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Polarity Asymmetry in Lightning Leaders: the Evolution of Ideas on Lightning Behavior from Strikes to Aircraft

This study is concerned with outstanding questions on the mechanism of lightning and its theoretical treatment as a bidirectional leader. Previous studies of lightning strikes to aircraft are reviewed to highlight the key physical phenomena: the simultaneous action of both positive and negative leaders, the frequent tendency for electrical current in certain channels to cut-off abruptly, and the subsequent tendency for recoil leaders to initiate in these previously cut-off channels to establish a new stroke in the flash.

Introduction

This study is concerned with outstanding questions on the mechanism of lightning and its theoretical treatment as a bidirectional leader. Previous studies of lightning strikes to aircraft are reviewed (§ "Evidence from aircraft lightning strikes") to highlight the key physical phenomena: the simultaneous action of both positive and negative leaders, the frequent tendency for electrical current in certain channels of the double-ended lightning 'tree' to cutoff abruptly, and the subsequent tendency for recoil leaders to initiate in these previously cutoff channels to establish a new stroke in the flash. The theoretical treatment of the asymmetrical bidirectional leader is reviewed in § "Theoretical treatment of the asymmetrical bidirectional leader", showing that current flow in the positive leader end will be consistently smaller than in the negative end. Two different physical mechanisms are presented to account for the current cutoff and recoil leader formation. They are compared and contrasted in § "Contrasting two explanations for current cutoff and formation of a subsequent stroke" with available observations as discussed in § "Comparison with available observations" toward distinguishing the two mechanisms.

Evidence from aircraft lightning strikes

Important physical evidence for bidirectional lightning development proposed theoretically by [1] came from studies of lightning interaction with aircraft [2]. Radar observations with the aircraft centered in the radar beam demonstrated that the aircraft served to trigger the bidirectional development, showing extension of the radar echo away from the pronounced metallic aircraft target in both directions along the fixed radar beam [2], leaving the aircraft in the 'trunk' of the evolving discharge with two distinct current contact points (one entry and one exit point) on the aircraft. Figure 1 shows an example of an aircraft in the trunk of a double-ended lightning tree, in this case beneath cloud base where the lightning geometry is clearly exposed.

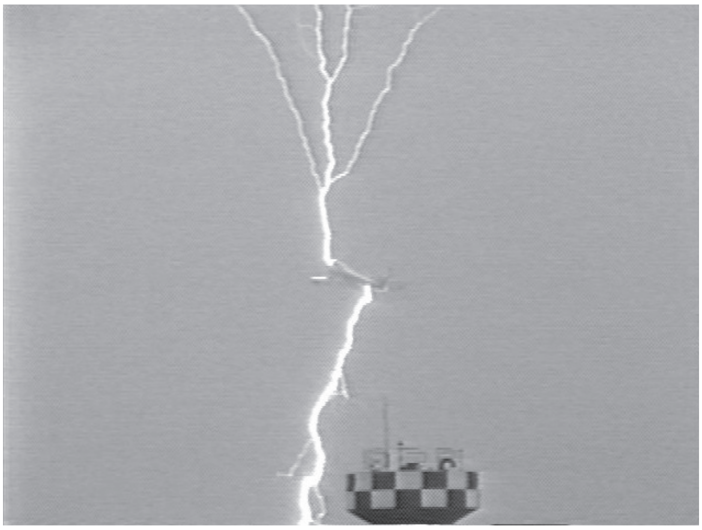

Figure 1 - Lightning strike to aircraft showing bidirectional leader development, with the aircraft in the 'trunk' of the 'tree' (from K. Michimoto and Z. Kawasaki).

A key feature of lightning polarity asymmetry [3]has also been documented in the case of lightning strikes to aircraft of the kind shown in figure 1. Recoil leader activity is confined to the positive end of the bidirectional leader [4], [5]. An antecedent condition for the recoil leader occurrence is a remarkable phenomenon also in common with natural lightning: complete cutoff of the channel current in those channels in which recoil leaders subsequently initiate [6], [7], [8].

The special location of the aircraft in series with the bidirectional leader in typical lightning aircraft interactions allows for unique observations of lightning both from within and on the surface of the aircraft.

Theoretical treatment of the asymmetrical bidirectional leader

Kasemir [1] seminal electrostatic treatment of lightning as a double-ended extension of a long, thin conductor aligned in a uniform electric field gave no preference to positive and negative ends. The shape of the analytically-tractable prolate spheroid conductor was identical at either end, as was the speed of extension in the electric field. As a consequence, the current is identical at both ends and the distribution of current in a prolate spheroid is uniform, consistent with recent applications of this model to observations of lightning [7], [9]. Both the positive and negative line charge densities $\lambda(z)$ increase linearly from midpoint of the conductor to their respective ends (figure 2).

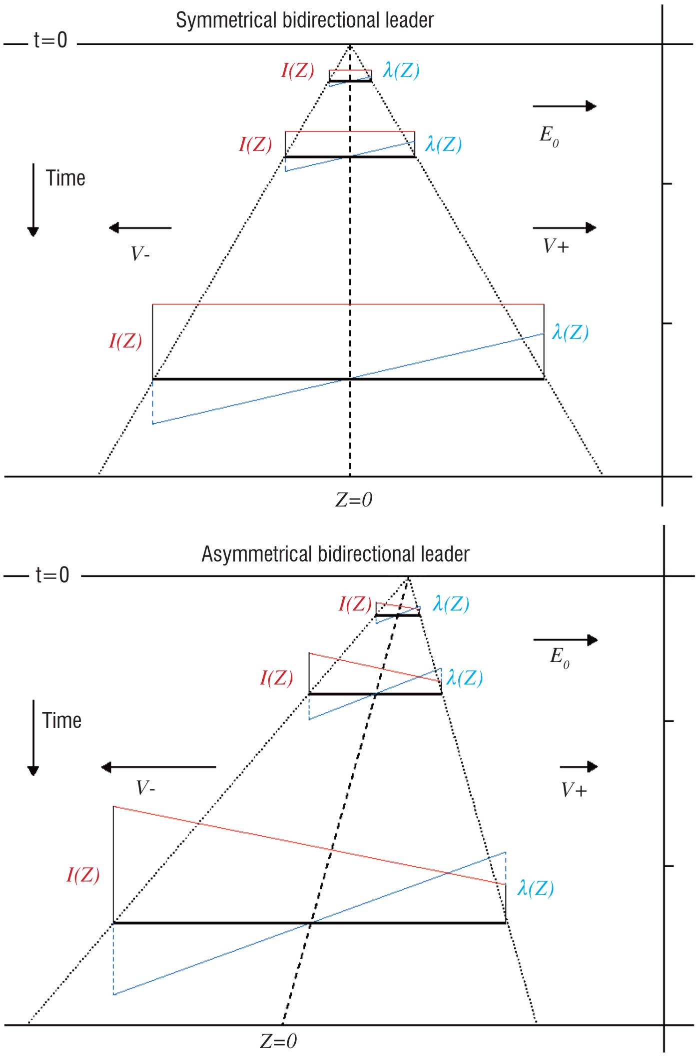

Figure 2 - Illustration of symmetrical and asymmetrical development of bidirectional leaders aligned with an imposed electric field [10].

Mazur and Ruhnke [7] first recognized and emphasized the polarity asymmetry in recoil leader development evident in both the aircraft-initiated bidirectional lightning and in natural lightning. They speculated that the "difference between negative and positive leader breakdown is the important factor involved". Recent studies by [10] have confirmed this earlier speculation by identifying evidence for a distinct contrast in the speed of positive and negative leader progression, and by generalizing the Kasemir [1] mathematical model to an asymmetrical bidirectional development. The behavior of the symmetrical (matched leader speeds) and asymmetrical case (faster negative leader speed) are contrasted in figure 2, where the variation of line charge density and current along the leader channel are also shown. The asymmetry in leader speed is consistent over a wide range of scales, from laboratory point-to-plane gap studies on meter scales [11], [12], [13], to 100 meter discharges with outdoor high voltage generators [14], [15], to rocket triggered lightning [16], [17] on kilometer scales into clouds of both polarities, to natural lightning strokes to towers [18], [19], [20], to detailed LMA analysis of leader propagation on thundercloud scales [21].

We do not have a fundamental quantitative explanation for the marked polarity asymmetry in leader speed, except to recall that a pronounced asymmetry in progression behavior is well established for negative and positive leaders, in both laboratory scale sparks [11], [12], [22] and in negative lightning stepped leaders [23], [24], [25]. On the scale of the respective leader "head", complicated streamer physics is controlling the leader extension. The negative progression is intermittent and discontinuous by virtue of the existence of "space leaders" that form out front of the main leader channel and which then extend in both directions to link with the main leader behind, setting up conditions for a new space leader, and so on. In contrast, the positive leader end progresses smoothly, led by positive streamers, generally with lower electric field thresholds for progression, and without the participation of space leaders. Evidently the jumpy progression at the negative end is faster despite the interruptions because the speed of space leader expansion is substantially greater than the positive streamers. The advent of ultra-high speed lightning imaging is likely to clarify this situation in the near future.

Returning to figure 2 in the symmetrical bidirectional leader, the current is constant with length, but in the asymmetrical case, the current varies linearly from the low speed positive end to the high-speed negative end. The current I at each end is given by

$$I = (2\pi\varepsilon_0/ln(L/r))\, E\, LV \qquad (1)$$

where L is the total length in meters, r is the semi-minor-axis of the prolate spheroid, E is the uniform electric field, and V is the leader tip speed at that end (in m/s). The distribution of line charge density $\lambda(z)$ remains symmetrical at any given time, assuring conservation of electric charge on the conductor. But the zero of line charge density translates in space at a speed which is half the difference of the two leader speeds.

Heckman [28] investigated the instability of lightning using an equivalent circuit consisting of three elements in parallel: a current source, a channel capacitance and a negative resistance. The current source represented the extension of the lightning conductor in the electric field of the thunderstorm. The channel capacitance, associated with charge and voltage on the conducting lightning channel, was represented analytically by

$$C = 2\pi\varepsilon_0 L/ln(L/r)$$

(with ε_0 the permittivity of free space, L the channel length and r the channel radius), an elementary result from electrostatics. The third circuit element is a negative resistance, based on observations of arc channels in air [26], [27] showing that for low current (generally <100 A), the channel voltage drop increases with decreasing current, and therefore exhibits negative differential resistance. The equivalent circuit described here is decidedly nonlinear by virtue of this third circuit element. [25] derived conditions for the linear instability of this circuit. These conditions, involving channel current and channel length, are shown in figure 2. The irregular black line boundary separates a stable region (upper left) for continuing current from an unstable region (lower right) in which the current is predicted to cutoff. The negative differential resistance plays a fundamental role here: reduced current imposes increased resistance, decreasing current and causing cooling of the arc, resulting in further increases in resistance, in a kind of runaway to vanishing arc current. Ordinary ohmic resistance does not behave in this way.

Based on the instability analysis of a long, thin current carrying arc with negative differential resistance, Heckman [28] produced a parameter space of current and arc channel length predicting when the current was stable (as a long continuing current) and when it was subject to cutoff. Additional strokes were made possible by the action of sustained leader extension into electric field, which then stressed the cutoff channel (by virtue of its reduced dielectric strength as a low density channel).

The unique current-length relationship (1) for the bidirectional leader was discussed previously in [10]. This relationship can be superimposed on the Heckman instability diagram, as shown in figure 3. Here the total range of (linearly varying) current in the asymmetrical bidirectional leader is shown, for propagation in a uniform field of 10^5 v/m, and with assumed positive and negative leader speeds of 10^4 m/s and 10^5 m/s, respectively. With this realistic selection of parameters, sections of the (slower) positive end of the bidirectional leader are predicted to be unstable, and hence prone to current cutoff, whereas the faster negative end remains stable. We will return to these predictions in interpreting the observations discussed in § "Comparison with available observations".

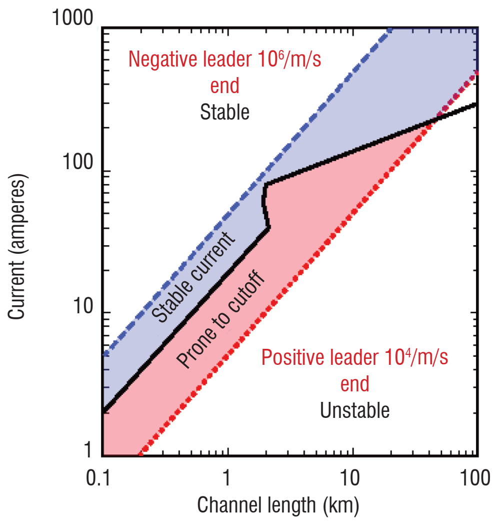

Figure 3 - Stability diagram for lightning (adapted from [10]), showing the range of current for every length of a asymmetrical bidirectional leader with negative tip speed of 105 m/s and a positive tip speed of 104 m/s.

Contrasting two explanations for current cutoff and formation of a subsequent stroke

Current cutoff

Previous sections have emphasized that the phenomena of current cutoff and subsequent recoil leaders leading to a new lightning stroke are common to lightning strikes to aircraft [5], [6], to rocket-triggered lightning [7] and to natural lightning as in figure 4 [29], [30], [31]. Twenty years ago, two distinct physical explanations for these phenomena were advanced, one by Mazur and Ruhnke [7] (with recent revision [32]) and one by Heckman [28]. Both the physical basis for current cutoff and for the subsequent breakdown to follow the same cutoff channel are distinctly different in these two treatments.

The physical picture of lightning in [7] and [32] (and subsequent work by the same authors) is based on the assumption that lightning leaders are isopotentials. Their mechanism for current cutoff is shown in figure 5 and is based on electrostatic shielding of the cloud electric field by these perfect conductors. Extensive lateral branching of the positive leader in advancing into negative space charge in the mid-region of thunderstorms leads to a reduction in the field in the channel connected to Earth. In a two-tiered development of the positive tree (see figure 5), the electric field lines terminating on the lower branches may be reduced as upper branches extend, thereby reducing the induced charge and enabling a current reversal from the side-branches to the main leader channel.

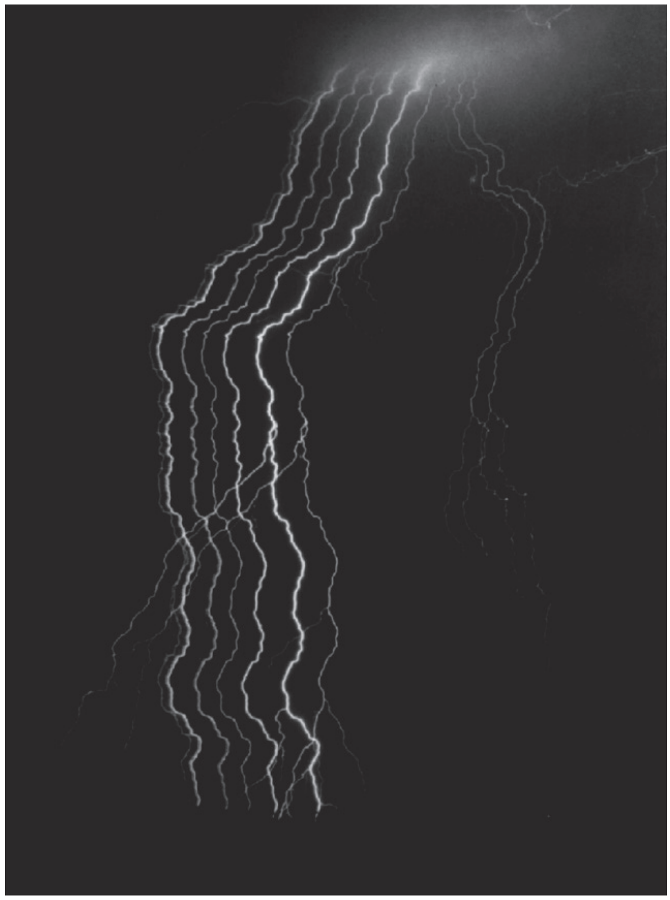

Figure 4 - Illustration of current cutoff in the channel to ground in a multi-stroke lightning flash [31]. Note the reproducibility of the fine structure of the channel tortuosity from stroke to stroke.

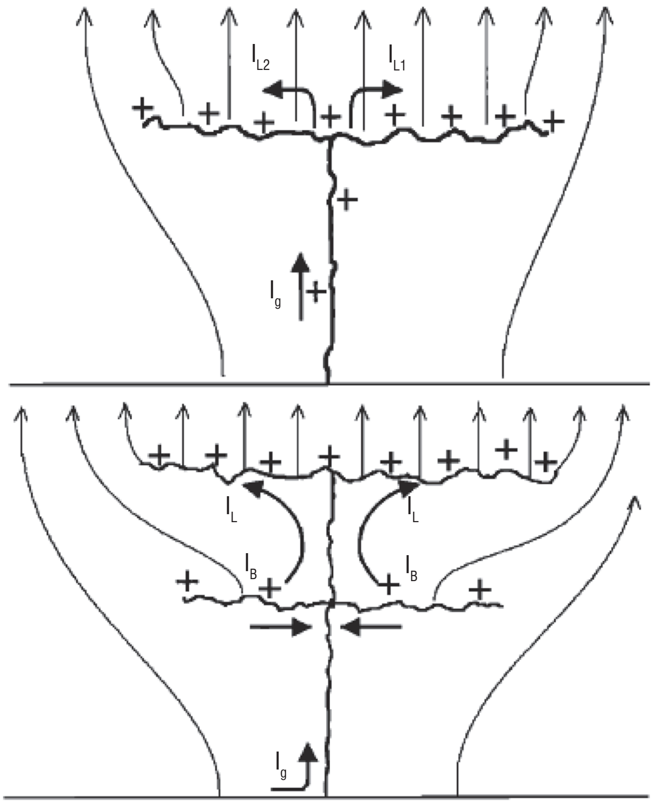

Figure 5 - Illustration of the mechanism of current cutoff by electrostatic screening, according to [7] and [37].

In contrast, the mechanism for current cutoff and current instability proposed by Heckman [28] is based on negative differential resistance in lightning channels (figure 6) and requires the departure of leader channels from the isopotential condition assumed by Mazur and Ruhnke [7], [9]). Heckman's work developed from the earlier suggestion of King [26] that "the negative resistance characteristics of the channel were important in causing the strokes to be discrete". Quantitative experiments with DC arcs in air ([33], [34], [26], [35]) show that the electric field in channels with current exceeding 100 amperes (and extending to current levels characteristic of lightning return strokes) is ~ 1 kV/m. For a leader channel length comparable to the size of a thunderstorm (~10 km), the estimated total voltage drop is 10 MV, already a significant portion of measured total potentials in thunderclouds [36]. But the mechanism for cutoff relies on the demonstrated tendency for arcs in air at currents less than 100 amperes (figure 6) to exhibit increasing channel field with decreasing current, the well-known characteristic of negative differential resistance [34], [26]. Heckman [28] and Williams [3] examined the stability of an analog electric circuit for lightning consisting of a long arc connected to a current source. This analysis established a boundary between stable and unstable lightning regimes shown in figure 3. The unstable regime leads to a diminishment of current, and the monotonic increase of arc channel electric field with decreasing current guarantees a complete current cutoff. In the lightning context, in contrast with the mechanism in [7] and [37], no branching of the arc channel is needed to produce current cutoff. This phenomenon is predicted whenever the interstroke extension of the positive leader provides less than the critical current [28].

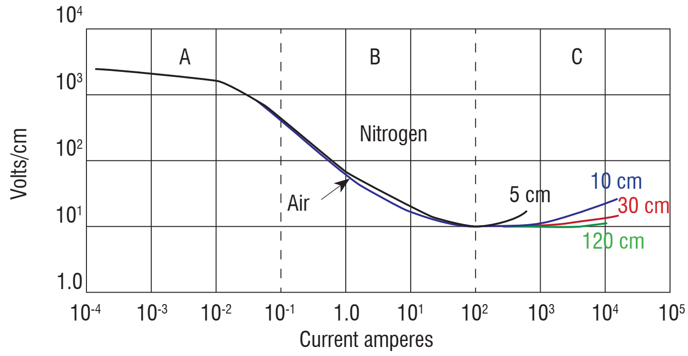

Figure 6 - Evidence for negative differential resistance in a DC arc in air [26].

Recoil leaders and subsequent strokes

The common ground in [7] and [28] is the mechanism for maintaining a current inside the thundercloud in the interstroke interval. Historically, the physical evidence for this "J-process" is indirect and was documented initially with electric field measurements by Malan and Schonland [38], showing that the negative charge increased overhead in the (cutoff) interval between strokes of a cloud-to-ground flash. Krehbiel's important contribution here [39],[30] was demonstrating that the interstroke current was predominantly horizontal rather than vertical, as [38] had argued earlier, consistent with a large body of contemporary evidence that the main negative charge region is relatively compact in the vertical in comparison with its horizontal extent. So in this context, the common mechanism for the maintenance of interstroke current is the continued progression of the positive leader(s) throughout the interstroke interval. As Mazur and Ruhnke [7] noted:

"*In their search for the origin of discrete strokes in CG flashes, Heckman and Williams[40] concluded that interstroke currents observed are entirely due to longitudinal channel extension, rather than corona envelope radial expansion. These findings concur with our concept of recoil streamer initiation.*"

Mazur and Ruhnke [7] and Heckman [28] also concur that the cutoff lightning channel becomes non-conducting, and this transition is essential for the increased voltage on the cutoff channel by the interstroke current which ultimately causes recoil leader initiation. Studies of the electrical conductivity of air versus temperature [41] show that the resistivity increases by more than 5 orders of magnitude between 3000 K (4.7 x 10^3 Ω.m) to 2000 K (1 x 10^9 Ω.m), leading Aleksandrov and al. [42] to conclude that "*such a high linear resistivity can be achieved only when in the current in the channel terminates*". This dramatic change goes hand-in-hand with the negative differential resistance with declining current depicted in figure 6. Mazur and Ruhnke [9] are noncommittal about why the subsequent recoil breakdown follows the same cutoff channel. In contrast, Heckman[28] is explicit in stating that the decayed channel is dielectrically weak because it is still warmer than ambient atmospheric temperature, and hence of low density. The cutoff channel may also be dielectrically weak because of the abundance of ions and their lower ionization potential in comparison with neutral species.

In both [7] and [28], the cutoff channel of lightning is electrically re-stressed by the increased voltage on the cutoff channel, caused in turn by the continued extension of the lightning 'tree'.

Comparison with available observations

Current cutoff

A large body of evidence for current cutoff between strokes of a lightning flash has accumulated, in the context of aircraft strikes, the rocket triggering of lightning and in all forms of natural lightning. It should be noted at the outset of this discussion that the common existence of discrete strokes superimposed on continuing current, a prevalent phenomenon in both aircraft lightning strikes and rocket-triggered lightning, is no indication that current cutoff played no role in the discrete stroke. It is only necessary that the current cutoff occur in a secondary branch also connected to the main channel in which the current is measured, and that the cutoff channel be at a different electrical potential than the main channel. A good example of this behavior is found in [9].

Evidence for cutoff in lightning strikes to aircraft is the absence of modification to the metallic skin of the aircraft as the current attachment point sweeps along the aircraft surface. Distinct pitting of the surface occurs at times of discrete strokes, but the surface is often unblemished in the interstroke intervals.

Pulse-to-pulse radar observations on lightning channels also provide evidence for current cutoff. Hewitt [43] noted systematic diminishments in radar returns during the latter portion of interstroke intervals in natural lightning. In commenting on these observations and their interpretation, Krehbiel and al. [39] noted the following:

"*An unresolved discrepancy between the present results and those of Hewitt concerns his observations that the interstroke echoes decreased in intensity during the latter portion of the interstroke period and that the next stroke generally did not occur until this decrease had taken place. If the echo intensity were an indication of the interstroke current, Hewitt noted, such a result would indicate that the current decreases substantially 10-20 ms priot to the subsequent stroke. Such an effect is not apparent in the electric field measurements, either of this investigation or others. Rather, the field changes uniformly throughout the interstroke interval, indicating that the dipole moment change (and hence current, assuming constant displacement) remains approximately constant.*"

A plausible resolution of this apparent discrepancy is that Hewitt's radar beam was aimed at the cutoff channel to ground and not the extending positive leader tips believed to maintain the interstroke current in other portions of the cloud. Radar observations on a rocket-triggered lightning channel at 10 m range [28], for which there is no ambiguity concerning the radar lightning target, indicate that current cutoff occurs on a time scale of milliseconds.

The complete disappearance of lightning channels to ground in optical/photographic observations of ground flashes is widely recognized [31]. Recent observations by Mazur and Ruhnke [9] also show evidence of channel disappearance, supporting current cutoff, in high speed video camera observations of upward lightning flashes from towers. In both cases, this darkening of the channels precedes the formation of recoil leaders. These inferred current cutoffs are not preceded immediately by the extensive multi-tiered branching envisaged in figure 5. It remains unclear how a screening process based on shielding by branching can succeed in complete suppression of the lightning current.

Recoil leaders

A distinct feature of recoil leaders, evident in lightning strikes to aircraft [4], [6], in rocket-triggered lightning [7], in lightning strikes initiated by towers [9], [44] and in natural lightning, both intracloud [45] and cloud-to-ground [30], is their marked polarity asymmetry. Recoil leaders are observed to initiate only in the positive end of the lightning 'tree'. In the words of Mazur [37]:

"*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.*"

Mazur and Ruhnke [9] later give emphasis to the "branching positive leader" as the "origin" of the recoil leader. However, many observations show that both ends of the lightning 'tree' are often highly branched (see figure 1 in this study and the cover photograph of the May 2012 issue of the Newsletter on Atmospheric Electricity [46]). On this basis, it seems unlikely that branching alone can account for the polarity asymmetry in recoil leader initiation. In contrast, a distinct polarity asymmetry has been identified in the speeds of lightning leaders [10], with implications for smaller currents in the positive end of the asymmetrical bidirectional leader (§ "Theoretical treatment of the asymetrical bidirectional leader"). According to the instability analysis of Heckman [28] and the arc behavior of figure 6, the instability to current cutoff based on negative differential resistance is more likely where current is smaller (all other things being equal), thereby favoring recoil leader initiation in the positive end of the lightning 'tree'.

The most detailed published observations on current cutoff in lightning channels that are subsequently re-illuminated by recoil leaders are those of Mazur and Ruhnke [9] and Warner and al. [44]. The observations come from high-speed video camera analysis with single-frame resolution of 139 μs and 18.5 μs, respectively. As with all other documented observations, the recoil leaders occur in the positive end of the lightning 'tree', on channels that typically disappear from detection in the high-speed imagery. In both cases, the recoil leaders show a bidirectional development (as speculated by [3]) and follow the same detailed channel form as the one inferred to be cutoff. A well-defined asymmetry in leader speed (x3 or greater), with larger speed on the negative end, is consistent with earlier evidence for polarity asymmetry in leaders [10]. The initiation locations for the bidirectional development are notably closer to the extending channel end than to the branch contact point on the continuously illuminated lightning 'tree', where the current prior to cutoff would be expected to be less and hence more susceptible to cutoff by negative differential resistance [28]. In both cases, the fully re-illuminated channel (following recoil leader extension) shows a greater extent away from its origin than was apparent for the channel prior to cutoff, consistent with the common view that the sustained channel extension in the electric field of the cloud was responsible for the re-stressing of the previously cutoff channel. One puzzlement in the observations of Mazur and Ruhnke [9] is why the distant end of the extending positive leader is not detectable in the high-speed imagery, despite the evidence in 'before' and 'after' image comparisons for such channel extension. This observation suggests that the disappearance of the channel in the imagery is no absolute guarantee that the channel current is zero. Further efforts aimed at the sensitivity to small currents in the video camera imagery are needed.

Conclusions

A wide variety of lightning observations have been revisited to support common features of bidirectional leader development in lightning strikes to aircraft, lightning triggered by wire-trailing rockets, lightning strikes to towers, and natural lightning (both intracloud and cloud-to-ground). Two long-standing mechanisms for current cutoff and the subsequent formation of a new stroke in the same tortuous channel have been reviewed and contrasted against the observational evidence. Current cutoff is more readily explained by negative resistance in the lightning channel as suggested initially by Krehbiel [30] than by electrostatic screening, because a real zero of current is guaranteed in the former situation and because lightning channels at low current (<100 A) cannot be accurately treated as isopotentials. The marked polarity asymmetry in recoil leader behavior is likewise more readily accounted for by the asymmetry in the antecedent leader speed than by polarity asymmetry in leader branching. The high speed video imagery reinforces the polarity asymmetry in leader behavior by showing a marked contrast in speeds of advance by the negative and positive ends of the bidirectional recoil leader.

Further progress in understanding lightning behavior will accrue from a return to video camera observations within lightning-stricken aircraft, equipped with high time resolution, where the trunk of the lightning 'tree' may be observed at very close range throughout the bidirectional development ■

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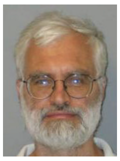
Acronyms

DC (Direct Current)
CG (flashes: Cloud-to-Ground flashes)

AUTHORS



Earle Williams is a physical meteorologist, currently dividing his time between the MIT campus and the Aviation Weather group at MIT Lincoln Laboratory. He has been engaged in research on thunderstorm electrification and atmospheric electricity for nearly forty years. These interests have taken him to all of the predominant tropical thunderstorm regions (Africa (Niger), South America (Brazil) and the Maritime Continent (Northern Australia)) for radar field experiments. Williams is presently focused on the Earth's Schumann resonances, a naturally occurring electromagnetic phenomenon trapped between the conductive Earth and the ionosphere, and on the use of that phenomenon for the continuous monitoring of the global lightning activity.

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