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# The physical concept of recoil leader formation

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ABSTRACT

The concept of recoil leader formation is based upon their nature as bidirectional and bipolar leaders. The analogy of the unipolar leaders to free-burning arcs was applied to interpret the processes during current cutoff in individual leader branches. These processes are essential to locating the origin and the timing of recoil leader formation. The difference in the density of the branching structures of positively- and negatively charged leaders is shown as the decisive factor affecting the occurrence of recoil leaders in positively charged channels, absence of them in negatively charged channels, and the lack of multiple return strokes in positive cloud-to-ground flashes.

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## 1. Introduction

Recoil leaders that occur tens of milliseconds following current cutoff in branched channels of positively charged leaders are essential parts in the development of intracloud (IC) and cloud-to-ground (CG) lightning flashes. Recoil leaders, however, are not observed in negatively charged leaders. Historically, recoil leaders have been identified, under the name “K-changes” [9], by their characteristic signature in electric field changes (a “hook”- type signature of negative change). Ogawa and Brook [18], suggested that K-changes are actually *negative “recoil streamers”* that occur when a positive leader, during the so-called “junction stage” in multistroke CG flashes, reaches a cloud region of concentrated negative charge. This interpretation made K-changes the equivalent of “mini return strokes” inside the cloud. The word “recoil,” as used by Ogawa and Brook [18], meaning “to return to a starting point or source,” by definition in Webster’s New World Dictionary, correctly reflects the reality of the process, i.e., propagation along remnants of the channels of the positively charged leaders which preceded them, toward the origins of these preceding leaders. However, the term “streamer” misrepresented the nature of the phenomenon, and has been replaced by the physically correct term “recoil leader,” that matches all the attributes of K-changes [13]. A new term, recently introduced [3] for this phenomenon, is “retrograde leader,” i.e., going backwards, which does not change or add anything to the meaning of the term “recoil leader,” but, in the author’s view, only contributes to the existing confusion in lightning terminology.

From the analysis of lightning radiation maps obtained with VHF interferometers, Mazur [10] and Shao et al [21] confirmed that recoil leaders carry negative charges, and propagate along the path of the previously-existing channel of the positively charged leader back to the leader’s origin. Only recently, with high-speed video observations, recoil leaders have been found to be bidirectional, bipolar leaders (e.g. [15]), which should have been expected because of their nature as electrodeless discharges.

One of the remaining challenging issues in the physics of lightning is the interpretation of recoil leaders that occur in the branched positively charged leader channels, or in the multistroke negative cloud-to-ground flashes during the periods between sequential return strokes. The mechanism of recoil leader initiation that would define both the probable location of recoil leader formation on the traces of the preceding leader and the timing of initiation after current cutoff remains unknown. The proposed physical concept is an attempt to qualitatively address the mystery of recoil leader formation. It is based on the accumulated knowledge of the features of recoil leaders, and on the application of the electrical characteristics of free-burning arcs to the development of the plasma channels of leaders, in view of the strong similarity between them.

## 2. The relationship between internal electric field and current in lightning leaders

The assumption of the leader as a perfect and equipotential conductor, made in an earlier, simplified computer-simulation

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model of leader development in a thundercloud [12,23], is only approximately valid for real-life leaders, and is not applicable for cooling leader channels. From initiation through decay, the leader channel is in a state of plasma, the features of which are very similar to those of a free-burning arc, with the current, *I*, and the internal longitudinal electric field, $E_{int}$, uniform along the channel, but changing in a wide range of values during the leader's lifetime. The potential $\varphi$ at the tip of the leader is the product of the internal, longitudinal electric field $E_{int} = -\text{grad}\ \varphi$ and the length of the channel, *l*. The value of $E_{int}$ can be found in the *E-I* characteristic of a free-burning arc in the modified King's curve [7] (Fig. 1) that depicts a negative relationship between the grad $\varphi$ and arc current *I* for the entire range of leader currents, from mA to hundreds of A [16]. (From now on $E_{int}$ will be use rather than grad $\varphi$.)

In the relationship between *E* and *I* in arcs there is a time lag, or long response time, of several tens of milliseconds between the changes of the current *I* and the response of the $E_{int}$. An example of this effect is observed during step-like application (switching on) of the 100 A current to a short laboratory arc (Fig. 2).

The similarity with a free-burning arc is most applicable to a unipolar leader, which is connected at one end to a current source. Therefore, we assume that unipolar leaders, like free-burning arcs, have uniform current and potential gradient along their length at any given moment of the leader-channel's development.

## 3. Current cutoff prior to occurrence of recoil leaders

A common understanding in the lightning literature, of the meaning of the word "cutoff," which is applied only to the current in the lightning channel (the phenomenon of current cutoff), is the disruption of current flow in the lightning channel that is accompanied by the loss of channel luminosity. This interpretation of current cutoff lacks any quantitative description regarding the current magnitude. Thus, not surprisingly, the questions of residual current and residual luminosity during current cutoff are still unsettled, and are often brought up in the literature (e.g., [17]). We define current cutoff as an irreversible decline of the current in the lightning channel, obviously accompanied by decreasing, and then disappearing, channel luminosity.

For a unipolar leader to advance, the longitudinal $E_{int}$ should be significantly smaller than the ambient *E* field, and the potential difference at the leader tip between the leader potential and the ambient potential should be greater than a certain minimal threshold value. When the potential difference at the leader's tip becomes equal to that threshold value, the propagation ceases and the leader's current cutoff begins. This type of current termination, called "the death of the channel" by Mazur and Ruhnke [16], is most clearly visible in the development of single, unbranched leader channels, and also of individual branches in the branched leaders. Current cutoff in unbranched channels starts as a process of the irreversible decline of the current, rather than as an instantaneous act (drop-off), and within a few tens of milliseconds brings the current to the value of tens of milliamps. This dynamic is seen in the current record of a multistroke negative CG flash (see Fig. 5) during the intervals between sequential return strokes. However, it takes several hundred milliseconds, if not a few seconds, to bring the current of the decaying return stroke to zero, evidence of which is seen in the record in Fig. 3, after the last return stroke current pulse. So, the answer to the rhetorical questions in the title of the paper by Ngin et al. [17]; "Does the lightning current go to zero between the ground strokes? Is there a current "cutoff?" may be as follows: Because the full current cutoff process (down to zero) lasts significantly longer than the time intervals between return strokes, the current does not come to zero before it is interrupted (at the current level of a few milliamps) by a dart leader that attaches to the ground, and starts the next return stroke. Thus, total current cutoff does not happen between return strokes, but rather occurs only after the final return stroke.

As current cutoff process continues in the cooling channels of both leaders and return strokes, the channels remain as charged plasma. The evidence of this is seen in the slowly-decreasing (for hundreds of milliseconds) electric field produced by the cooling leader channel long after the current there has dropped to near-zero (see example in Fig. 4), and in the residual ionization present in the cooling return stroke channel prior to the occurrence of a dart leader (see Fig. 5). The E-field record in Fig. 4 also provides another illustration of the time-lag of the potential gradient behind the current change in the free-burning arc, as described earlier. The presence of a small residual current (in milliamps) during the cooling of the channel is evident from the current record after the last return stroke in Fig. 3.

Branched lightning leaders are similar to the living branching trees, where the shielding, from ambient light, of the lower branches by the higher branches, is akin to shielding the lower branches of lightning leaders from the ambient electric field needed to support their growth. In branched leader channels, in addition to the phenomenon of "the death of the channel" in each straight branch, the screening of branches exists within the branched structure, which affects the changing total current in its trunk [16]. The screened branches cease propagation, so the current within them dies, while the upper branches continue to develop, and contribute to the total current at the leader's trunk. The

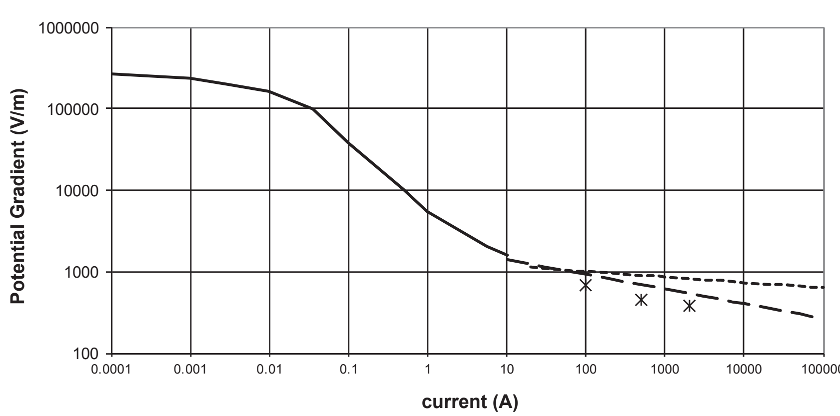


**Fig. 1.** Modified King's curve of the *E-I* characteristic of a free-burning arc in air for the entire range of lightning currents. The dashed lines and stars depict results of experiments with arcs of longer length than the 5.2 cm in the original King's curve [7], which is marked by a solid line [16].

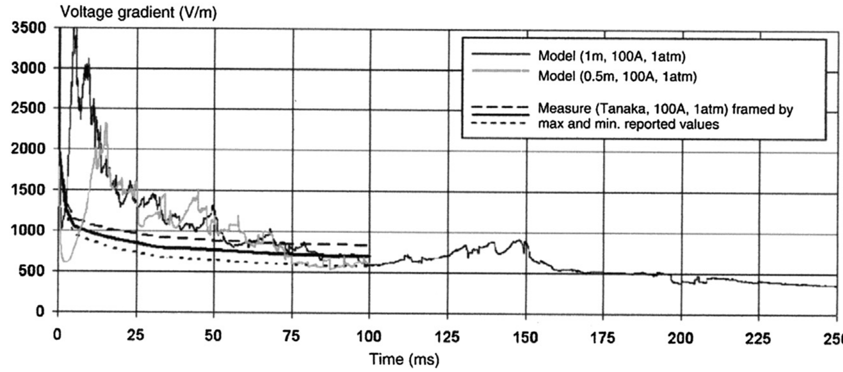


**Fig. 2.** Evolution of the measured and computed internal voltage gradient $E_{int}$ in a free-burning arc after applying 100 A step-current (adapted from Ref. [2]. Modeled are two leader channels 0f of 0.5 m and 1 m length. The $E_{int}$ approaches asymptotically its final value in the course of more than 100 ms after the current was switched on.

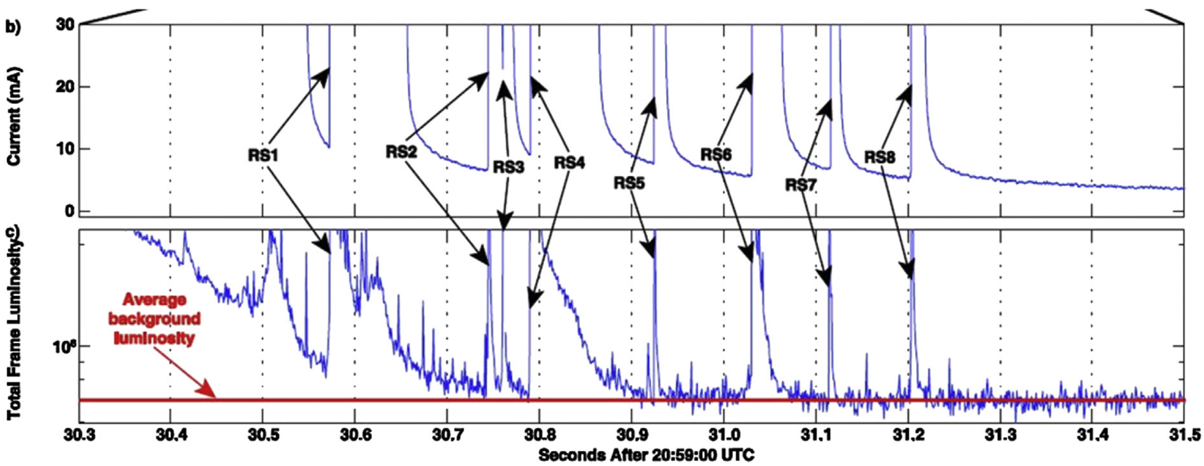


**Fig. 3.** The 1.2 s plot of current on a linear scale and the total frame luminosity on a log scale of a multistroke CG flash. The current did not drop below 5 mA between return strokes in the event. (Adapted from Ref. [17].

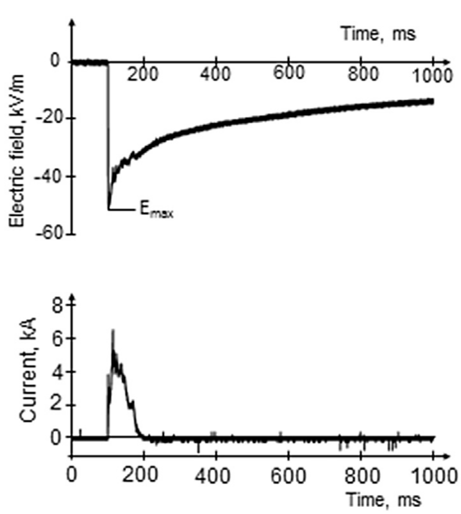


**Fig. 4.** Records of electric-field change on the ground and current in the upward negative leader triggered from the Peissenberg tower in Germany (Courtesy F. Heidler).

conclusion reached by Mazur and Ruhnke [16] was that, in branched leaders of both polarities, the current in the leader trunk is affected by two processes: (1) the growth of upper branches which contribute to increasing current; and (2) the screening effect from upper branches on the lower ones, which contributes to decreasing current. However, the total current in the leader's trunk, reaching a zero value, will not occur until all upper branches cease to propagate.

## 4. Development of recoil leaders

Recoil leaders are major players in almost all types of lightning flashes; in triggered, upward positive leaders and in multistroke, negative CG flashes, by reaching the ground as dart leaders after current cutoff, they lead to subsequent return strokes. Also, by attaching to the trunk of the leader, or to a return stroke channel with continuing current flowing, recoil leaders lead to subsequent M events [14]. Here is a summary of the known facts obtained from various observations related to recoil leaders, which should be addressed in any proposed physical model of recoil leader formation:

- There is no observational evidence of "positive" recoil leaders occurring in (1) negative leaders triggered by the rocket-and-wire technique [6], or (2) in return stroke channels of positive CG flashes after the channel cutoff, or (3) from the negative end of the lightning tree during the initial stage of the IC flash [10].
- An upward positively charged leader initiated by a tall structure exhibits a pulse-type luminosity produced by M-events, and thus, by recoil leaders, in a branched structure outside or within

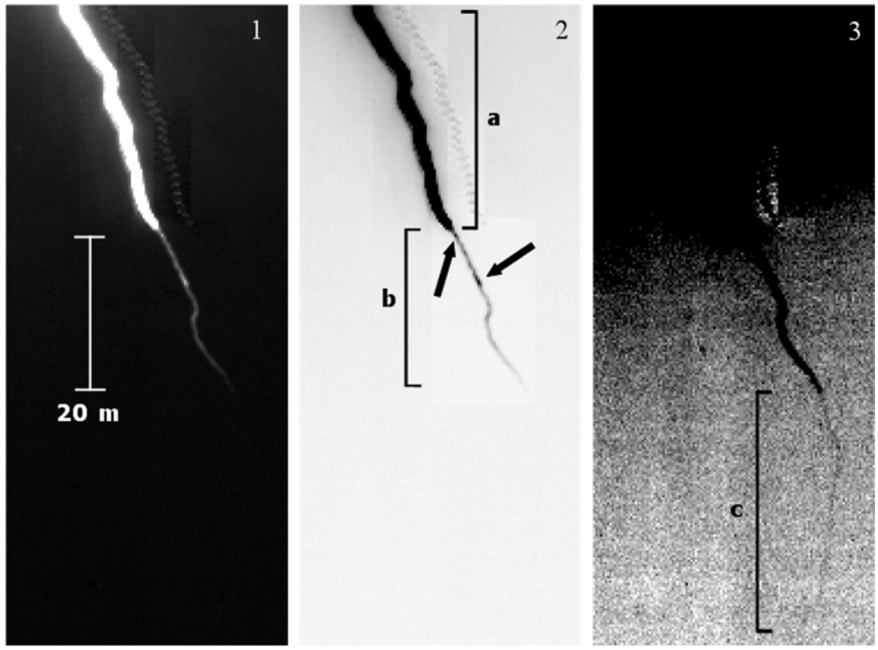


**Fig. 5.** Close-up positive and inverted (negative) images of a descending negative dart leader. (a) A highly-luminous leader channel; (b) and (c) low-luminosity zones ahead of the leader tip, along the path of the previously-existing positively-charged channel of the return stroke. The high-speed camera, a Photron SA1.1, was operated at a frame rate of 10,000 fps. The lack of any observable luminous channel in the frame immediately prior this sequence indicates the absence of residual luminosity from the prior return stroke [19].

a cloud region. Evidence for this is presented in high-speed video observations in Ref. [14] and in Ref. [24], and also in observations with Lightning Mapping Array (LMA) (e.g., [5] and [3]).

- On the other hand, an unbranched upward positively charged leader that is initiated by a tall structure, and dies off *without the ensuing dart leader* to ground, exhibits the type of slow-luminosity variation associated with changing ambient potential distribution in the cloud regions. The evidence and analysis of this is presented in Refs. [14,16].
- Recoil leaders have been mistakenly perceived as negatively charged, unipolar leaders propagating along the path of a previous positively charged leader or return stroke of a negative CG flash towards the branching points, or towards the ground. This perception, which made no physical sense for an electrodeless discharge, has been disproved by a high-speed video observation of a recoil leader [15] that showed the bidirectional development of a bipolar recoil leader occurring along an old branch of a positively charged leader initiated from a tall tower. The recoil leader, the development of which is depicted in Fig. 6, started 10 ms after the current cutoff of the preceding positively charged branch. The configuration of the preceding branch is restored after the recoil leader's attachment to the trunk seen in Frame 10.
- In branching leaders, recoil leaders do not occur while the positively charged branch is still visibly developing, but do so tens of milliseconds after the preceding branches become invisible. The evidence for this is obtained from LMA observations [23] and high-speed observations [14].
- In branching leaders, recoil leaders do not originate at the tips of preceding branches. The suggestion that recoil leader originates *near* the tip of the preceding positively charged branch, based on observations with LMA [23], corresponds to the observation that the positively charged part of the bidirectional recoil leader is much shorter than the negatively charged one, and thus, closer to tip of the preceding positively charged branch (see Fig. 6).
- Electrostatics cannot explain and, thus, are not applicable to the process of transformation (cooling) of the leader channel after current cutoff, which lasts hundreds of milliseconds [20].
- The "negative resistance" in the *E-I* relationship of free-burning arcs, and therefore, the arc's features — a uniform current and a potential gradient (internal E-field) along the arc channel — are applicable to a unipolar leader channel. The assumption of a uniform current in the leader channel is more fitting for individual branches than for the trunk of the branching leader, because the current in the trunk of the growing leader is not always uniform [16].
- There can be no further propagation of the leader after its tip reaches a region with a critical potential drop, a condition of "the death of the channel."

The earlier hypothesis, of recoil leader formation from the lower end of the developing positively charged leader [11] was based on the assumption that a leader can continue to propagate after current cutoff from the ground, which is not the case, as we now know. Also, the purely electrostatic approach to recoil leader formation used in the hypothesis cannot be applied to the state of transformation of the leader channel after current cutoff.

An analysis of the listed observations brings us to the following conclusions that should be borne out by a conceptual model for recoil leader formation:

1. Recoil leaders occur only in branching positively charged leaders (either inside or outside the cloud), which either follow return strokes that enter the cloud in negative CG flashes, or are parts of IC flashes, or are initiated by a rocket-and-wire technique or tall ground structures.
2. The conditions for recoil leader formation should exist in a single unipolar branch of a branched leader. The propagation and termination of this branch will be affected by the "screening effect" from neighboring branches [8] and current cutoff in the branch will occur as "the death of the channel."

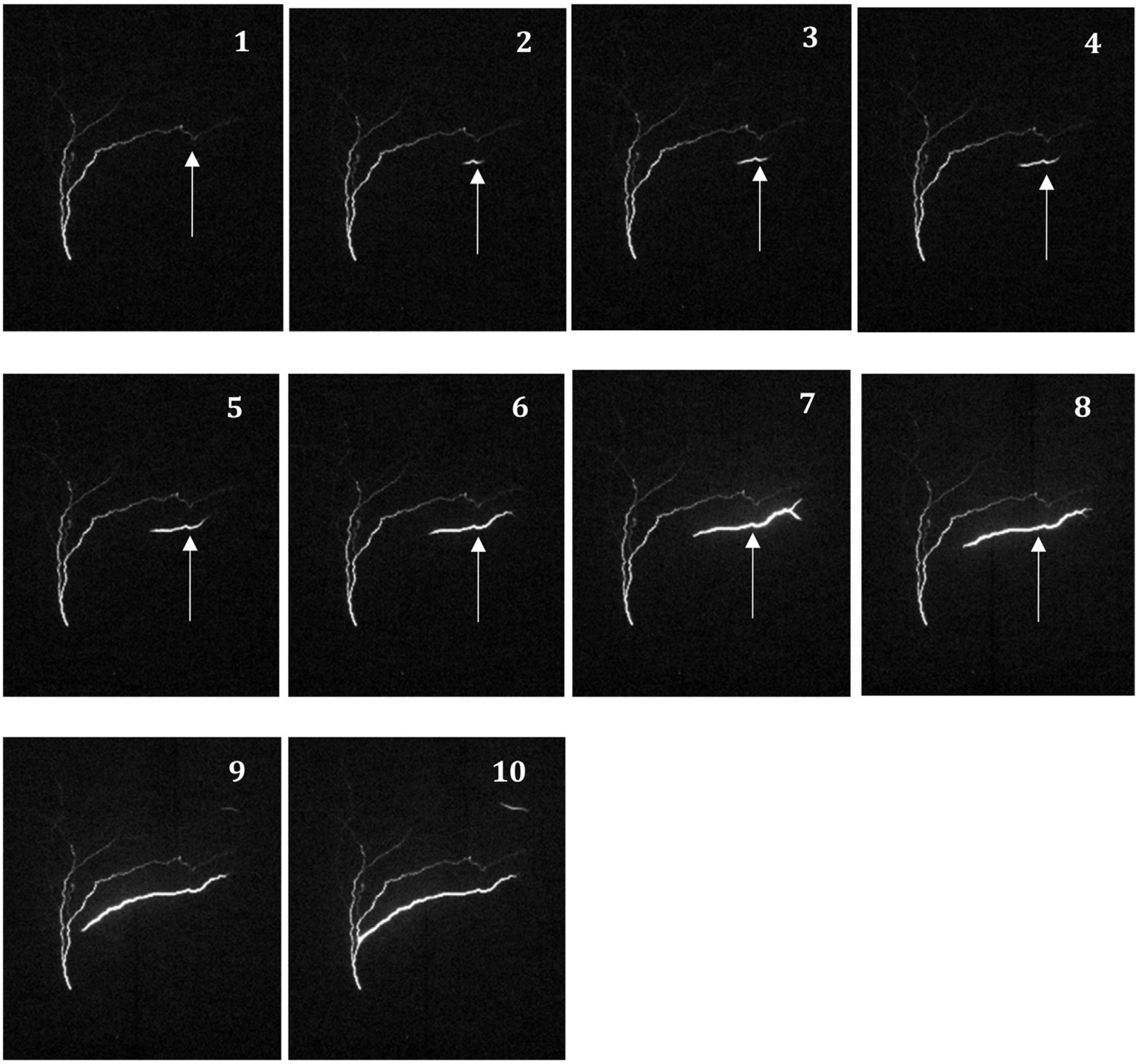


**Fig. 6.** Formation of a recoil leader into a bipolar, bidirectional leader, from video observation with recording speed of 54,000 fps [15]. The bidirectional development of the recoil leader is clearly seen starting in frame 2, and continuing until frame 7 for ~110 μs, while the total duration of a recoil leader up to attachment to the old branching point is ~180 μs After frame 7, the development of the positively charged part of the recoil leader ceases, while the negatively charged part reaches the branching point of the main leader trunk. The vertical arrow points to the location of the starting point of the recoil leader. It is important to notice the starting point of this recoil leader, which is not at the tip of the preceding branch.

3. The mechanism of recoil leader formation should be based on the electrodynamic (not electrostatic) approach that applies the similarities of lightning leaders to a free-burning arc.

## 5. A proposed conceptual model of recoil leader formation

Any branched leader consists of a number of individual branches that are separated in space, creating together a branched structure of a certain density. The conceptual model is applied to recoil leader formation in an individual branch of the branched leader that develops current cutoff, regardless of the leader polarity.

Recoil leaders, by their very nature as electrodeless discharges, are similar to leaders that are parts of IC and CG flashes ("natural leaders"). The main difference between recoil and such natural leaders is in their origins, one that occurs at a point on the existing cooling plasma channel, the other which occurs in "virgin" air. This difference in origins leads to the different types of paths of natural and recoil leaders, and consequently, to differences in speed, current, luminosity and the branching structure of the two leaders (absent in recoil leaders, but present in natural ones). However, because of the similarity in the *nature* of recoil and leaders of IC and CG flashes, it is reasonable to assume that the conditions for recoil leader formation are similar to those in natural leaders. Then remaining unknown are the magnitudes of the variables that constitute the initiation conditions, which may be different in the two cases.

We still do not know what constitutes the specific electrical conditions present during the initiation of natural leaders. It is well understood, however, that residual ionization in the cooling channel of the preceding positively charged leader, present for hundreds of milliseconds, would ease the formation of a recoil leader, e.g., by diminishing the ambient E-field for the initial electrical breakdown.

The current of the leader is proportional to its speed of changing induced charges, $dQ/dt$, and the leader's speed is affected by the potential drop at the leader tip, $\Delta\varphi$. The empirical relationship $V$ (m s$^{-1}$) $= 15\ \Delta\varphi^{0.5}$ suggested in Bazelyan and Raizer [1] explains the effect of the potential drop on both the speed and electrical features of the propagating leader.

The usual development of any unipolar, single channel leader (e.g., upward rocket-triggered positively charged leader) starts with acceleration, during which the potential drop at the leader tip $\Delta\varphi$ increases, then slows down, during which the potential drop at the leader tip $\Delta\varphi$ decreases, before reaching equilibrium with the ambient potential, and ends with the "death of the channel"- type current cutoff. The shape of the ambient potential distribution to accommodate such development of a unipolar positively charged leader, regardless of the orientation of its propagation path, should look like the one shown in Fig. 7. The vertical scale in Fig. 7 is the length of the leader's path, from the origin (e.g., a branching point) to the point of termination. The horizontal scale, for the case of the positively charged branch, is the ambient potential of negative values, starting either at a zero ground potential in the case of a rocket-triggered upward leader, or at the potential of a branching point on the conductive trunk of a branched leader. The plot in Fig. 7 also illustrates a qualitative relationship between the ambient electrical environment and the propagating unipolar leader before the termination of the leader. Similarly, plot in Fig. 8 is used to illustrate a qualitative relationship between the ambient electrical environment and a recoil leader during cooling of the channel of the preceding leader.

From the "negative" *E-I* relationship in the free-burning arc channel depicted in Fig. 1, one obtains a value of the potential gradient, grad $\varphi = -E_{int}$ for a given leader's current; both the current and the potential gradient are assumed to be uniform along the leader channel. Two factors affect the potential at the tip of the developing leader channel, which is $\varphi$ = grad $\varphi\ l$: the potential increases with the length of the channel, $l$, and with the changing of the potential gradient, grad $\varphi = -E_{int}$, as the result of the changing current of the leader. Therefore, the arrow representing the potential of the leader channel in Fig. 7 changes its length during propagation and changes its tilt toward negative ambient potential, responding to the changes in leader current. The low end of the propagating leader channel remains at the initial potential value.

When the unipolar leader reaches the region of the cloud where the potential drop $\Delta\varphi$ is close to the threshold value, the channel

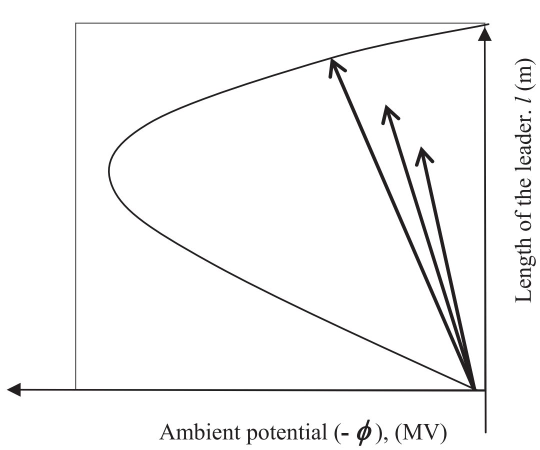


**Fig. 7.** Conceptual sketch of the evolution of the potential of the ascending unipolar, positively charged leader at the slowing phase of its propagation. The potentials are marked by the sequence of arrows on a background of the vertical profile of the ambient potential distribution.

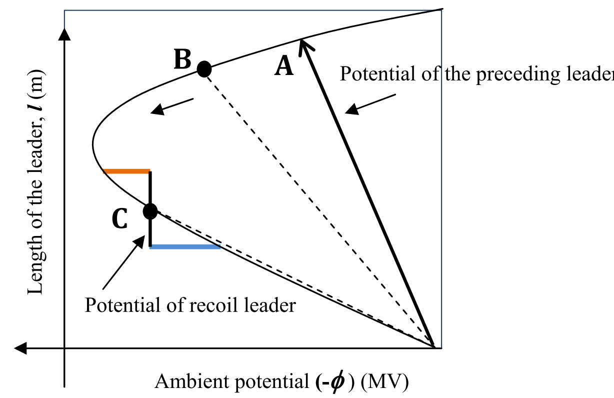


**Fig. 8.** Conceptual sketch of the evolution of the potential of an old leader channel during its cooling stage, marked by the sequence of dashed lines that slide along the ambient potential line, from point A towards points B and then C, coinciding with the decreasing length of the cooling channel that merges with the ambient electric environment. Conditions for formation of a recoil leader occur at point C, where the ambient E-field is sufficient for initial electrical breakdown. The potential drops $\Delta\varphi$ at the tips of the negatively- and positively-charged parts of the formed recoil leader are marked as blue and red lines, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extension stops, and the process of current cutoff begins. With the continuing decrease of the current in the cooling plasma channel of the leader, the potential gradient in the channel, and so also the potential at the tip of the decaying channel, will increase. This potential, however, cannot become greater than the ambient cloud potential, because the decaying channel can only gradually merge or dissolve into a surrounding environment, which is characterized by the ambient potential distribution. There is no other ending for the cooling, decaying plasma channel that would make any physical sense.

We assume that the process of the merging of the old leader channel into the ambient potential begins from the top of the cooling channel, where the cessation of propagation occurred, and that the merging continues downwards. This dynamic is depicted as the sliding of the tip of the cooling channel potential downwards along the curve of the ambient potential profile, while the length of the remaining (lower) part of the cooling channel decreases (see Fig. 8). If, or when, in the process of this evolution, the tip of the cooling channel reaches the region of the electrified cloud (a point on the ambient potential curve) with an ambient E-field sufficient to initiate electrical breakdown, this may become a condition for a streamer-leader transition followed by the formation of a bidirectional and bipolar recoil leader.

The development of a bipolar recoil leader in a conceptual model should be similar to that which is observed in recoil leaders in nature (see Fig. 6), i.e., with a negatively charged part of the leader moving towards the old channel origin (seen as downward in Fig. 8) and a positively charged part of the leader moving in the opposite direction (seen as moving upward). In the case of the ambient potential distribution depicted in Fig. 8, such a development may occur only if the formation of the recoil leader takes place at the lower slope of the ambient potential curve, e.g., at point C, and not earlier, at its upper slope, e.g., point B.

The negatively charged part of the bidirectional recoil leader has a "green light" for propagation all the way to the branching point, because its potential drop at the tip will only increase with the leader's approach to the branching point. The positively charged part of the bidirectional recoil leader will develop in the opposite direction until its tip reaches the point of equal potential with the environment. These dynamics of recoil leader development are

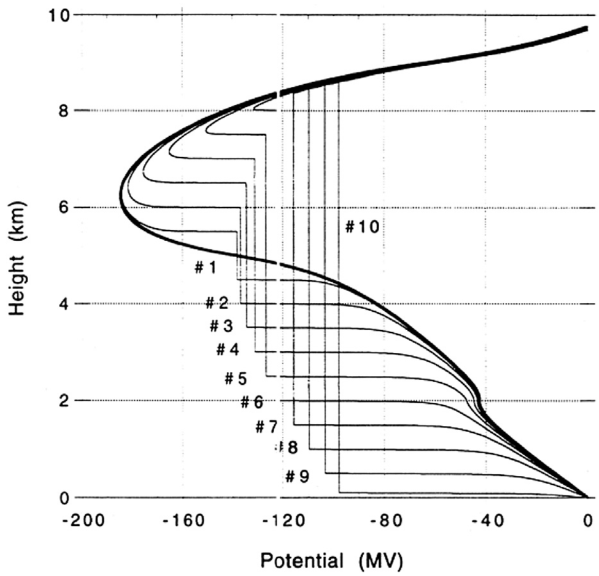


**Fig. 9.** Evolution of the potential profiles of the developing cloud-to-ground leader in a model of a mature stage thunderstorm (Adapted from Ref. [12]).

observed in the series of high-speed video frames showing a developing recoil leader in Fig. 6.

The duration of the cooling process from the beginning of the current cutoff (point A) until the initiation of the recoil leader (point C), but not to zero current value, could be in tens of milliseconds, depending on the ambient electrical environment.

The dynamics of recoil leader development depicted in Fig. 8 are similar to those of natural leaders that start from the region with the highest ambient E-field, and which propagate with equal speeds (see Fig. 9), or have faster negative leader and slower positive leader speeds [23]. In essence, the possibility of recoil leader formation is determined by the profile of the ambient potential along the cooling and still-ionized path of the preceding unipolar leader, and thus, by the presence of an ambient E-field sufficient for the initial electrical breakdown for recoil leader formation. Absent these conditions, recoil leaders would occur in every CG flash with a single return stroke, or in every case of an unbranched upward positive leader. This seems not to be the case at all.

### *5.1. Recoil leader formation and polarity asymmetry in branched leaders*

Current cutoff is observed in branching leaders of both polarities: in IC and CG flashes, and in upward negatively- and positively charged leaders triggered with rocket-and-wire techniques. However, recoil leaders are observed only in positively charged branching leaders, while overwhelming evidence points to the total absence of recoil leaders in negatively charged branched leaders, and consequently, in the return strokes of positive CG flashes, which have only a single return stroke. This evidence also suggests that the requirement for a suitable ambient potential distribution for the formation of recoil leaders is fulfilled only in positively charged branching leaders. Claims of more than a single return stroke in positive CG flashes lack the needed support of carefully analyzed observations that should confirm occurrence of more than a single return stroke along the same channel to ground or commonality of origins for sequential return strokes. However, positive CG flashes with several channels to ground separated by distances of tens of km from each other have been observed in summer thunderstorms [22].

In search of an explanation for the observed difference in recoil leader occurrence in branched leaders of two polarity, we shall examine the polarity asymmetry in leaders of both polarities, which manifests itself in their speed of propagation, and thus, in their currents, and also in the branching features of the two types of leaders. The spatial composition of the branching structure, and the number and sizes of the branches, would affect, by the screening effects, the exposure of individual branches to the ambient E-field, and thus, the branch's current.

High-speed video observations of downward negatively charged leaders below the cloud base reveal a highly dense dendritic structure made of *small branches* (see example in Fig. 10A). On the other hand, most downward positively charged leaders are made of single channels and, when branched, have a structure distinctly different from that in negative leaders, with only a few individual *long branches* separated by large spaces (see Fig. 10B).

The same profound difference in the density of branches, their numbers and sizes between positive and negative leaders is observed inside the cloud, when we compare both the plain view and vertical profiles of the map of radiation sources of these leaders (Fig. 11).

The difference between positively - and negatively charged leaders in their speeds of propagation and also in branching structures apparently affects (1) the duration of the continuing current prior to the beginning of the current cutoff process (hundreds of milliseconds vs. tens of milliseconds, respectively), (2) the magnitude of this current (hundreds of Amperes vs. few kilo Amperes, respectively), and (3) the rise-time and drop-time of the continuing current (a few milliseconds vs. tens of millisecons, respectively) and the duration of the current cutoff process [4].

It is reasonable to assume that the ambient potential

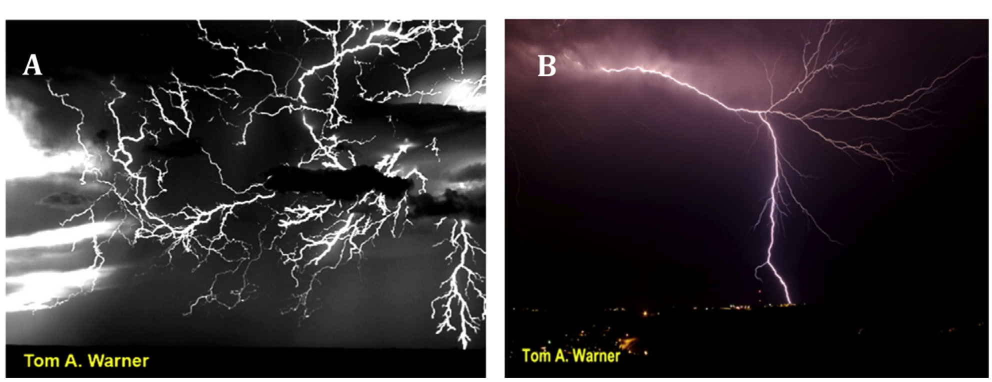


**Fig. 10.** Time-compressed images from high-speed video observation of (A) branched negative leaders below the cloud base, and (B) a branched downward positive leader of a positive CG flash (courtesy T.A. Warner).

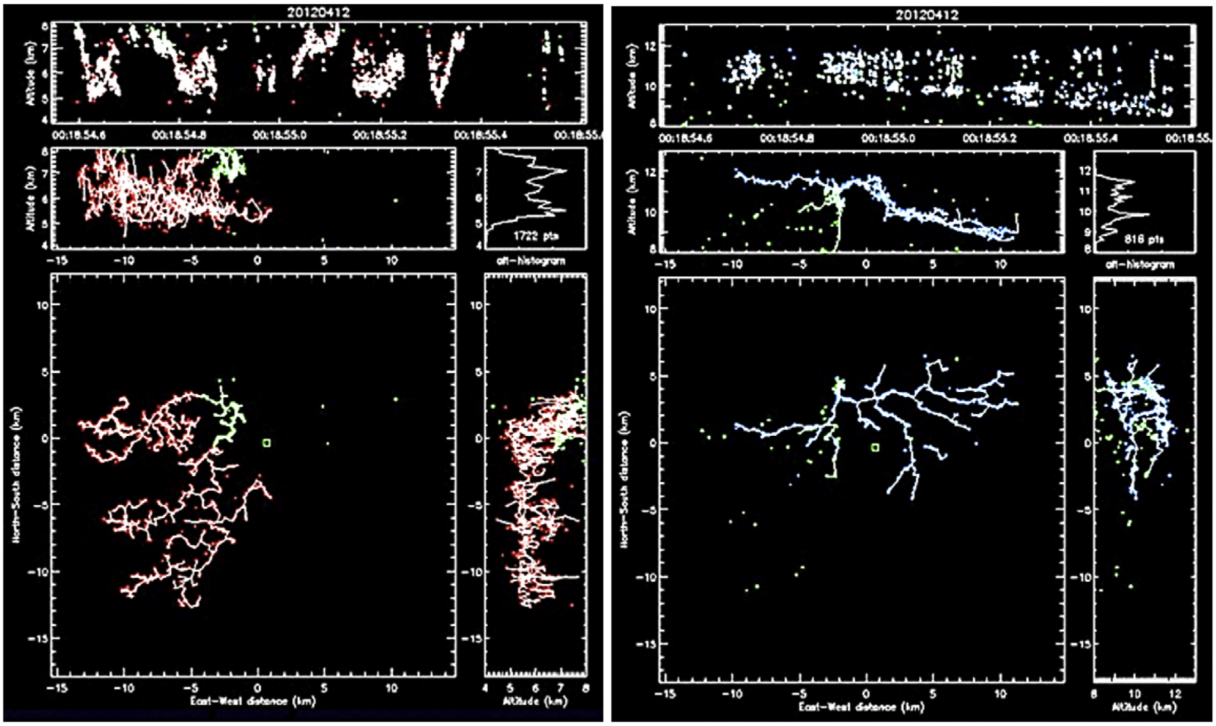


**Fig. 11.** Radiation map of two parts: the region of negative breakdowns (left panel) and the region of positive breakdowns (right panel) of an intracloud flash, obtained with the Lightning Mapping Array (LMA) system. The panels in the figure from top to bottom are: (1) Altitude-Time, (2) Altitude-Distance (East-West), (3) Distance (North-South) – Distance (East-West), (4) Distance (North-South)-Altitude. (Courtesy of Paul Krehbiel).

distribution in a *larger* spatial gap between *longer* branches of positively charged leaders is suitable for formation of a recoil leader in the cooling channel of a preceding branch. On the other hand, a much higher number of *smaller* branches per-unit-volume in negatively charged leaders produces a significant reduction of the ambient E-field in the *smaller* spaces between shorter channels, making the E-field unsuitable for the recoil leader formation. This explains why the proposed model of recoil leader formation may not lead to the occurrence of recoil leaders in heavily branched negatively charged leaders. The conclusion that the highly dendritic structure of negative branching leaders prevents the formation of recoil leaders may seem like an intuitive one, but this is perhaps the only conclusion that can properly explain why the proposed qualitative concept of recoil leader formation, which is indifferent to the polarity of the preceding unipolar leader, actually works only in cases of positively charged branched leaders.

## 6. Conclusion

The proposed qualitative concept of recoil leader formation has four essential components in its foundation:

(1) It is based on the mechanism of the current cutoff process presented in Mazur and Ruhnke [16]; which is "the death of the channel" in unbranched channels, plus an additional screening effect in branched channels.
(2) It uses the analogy of a unipolar leader (a branch in a branched structure) to a free-burning arc with a uniform current and internal E-field.
(3) It interprets the cooling of the preceding leaders during the current cutoff process as being similar to the transformation of current and potential gradient in a free-burning arc channel, which leads to the gradual merging of the cooling channel, starting from its tip, into the ambient environment.
(4) It assumes that the conditions for the initiation and bidirectional, bipolar development of a recoil leader are qualitatively similar to those in natural lightning leaders, but require a lesser ambient E-field, due to the presence of the ionized media in the cooling channel of a preceding leader.

The absence of recoil leaders in branched negatively-charged leaders, as well as the always-single incidence of return stokes in positive CG flashes, is interpreted as the effect of the dense branching structure of small and numerous branches of these leaders, which prevents the ambient electric field from reaching the level necessary for initiation of an electrodeless discharge, such as a recoil leader.

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