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Luminous pulses during triggered lightning

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[1] A triggered lightning flash that transferred negative charge to ground in central New Mexico produced more than three levels of branching above the main channel to ground in a 1 km vertical field of view. A high-speed video recording shows that the main channel had about 50 brief luminous pulses, many of which were superimposed on a slowly changing persistent luminosity. In contrast, superposition was rare in the uppermost visible branches because luminous pulses first appeared on preexisting dark channels before merging into a luminous channel. This observation suggests that luminous pulses in triggered and natural lightning originate only on dark branches and that the complexity of the main channel to ground is the result of multiple mergers of dark branches with pulses into luminous branches without pulses. This suggestion is contrary to an earlier conclusion that there are two kinds of luminous pulses. We also observe behavior characteristic of electromagnetic waves on transmission lines: when a downward propagating luminous pulse reaches a junction with another initially dark branch, it travels both upward and downward along that branch. Upon reaching the ground the downward propagating wave produces a bright reflection which also splits at the junctions, producing luminosity for a short distance upward in one direction while propagating much farther upward along the path charged by the downward propagating wave. However, when a downward moving luminous pulse reaches a junction with an initially luminous branch, splitting is not evident, probably due to the greater conductivity of the luminous channel.

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1. Introduction

[2] The lightning flash to be described below, which transferred negative charge to ground, was triggered by a rocket that unspooled wire from a bobbin connected to ground. As in past observations [*Rakov and Uman*, 2003, p. 273, Figure 7.1a], the negative charge brought to ground started as an initial continuous current (ICC) supplied by positive leaders that emanated from the wire tip and traveled upward toward the dominant negative charge in the thunderstorm overhead. The time interval from the beginning of positive leaders to the end of the ICC is known as the initial stage (IS) of the triggered flash [*Rakov and Uman*, 2003, pp. 266–267]. Pulses of luminosity and current—called ICC pulses—are often superimposed on the relatively steady initial continuous current and luminosity during the initial stage.

[3] After the initial stage of a triggered flash, when the initial continuous current has subsided, the remaining activity appears to be typical of natural cloud-to-ground (CG) lightning flashes after the first stepped leader and return stroke. Dart leaders propagate down to earth on existing channels whose luminosity is not visible, and they give rise to additional return strokes, which are sometimes followed by continuing currents. Pulses called M components sometimes occur during the continuing currents. *Shao et al.* [1995, p. 2780] classify M components into early and late-type M events. The early type are "those which are produced by positive streamer–fast negative recoil sequences immediately following return strokes," and the late type are "those produced by negative breakdown into the channel, later in a continuing current." *Rakov and Uman* [2003, p. 181] suggest that the two types "may differ only in the way in which the negative charge source is connected to the conducting channel to ground, not in the processes occurring in that channel." *Rakov et al.* [2001] show that M components transfer negative charge to ground and consist of a superposition of a downward incident wave and an upward reflected wave with nearly equal current amplitudes. The waves are guided by the preexisting conducting channel.

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[4] Branch components are luminosity pulses produced when a return stroke drains negative charge from an adjoining branch [*Rakov and Uman*, 2003, p. 148].

[5] K waves (also called K process waves, K leaders, K streamers, recoil leaders, recoil streamers, and retrograde leaders) carry negative charge along existing channels and travel in the direction away from positive leader tips toward negative leader tips. They appear to be the same as dart leaders except that sometimes they do not travel all the way to the ground, and at other times they merge into a luminous channel and become the downward moving part of an M component [*Shao et al.*, 1995]. A summary of research on pulses and currents in lightning flashes can be found in the book by *Rakov and Uman* [2003, chapters 4 and 7]. For more recent results and reviews on triggered flashes and flashes to towers see the articles by *Rakov et al.* [2003], *Miki et al.* [2005], *Campos et al.* [2007], *Flache et al.* [2008], *Campos et al.* [2009], *Akita et al.* [2010], and *Qie et al.* [2011].

[6] Some of the variously named pulses in natural lightning are thought to have identical origins. *Shao et al.* [1995, p. 2776] say, "dart leaders, attempted leaders, K events, and M events would all appear to be the same process (or, in the case of M events, to be initiated by the same process)." *Rakov et al.* [2001, p. 22,819] expand the list of identical pulses to include those in triggered and other lightning: "Thus the M-component mode of charge transfer to ground also occurs during the initial stage of rocket-triggered lightning. It is also likely to occur during the initial stage of upward natural lightning that is initiated from tall objects."

[7] However, *Flache et al.* [2008] postulated the existence of two types of ICC pulses based on video images and current risetimes of lightning flashes initiated from a 160 m high tower in Germany. In one type—the dart leader/return stroke mode—video images usually show dart leaders merging into luminous channels when the current pulses have short risetimes (less than 8 μs). In the other type—an M-component mode—video images usually show pulses on luminous channels when the current pulses have longer risetimes (greater than 8 μs).

[8] Contrary to the postulate of *Flache et al.* [2008], the video record described below suggests only a single mode for ICC pulses during the initial stage of a triggered lightning flash. The single mode is the merger of a dart leader on a relatively dark branch into an illuminated branch. The dart leader finishes its path to ground on the illuminated branch to produce a return stroke. "Dark branch" refers to a previously luminous branch that is not currently bright enough to appear on the video record.

[9] We suspect that the ICC pulses in the M-component mode of *Flache et al.* [2008] were the result of mergers of dart leaders into luminous channels inside the cloud or above the field of view of their camera.

[10] Our video records described below also show the behavior of pulses that encounter the ground or a junction with another channel.

2. Equipment and Methods

[11] The triggering rocket was powered by a G-class model rocket motor from Aerotech Division of RCS Rocket Motor Components. The motors had an average thrust of 78 N and a burn time of 1.7 s. The wire was copper-coated steel with a diameter of 0.22 mm.

[12] A Phantom model 7.3 high-speed video camera was positioned approximately 1.8 km away from the launch site, providing a field of view that extended about 1 km above the launch site and included 800 m above the top of the triggering wire. The camera had a 20 mm wide-angle lens and acquired 6,400 images per second (156 μs between images) with an exposure time of 150 μs. The images consist of 800×600 pixels each with a 14-bit gray scale.

[13] Data from the Phantom video camera were used to compare the luminosity versus time of the various channels. To do this, the signal from the camera pixel showing the maximum brightness within a horizontal range of pixels known to include the channel was reduced by the average of the intensity values of the fifth pixel away from the channel on each side. For the main channel, the signal of the brightest pixel was reduced by the average value of the 30th pixel on each side of the channel. This method allows for some drift in the channel due to horizontal wind and removes the contributions from light scattered from the sun and from other channel segments. The subtraction produces an unwanted side effect: when an intense pulse saturates pixels and sufficiently broadens the channel diameter, the subtraction produces an unrealistically small value, which can look like a negative-going pulse or a sharp dip in the middle of a pulse, giving the appearance of two pulses where only a single pulse exists. The conditions that produce this artifact are easily recognizable in the individual camera images.

[14] An electric field sensor (field mill) with a sample rate of 1 Hz was situated about 20 meters from the triggering site.

[15] Measurements of the channel current to ground are not available for the time of the flash described below.

3. Observations

[16] On 3 August 2010, just after 20:42:09 Universal Coordinated Time (UTC), the Phantom Camera at Langmuir Laboratory in central New Mexico captured a complex sequence of luminous events during a lightning flash triggered with a wire hoisted up by a rocket. The field mill showed that this flash brought negative charge to ground and thus the upward moving leaders were positive leaders. These positive leaders branched several times above the top end of the triggering wire before disappearing above the 1 km field of view of the camera. Since not all branches were visible at a single time, Figure 1 superimposes the branching pattern at several times. The letter A and the numbers 1, 2, 3, 4, 1.1, 2.1, etc., are near pixels whose luminosity versus time are shown in Figures 2, 3, and 4. Branch 3 is not graphed because it contributed only two pulses near the beginning of the flash.

[17] The luminosity versus time at location A (see Figure 1) on the main channel above the triggering wire is graphed in the bottom of Figure 2. The initial continuous luminosity of A lasted until about 1.06 s. A sequence of about 50 pulses began at 0.79 s during the initial continuous luminosity and continued until the end of the flash at 1.3 s.

[18] The first pulse illuminating the pixel on branch 1 (see Figure 2, top) did not reach the main channel. This pulse and

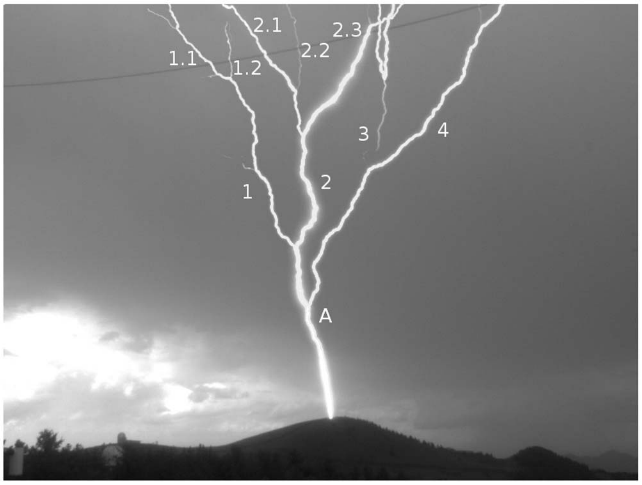

Figure 1. Branching of the triggered lightning flash beginning at 20:42:09 UTC on 3 August 2010. Since not all the channels were visible at a single time, the picture is a superposition of images at several times. The luminosity of branch 3 is not graphed in the following figures because it was short lived. The vertical distance from the triggering site to the altitude at the top of the frame is about 1 km.

others like it were, however, located on branches that later appeared in the camera record. Such pulses were probably K waves, i.e., dart leaders that did not reach the ground. Thus the luminosity of the initial upward moving positive leaders was below the threshold of the camera and the K waves were brighter than the initial positive leaders.

[19] Before $t = 1$ s (Figure 2, top), branch 1 supplied only pulses to the main channel, while branch 4 supplied only a slowly varying current. This is the beginning of a pattern: ICC pulses originated as dart leaders on channels whose luminosity was below the threshold of the camera. After the dart leader merged into a luminous channel and produced a reflection, it became what is called an ICC pulse on the originally luminous channel segment. It looks like a return stroke.

[20] Branch 2 (Figure 3, bottom) appears to be contrary to the pattern. It supplied to the main channel pulses that were already superimposed on an initial continuous luminosity. However, looking at the subbranches 2.1 and 2.2 in Figure 3, we see that branch 2.1 supplied only pulses, while branch 2.2 supplied only an initial continuous current during the superposition.

[21] Again, branch 2.3 in Figure 3 appears to be contrary to the pattern because it supplied four pulses that were superimposed on an initial continuous current. However, subbranch 2.3.1 supplied only pulses and subbranch 2.3.2 supplied only a continuous current. These subbranches are not labeled in Figure 1 to avoid clutter, and their luminosity versus time is not graphed because their behavior is difficult to follow except by examining sequences of camera images.

[22] Notice in Figure 3 that a pulse with a negative excursion to zero luminosity appears on the graphs for branches 2, 2.2, and 2.3 at $t = 0.935$ s. The negative excursion is an example of the unwanted side effect mentioned above: intense light from branch 1 scattered to the off-channel pixels that were used to reduce the effect of scattered light from branch 2 and its subbranches.

[23] After all the mergers described above, there remain four pulses out of about 50 that still need to be considered for adherence to the pattern. Beginning at 1.001875 s, branch 1 and subbranch 1.1 (Figure 4) show a sequence of four pulses that occurred during the continuous current still persisting on branch 2 and on the main channel A. The first pulse began when subbranch 1.1 was dark, so it is not an exception to the pattern. The second pulse may have begun before the end of the continuing current from the first pulse, but, from an examination of individual images

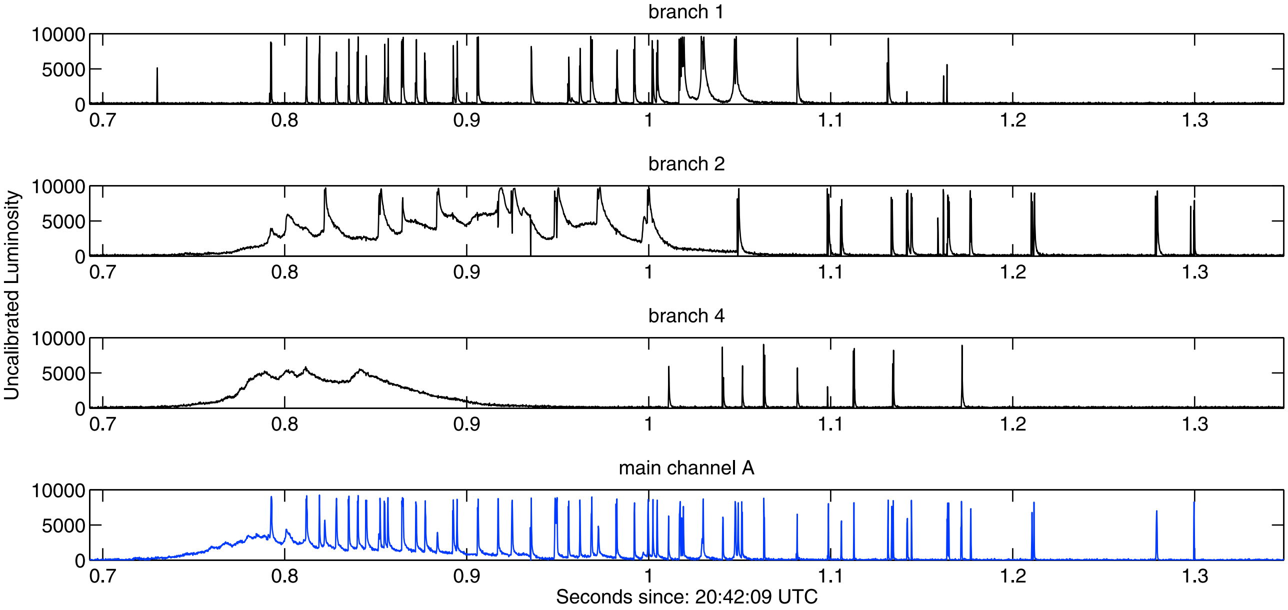

Figure 2. Luminosity of the main channel and its primary branches versus time. The luminosity of the main channel is taken at a point above the triggering wire and below the lowest branch junction.

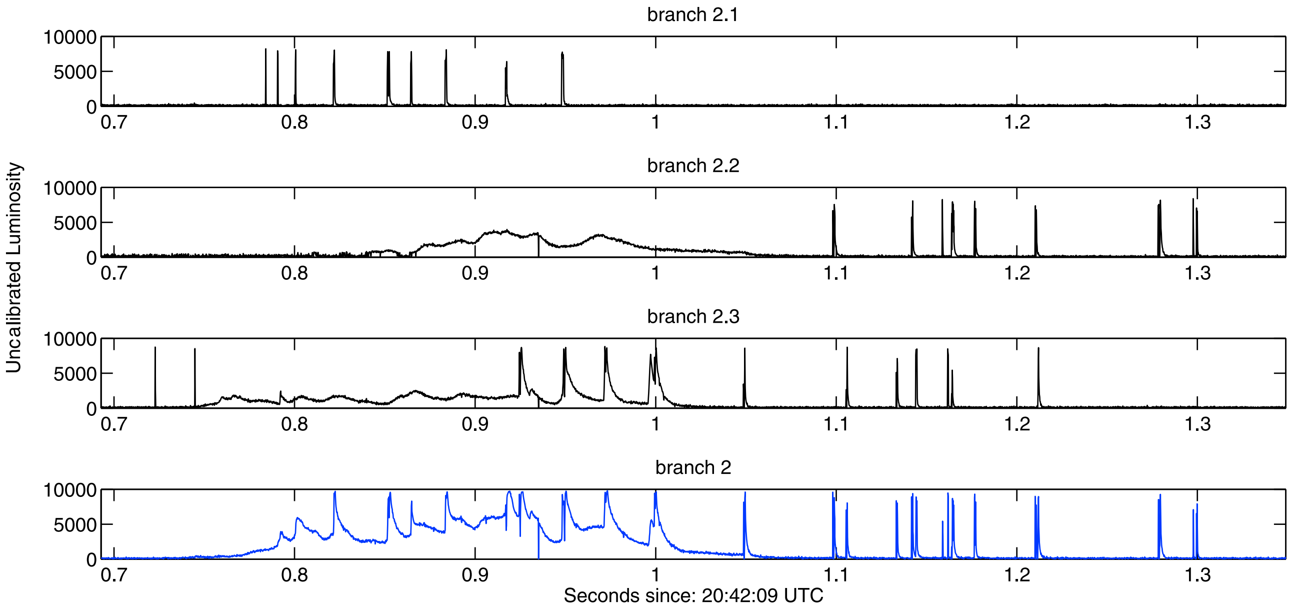

Figure 3. Luminosity versus time of branch 2 and its subbranches 2.1, 2.2, and 2.3.

(not shown) from the camera, it is possible to see that its branch split twice and that the second pulse originated on a dark branch. Thus only the third and fourth of the four pulses cannot be traced far enough upward to determine whether or not they began on a dark channel.

[24] An example of the evolution of an ICC pulse—beginning with the merger of a dart leader with a luminous channel—is presented in Figure 5 as a sequence of consecutive frames from the video camera. A dart leader is first visible on a subbranch at the top of the first (leftmost) frame. In the second frame the dart leader has progressed onto branch 1. In the third frame the dart leader has merged with the luminous branch 2 and traveled down to earth to initiate the brightest part of the ICC pulse, which differs from a return stroke only by propagating briefly along a luminous channel segment just before coming in contact with the ground. In other words, the brightest part of an ICC pulse is essentially a return stroke. The remaining frame shows the decline in luminosity toward the initial state. The luminosity of the part of the originally luminous channel not traversed by the ICC pulse appears to be unchanged throughout the duration of the ICC pulse.

[25] Images of a dart leader merging into a dark channel (Figure 6) show something not seen in the merger with a luminous channel (Figure 5): luminous spurs appeared on the dark channel (Figure 6) as the dart leader passed by. In the first (leftmost) image in Figure 6, a dart leader was caught coming down into view on branch 2.2. In the second panel, the dart leader had passed the junction with branch 2.3 and illuminated (faintly) part of branch 2.3 upward from the junction. In the third panel the dart leader had also split at junctions with branches 1 and 4 and had illuminated them upward. In the fourth panel, the dart leader had reached the ground and a return stroke had ascended all the way up beyond the field of view and had increased the brightness of the spurs above the junctions. In the fourth and fifth frames

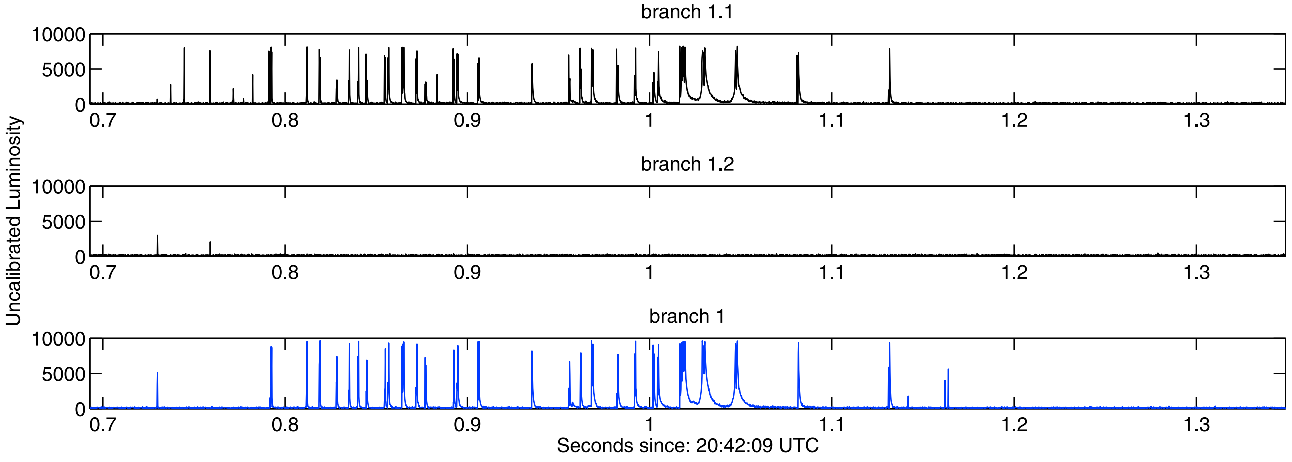

Figure 4. Luminosity versus time of branch 1 and its subbranches 1.1 and 1.2.

Figure 5. Camera frames beginning at 0.905625 s after 20:42:09 UTC showing a dart leader traveling down the dark branch 1, merging with the luminous branch 2, and initiating a return stroke upon reaching the ground. The exposure time for each frame is 150 μs. The time interval from the beginning of one frame to the beginning of the next frame is 156 μs except for the last frame, which follows the beginning of the third frame by 469 μs. The vertical distance from the triggering site to the altitude at the top of the frame is about 1 km.

the luminosity of the spurs had decreased below the background light. Thus both the dart leader and the return stroke traveled in both directions at junctions.

[26] Spurs can also be seen in Figure 4, in which the last two pulses (very close together) on branch 1 do not appear on either subbranch 1.1 or 1.2. These pulses were caused by dart leaders that propagated down branch 2 and split at the junction with branch 1 to travel in both directions. The wave traveling downward reached the ground and produced what looks like a return stroke, while the luminosity traveling upward along branch 1 attenuated before reaching subbranch 1.1 or 1.2. This flash has a number of examples of propagation in two directions after a dart leader reaches a junction, but for most of them the luminosity in the upward direction did not reach far enough to be seen in one of the pixels whose luminosity is graphed as a function of time.

4. Interpretations

4.1. Modes of Charge Transport by Pulses

[27] The fact that a great majority (48 out of 50) of the luminous pulses were seen to arise from dart leaders in dark

Figure 6. Consecutive frames beginning at 1.209842 s after 20:42:09 UTC showing a dart leader traveling down branch 2. The dart leader initiates luminous waves that travel up the branches it meets and is followed by a reflection (return stroke) upon reaching the ground. The return stroke also initiates luminous waves upward along branches at junctions, just like the dart leader did. The exposure time for each frame is 150 μs. The time interval from the beginning of one frame to the beginning of the next frame is 156 μs. The vertical distance from the triggering site to the altitude at the top of the frame is about 1 km.

branches that merged with other branches or the main channel suggests that the remaining two pulses also originated in this manner, although at a higher altitude, above the field of view of the camera. This observation is in agreement with the finding of *Shao et al.* [1995] about late-type M components in natural lightning flashes, which, as we mentioned in the Introduction, are produced by the merging of a negative leader into a branch with continuing current to ground.

[28] Our observations are not in agreement with the conclusion of *Flache et al.* [2008], who proposed the existence of two modes of charge transfer when pulses are superimposed on relatively steady currents. One mode—the dart leader/return stroke mode—is the one we observe, in which a dart leader on a dark channel merges into a luminous branch. *Flache et al.* [2008] found that in 6 out of 7 cases such a merger produced a current pulse with a fast risetime (less than 8 μs). In the other mode—which *Flache et al.* [2008] call the "M-component mode"—luminous pulses were first visible in already luminous channels, and the corresponding current pulses usually (in 25 out of 26 cases) had longer risetimes (greater than 8 μs). A histogram of pulse-current risetimes [*Flache et al.*, 2008, Figure 2] has a bimodal distribution.

[29] Calling the other mode the M-component mode is problematic because the M-component mode in natural flashes is thought to be the result of a dart leader merging into a luminous channel [*Shao et al.*, 1995]. In addition, we question the "two mode" conclusion of *Flache et al.* [2008] for several reasons. (1) Two pulses in their histogram do not fit the pattern. (2) The bimodal appearance of the histogram [*Flache et al.*, 2008, Figure 2] depends on the lack of only two risetimes in the bin between 8 and 16 μs. (3) The bimodal appearance of the histogram would vanish if bin sizes with equal time intervals were used instead of geometrically increasing bin sizes. (4) Histograms of risetimes by *Miki et al.* [2005, Figure 13] from three tall structures and rocket-triggered lightning do not show convincing bimodal distributions. (5) Dart leaders are expected to occur only after a time interval during which part of the channel to ground is nonconducting [*Malan and Schonland*, 1951; *Fisher et al.*, 1993; *Mazur*, 2002], and thus dart leader origination would not be expected within a channel having a continuing or continuous current.

[30] Thus it appears from an examination of 50 luminous pulses in one triggered lightning flash that, in both triggered and natural lightning, all ICC pulses and ordinary M components (perhaps excluding the early type described by *Shao et al.* [1995]) begin as dart leaders that merge into a branch, subbranch, or the main channel having an initial continuous current or a continuing current. The brightest luminosity of each pulse is the result of a reflection (a return stroke or an M component) that follows a dart leader.

[31] There are two other generalizations from Figures 2, 3, and 4: (1) the current on a branch is largely independent of the current on branches that are connected at lower altitudes, which is not surprising because the propagation of a leader is governed by the local electric field into which it propagates; and (2) a branch with only a continuous current can change into a branch with only pulses, which is the case with branch 2.2 in Figure 3.

4.2. Categorizing Flashes and Branches

[32] *Hubert et al.* [1984], who triggered lightning at Langmuir Laboratory in New Mexico in 1981, divided the triggered flashes into categories based on current measurements: classical (C) triggered flashes that begin with a continuous current (now called initial continuous current), slow (S) discharges having a continuous current only, weak flashes that only melt (M) the triggering wire, anomalous (A) flashes that do not follow the wire, anomalous (A*) flashes do not follow the wire but come back to it near the ground, allowing a measurement of current, and pseudoclassical (PC) pulses that follow the wire but have a current variation as in the anomalous case. *Hubert et al.* [1984, p. 2515, Table 1, Flash 18] also mention a unique triggered flash (categorized as PC) that did not have an initial continuous current. (Currents as low as about 1 A were measureable, judging from the noise amplitudes in their graphs.)

[33] Based on the above categories, the flash described in this paper was a classical (C) flash because the main channel began with an initial continuous current. However, since the currents in separate branches are independent, it makes sense to categorize each branch and subbranch separately. Branches 2, 2.2, and 4 were also in the classical category. The luminosity of Branch 4 is similar to the current recorded during a triggered flash at Fort McClellan, Alabama, described by *Fisher et al.* [1993, Figure 2], in which the major pulses occurred only after the initial continuous current ended.

[34] Branch 1 is the most interesting branch because it had pulses but no initial continuous luminosity above the threshold of the camera. If it also had no initial continuous current, it may have been analogous to the unique triggered flash (#18) reported by *Hubert et al.* [1984] and mentioned above. It is not clear how a channel supporting pulses can be established without an initial continuous current.

4.3. Splitting and Reflections at Junctions

[35] Unlike Figure 5, in Figure 6 a dart leader merges with dark branches instead of with luminous branches. The dart leader produces luminous spurs around 100 m in length upward from each junction with an adjoining dark branch. Thus the dart leader splits, mainly propagating downward but also propagating some distance upward along each dark branch. Similarly, the return stroke intensifies the luminosities along the spurs. It also splits at the junctions.

[36] The splitting at junctions also occurs in natural lightning flashes when the initial return stroke following a stepped leader illuminates the downward branches of the stepped leader that are not connected to ground [*Rakov and Uman*, 2003, p. 148]. The splitting at the junctions removes negative charge from both the main channel and the branches that are not connected to ground. In triggered lightning the visible junctions are those with channels formed by upward moving positive leaders. The dart leaders probably place negative charge for some distance upward along the branches they encounter, and the subsequent return strokes remove the negative charge from those branches and from the main path of the dart leader.

[37] The appearance of a return stroke when a dart leader reaches the ground has been interpreted as a reflection of a propagating electromagnetic wave (a dart leader) when it reaches a ground resistance that is much less than the characteristic impedance associated with the channel [*Rakov et al.*, 2001, p. 22,827]. The splitting of dart leaders and return strokes at junctions, as illustrated in Figure 6, is also

characteristic of waves. Given the wave-like behavior of leaders and return strokes, we expect a partial reflection as the dart leader in Figure 5 meets the luminous channel in addition to the more complete reflection as it meets the ground. The time resolution of our camera is not sufficient to resolve the two separate reflections.

5. Summary

[38] The following statements combine past and present observations about the transport of electrical charge on the branches of triggered lightning flashes that bring negative charge to ground.

[39] 1. Currents along separate branches are independent.

[40] 2. There are three primitive current modes:

[41] (i) Slowly varying currents. These currents include the initial continuous current that is initiated by an upward propagating positive leader and continuing currents that sometimes follow return strokes.

[42] (ii) Current pulses from downward propagating waves that add negative charge to a channel. These pulses originate as dart leaders and are known as K waves if they do not reach the ground. If dart leaders reach the ground after merging with a branch having an initial continuous current (ICC) they are known as the downward part of an ICC pulse, or if they reach the ground after merging with a branch having a continuing current following a return stroke, they are known as the downward part of an M component.

[43] (iii) Current pulses from upward propagating waves that drain negative charge to ground from negatively charged channels. These pulses include return strokes and the upward propagating parts of M components and ICC pulses. All appear to be reflections from waves that originate as dart leaders.

[44] 3. The simultaneous occurrence of slowly varying currents and current pulses on a single branch is the result of the merger of two branches—a branch with pulses only and a branch with only a slowly varying current. Pulses do not originate on luminous branches.

[45] 4. A branch with only an initial continuous current can become a branch with only pulses.

[46] 5. Pulses exhibit behavior characteristic of electromagnetic waves—splitting at junctions and reflecting at discontinuities.

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