainly on empirical, rather than scientific, grounds, and should withstand the scrutiny of scientific investigation based on our more recent understanding of lightning processes. The study of upward leaders from the ground structures is most directly related to the lightning protection issues. Upward leaders from tall structures, and triggered by the rocket-triggering technique, have been extensively measured. However, the conditions for sustainable self-propagation of an upward leader from a ground structure, in relation to the downward leader of a cloud-to-ground flash, are still not clear. An investigation of the quantitative relationship between the characteristics of an upward leader and the height of a structure, and the characteristics of a downward leader and its distance from the structure, has never been conducted, and is critically important for verifying conventional or designing new concepts of the lightning protection.

9. Conclusion

The bi-directional, zero-net-charge leader concept first proposed by Heinz Kasemir [1] provided physical sense to the interpretations of many elements of the lightning puzzle that had been described only from observations, and also fundamentally changed our understanding of lightning processes in the storm scale. Now, instead of disconnected fragments of the ‘big picture’, a clear and elegant structure of a lightning flash built of two basic processes, that is, positive and negative leaders, emerges. The same basic structure manifests itself in all types of lightning flashes and in a variety of electrical conditions inside thunderstorms.

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