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High-Speed Video Observations of the Preliminary Breakdown Phase of a Negative Cloud-to-Ground Lightning Flash

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ABSTRACT: We present new observations of the preliminary breakdown phase of a negative cloud-to-ground lightning flash. A largely unobscured view of preliminary breakdown was observed with a high-speed camera at 9,000 frames per second, along with synchronous observations from a fast electric field antenna, a VHF antenna, and a fast optical detector. The photographic data shows high-luminosity breakdown beginning at an altitude of approximately 4.8 km and extending downward along an apparent single vertical path for several hundred meters until branching into three or more separate channels. The fast electric field data begins with an initial weak pulse followed by a sequence of high-amplitude “characteristic” pulses that were coincident with bright channel extension. The high-amplitude electric field pulses exhibited a distinct bimodal distribution, with short-duration pulses having pulse widths on the order of one 1microsecond superimposed onto long-duration pulses of similar amplitude and pulse widths on the order of 20 microseconds. Optical pulses were observed to coincide with the long-duration fast electric field pulses, with optical pulse widths on the order of 100 microseconds. VHF pulses were observed nearly continuously upon initiation of the sequence, beginning with the first detected fast electric field pulse and reaching maximum amplitude coincident with the strongest electric field pulses. The data suggests that preliminary breakdown, especially that associated with the large electric field pulses, consists of stepwise leader-type propagation with step lengths of 100 meters or more.

INTRODUCTION

The early breakdown phase of lightning has long fascinated lightning researchers. Understanding the early stages of lightning has been problematic due primarily to the difficulty in observing the early stages of lightning in its natural environment. The primary mode of studying the early stages of lightning has been through monitoring the motion of electrical charge using sensitive capacitive (or “electric field”) antennas. The history of this line of research is quite lengthy and detailed, so we refer the reader to the recent texts by Stolzenburg et al. [2013], Campos and Saba [2013], and Baharudin et al. [2012] for a brief review. Figure 1 depicts an observed electric field waveform for a negative cloud-to-ground lightning flash.

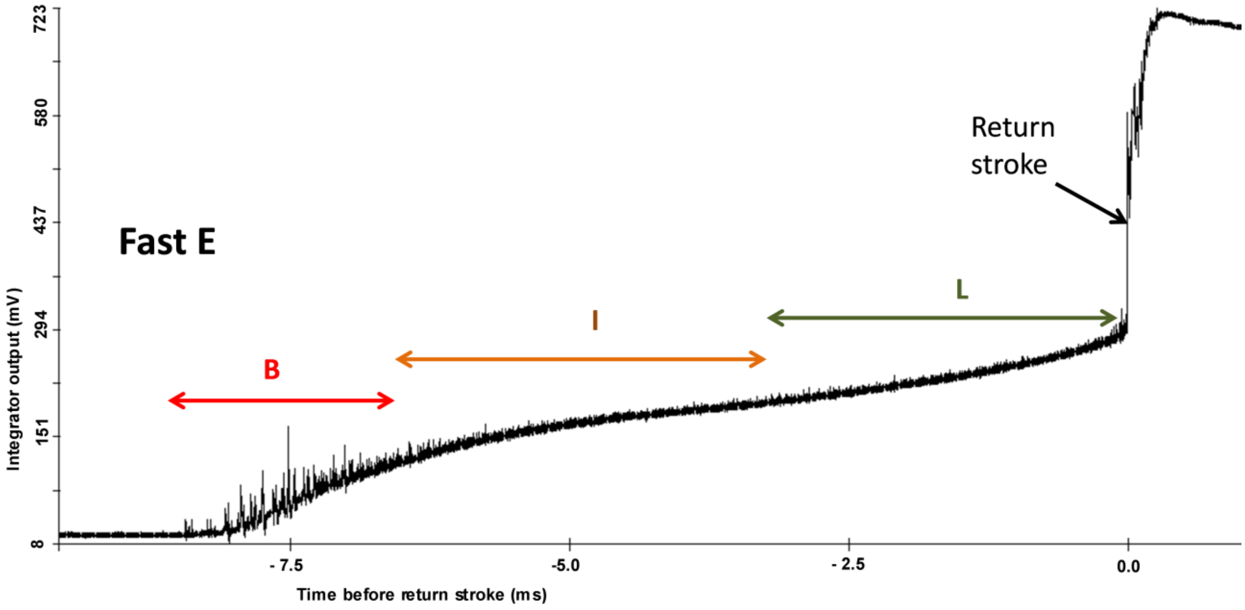

Figure 1 Complete fast electric field waveform of the flash examined in this paper. This waveform is typical for a negative cloud-to-ground lightning flash. According to Clarance and Malan [1957], a flash can be divided into three stages, B (for breakdown), I (for intermediate), and L (for leader) according to the electric field waveform structure and visible appearance of the negative stepped leader beneath cloud base.

Figure 1 is the fast electric field waveform of the flash examined in this paper. The structure of this waveform is typical of negative cloud-to-ground flashes. The earliest portion of the waveform, termed “preliminary breakdown”, exhibits prominent high-amplitude pulses termed “characteristic pulses” by Beasley et al. [1982]. The cause of these pulses has long been a subject of study and fascination, but due to a lack of definitive data no clear consensus has been arrived at to explain them.

Recent observations using high-speed photography have begun to shed light onto the origin of preliminary breakdown. Stolzenburg et al. [2013] contains 15 high-speed video observations of preliminary breakdown taken at or near 50,000 frames per second, showing it to be a strong emitter of optical radiation and to at least sometimes form linear segments of length on the order of 100+ meters. Based on their observations, they have suggested that preliminary breakdown is due to the appearance of what they term an “initial leader”, a leader process that is distinct from the conventional negative stepped leader process and which forges the initial leader channel that eventually supports ordinary negative stepped leader breakdown. Campos and Saba [2013] present a single high-speed video taken at 4,000 frames per second of a negative cloud-to-ground flash. They show a bright linear-to-branching channel extension during the preliminary breakdown phase that is coincident with characteristic pulses. Based on their observations, they suggest that the channel extension may be similar to ordinary negative stepped leader extension.

The new observations presented herein take these studies a step further. We argue that not only are the characteristic pulses of preliminary breakdown associated with early and vigorous negative leader extension, but that the characteristic pulses have a bimodal pulse width distribution and that this distribution corresponds to a bimodal distribution of step lengths during early negative leader progression. The cause of this bimodal distribution of step lengths is not well understood, but we suspect it is due to the formation of distant space leaders due to the strong large-scale ambient electric field that is present before and during the early stages of a lightning discharge. (For an explanation of space leaders and negative stepped leader extension, see Petersen et al. [2008])

INSTRUMENTATION

High-speed camera

Images of the event were captured using a Photron SA1.1 high-speed camera at 9,000 frames per second. The camera lens was an AF-S Nikkor lens with a focal length of 24 mm and an F-stop setting of 3, and illuminated a 1024 × 656 (width × height) array of CMOS optical detector elements, each being square with a side length of 20 µm. The camera was elevated at an angle of 10.6° above horizontal. The camera was triggered by the return stroke illumination pulse using a horizontally oriented collimated optical detector. Each image contained a GPS timestamp generated from an IRIG-B signal that was supplied by a Symmetricom GPS receiver.

Fast electric field antenna

A flat-plate antenna was used to detect fast changes in the electric field during the discharge. The antenna consisted of a circular disk of 25 cm radius surrounded by a ground plane with side length of 75 cm, and was placed on the roof of the National Weather Center building in Norman OK at a height of approximately 30 meters above ground level. The antenna was connected to an integrator with a receiver bandwidth of over 2 MHz, a gain of 11 mV/nA and a decay time constant of 10 milliseconds. Output of the integrator was fed into a Gage Octopus 8-channel digitizer card operating at a bit depth of 12 bits and a sampling frequency of 25 MS/s.

VHF detector

VHF radiation was observed using a ground-plane antenna tuned to Channel 10 (North American standard, 197 MHz center frequency), mounted on the roof of the National Weather Center building. The signal was pre-filtered, amplified and then filtered again to a 6 MHz bandwidth. The signal was then fed into a logarithmic power detector with an output rise/fall time of 100 nanoseconds, and the output was fed into the digitizer card at a bit depth of 12 bits and a sampling frequency of 25 MS/s.

Fast optical detector

A collimated optical detector was used, consisting of an avalanche photodiode placed in a rectangular box with a rectangular front viewing window of 14° × 4° and an elevation angle of 8.9° above horizontal. The view of the photodiode was aligned with the camera field of view, such that it did not obtain a direct view of the breakdown but instead detected the light scattered from the storm cloud just beneath the breakdown region.

OBSERVATIONS

The following observations were made of a negative cloud-to-ground lightning flash that connected to ground at a distance of approximately 12.4 km south of the National Weather Center in Norman, OK at 22:27:12.269854 UTC of July 16 2013. The lightning flash was observed from a south-facing room on the 5th floor (the high speed camera and fast optical detector) and from the roof just above the lab (the fast electric field antenna and VHF antenna). The National Lightning Detection Network (NLDN) detected the return stroke at a latitude and longitude of (35.0686, -97.4207) with a peak current of -80 kA while the Earth Networks Total Lightning Network detected the return stroke at a latitude and longitude of (35.06995, -97.4181) and a peak current of -89 kA.

High-speed video images

Figure 2 shows a composite image of the breakdown phase of the flash, up to the frame just prior to the return stroke, made by retaining the brightest pixels from all frames during the flash. Of particular interest is the upper portion of the flash, identifiable by the highly luminous channels branching outward from a partially obscured central channel near the top of the image.

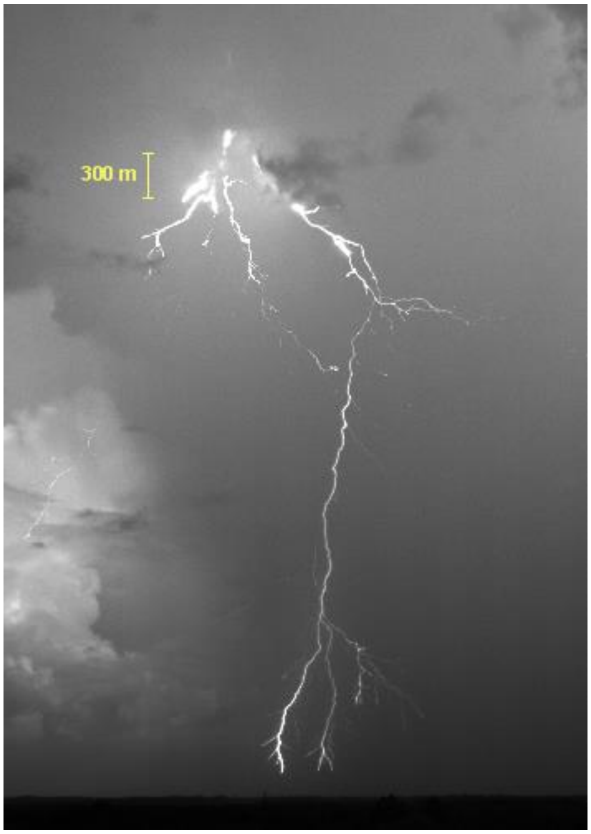

Figure 2 Composite image of the negative cloud-to-ground flash, created by retaining the brightest pixel from all frames during the breakdown phase of the flash. The flash ground connection point was located at a distance of approximately 12.4 km from the camera. The scale indicated near the top of the image was

created by assuming a vertical orientation of the flash.

Figure 3 contains the first 9 sequential images of the flash with detectable channel structure, in unmodified format. Figure 4 contains the same images as figure 2, but with the images intensity-inverted and enhanced to accentuate the linear discharge features.

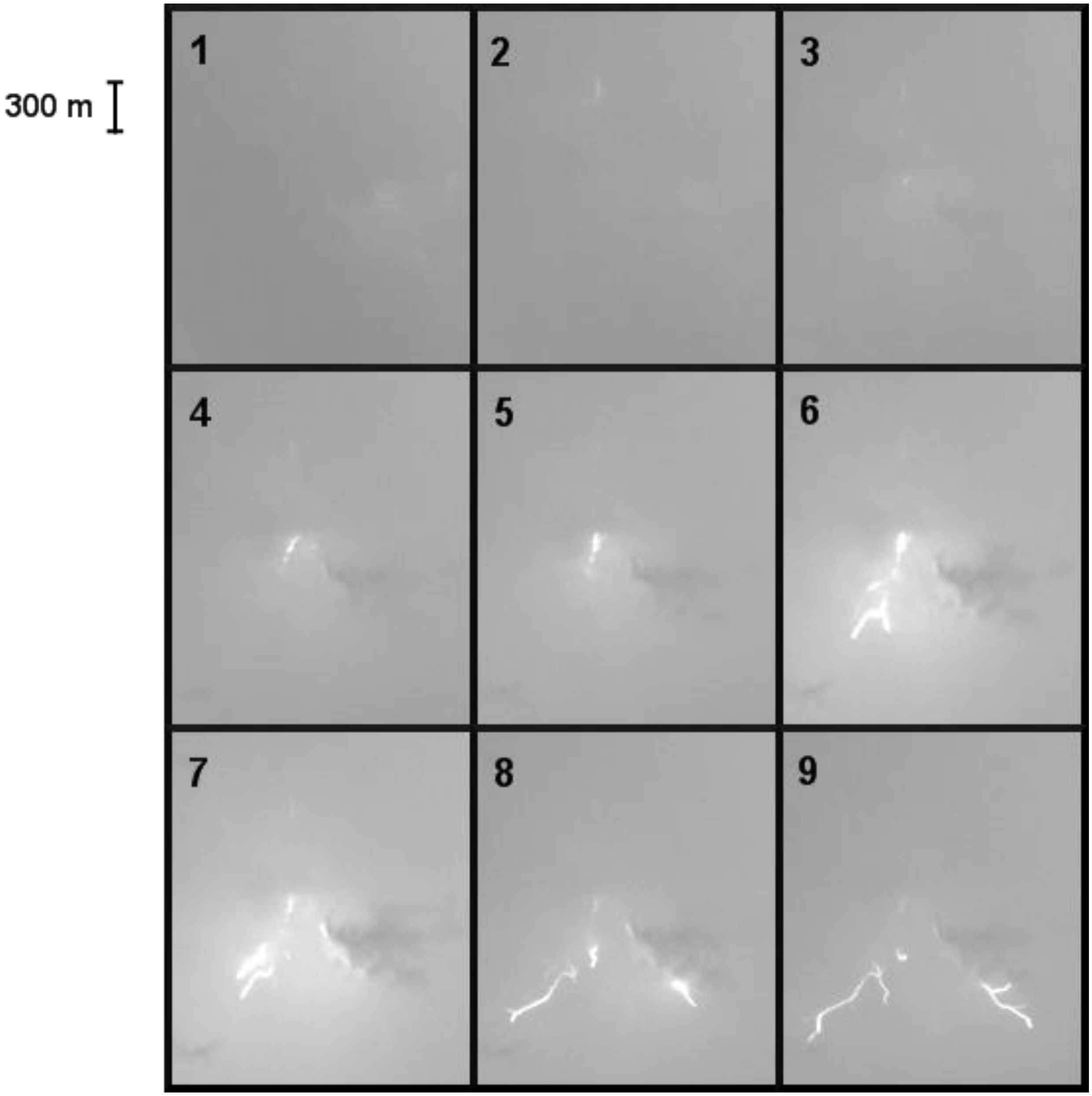

Figure 3 Images 1 – 9 are unmodified sequential images of the earliest portion of the lightning flash that displayed discernable channel segments. Two frames prior to frame 1 also contained detectable photoemissions, but no discernable channel segments. The indicated scale assumes that the observed breakdown was approximately 12 km from the camera. The frames are indicated on figure 4 for comparison with fast optical, fast electric field and VHF data.

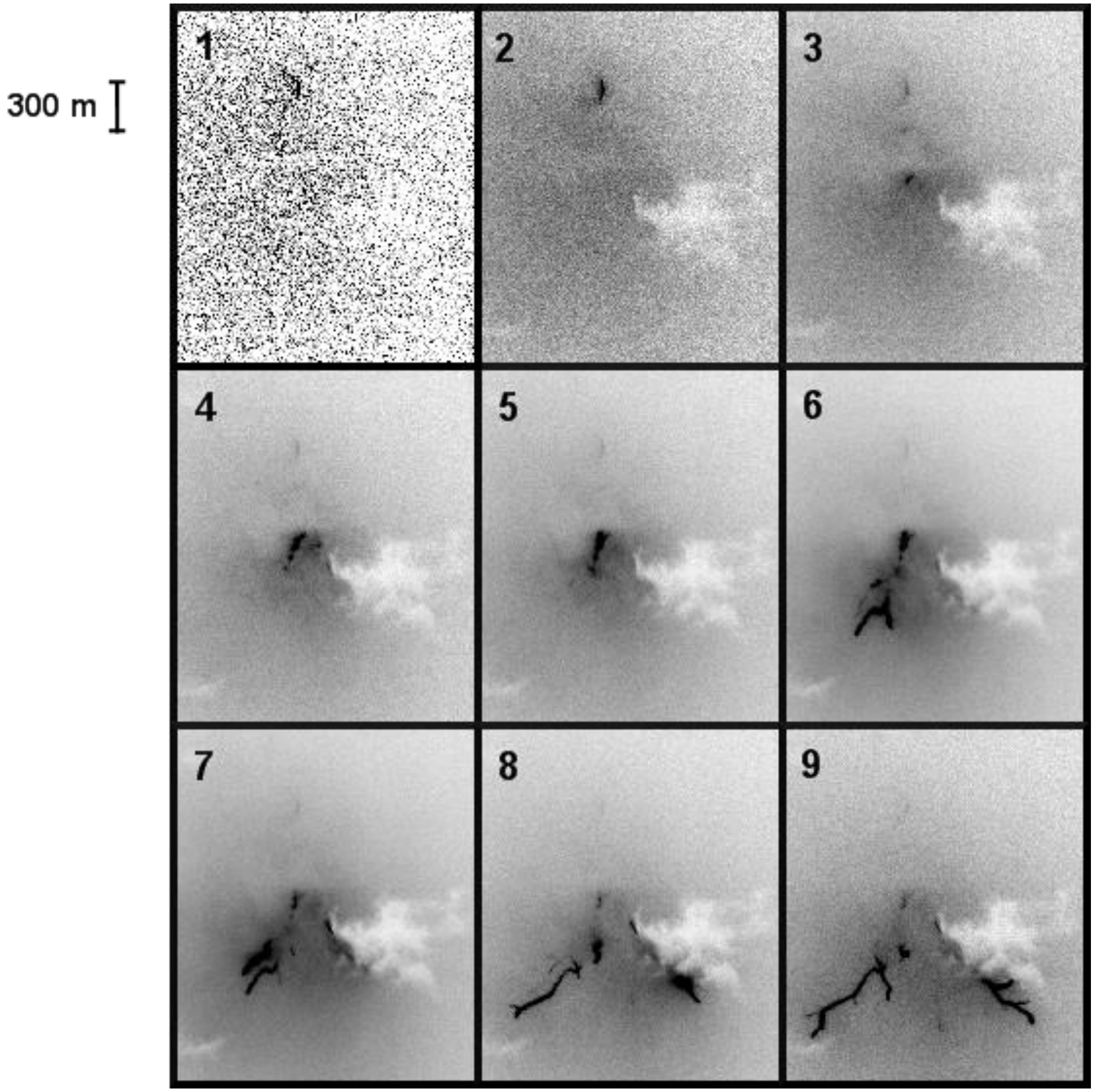

Figure 4 Images 1 – 9 are intensity-inverted and enhanced versions of the images shown on figure 3. Of note is the apparent and partially obscured 500 meter long single-channel vertical structure visible on image 3, followed by outward branching along at least 3 distinct paths. Also of note are the apparent step lengths of 200+ meters.

Figures 3 and 4 show the early stages of the lightning flash as it emerged from the cloud base at a height of 4.5 to 5 km above ground level. The uppermost portion of the flash is partially cloud-obscured, while the remaining portions are in clear view.

Fast electric field, VHF and fast optical observations

Figure 5 contains fast electric field, VHF and fast optical waveforms taken during the preliminary breakdown phase of the lightning flash.

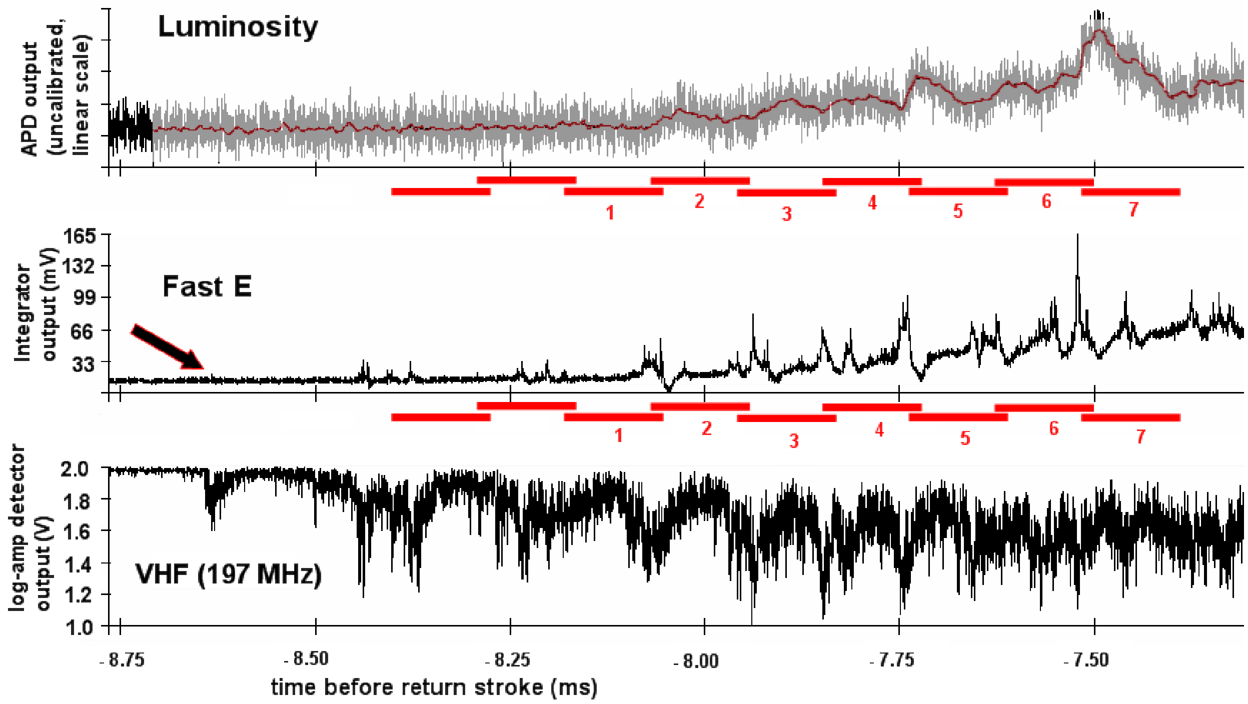

Figure 5 Waveforms taken from the fast optical detector (upper), fast electric field antenna (middle) and VHF antenna during the preliminary breakdown phase of the lightning flash. The luminosity, as observed with the fast optical detector, is presented in the upper graph in both a raw (black) and smoothed (red) format. The horizontal red lines beneath the upper and middle graphs denote the high-speed video frames corresponding to the indicated time periods. The overlap in the red lines is due to uncertainty in timing of the camera frames, and the line numbering indicates the frames shown on figures 3 and 4. Two camera frames, indicated by the two unlabeled red lines, are included to indicate camera frames that contained detectable optical emissions but no visible channel segments. The initial fast electric field pulse, indicated by the arrow, is difficult to discern on this graph but is clearly identifiable on the full-resolution waveform record. The VHF detector output, shown in the lower graph, is inverted such that increases in the VHF received power result in a decrease in the detector output voltage.

Figure 5 shows a few important observations. The luminosity pulses (figure 5, top graph) have a characteristic duration on the order of 100 μs, which is similar to the duration of individual camera frames. This supports the interpretation of the forward extension of the leader channel between frames as singular events rather than multiple events accumulated on a single frame. The fast electric field waveform (figure 5, middle graph) displays the “characteristic pulse” structure that typically occurs during preliminary breakdown. All pulses, except for the very first weak pulse, display this structure to some extent. The VHF waveform (figure 5, lower graph) suggests a near-continuous chain of breakdown events punctuated by strong emissions coincident with the large pulses on the electric field record. Additionally, the VHF record shows significant emissions coincident with the first weak electric field pulse.

Figure 6 is a close-up view of the fast electric field waveform during a portion of the preliminary breakdown phase and a comparison with the fast electric field waveform immediately prior to the return stroke as the negative stepped leader approaches ground.

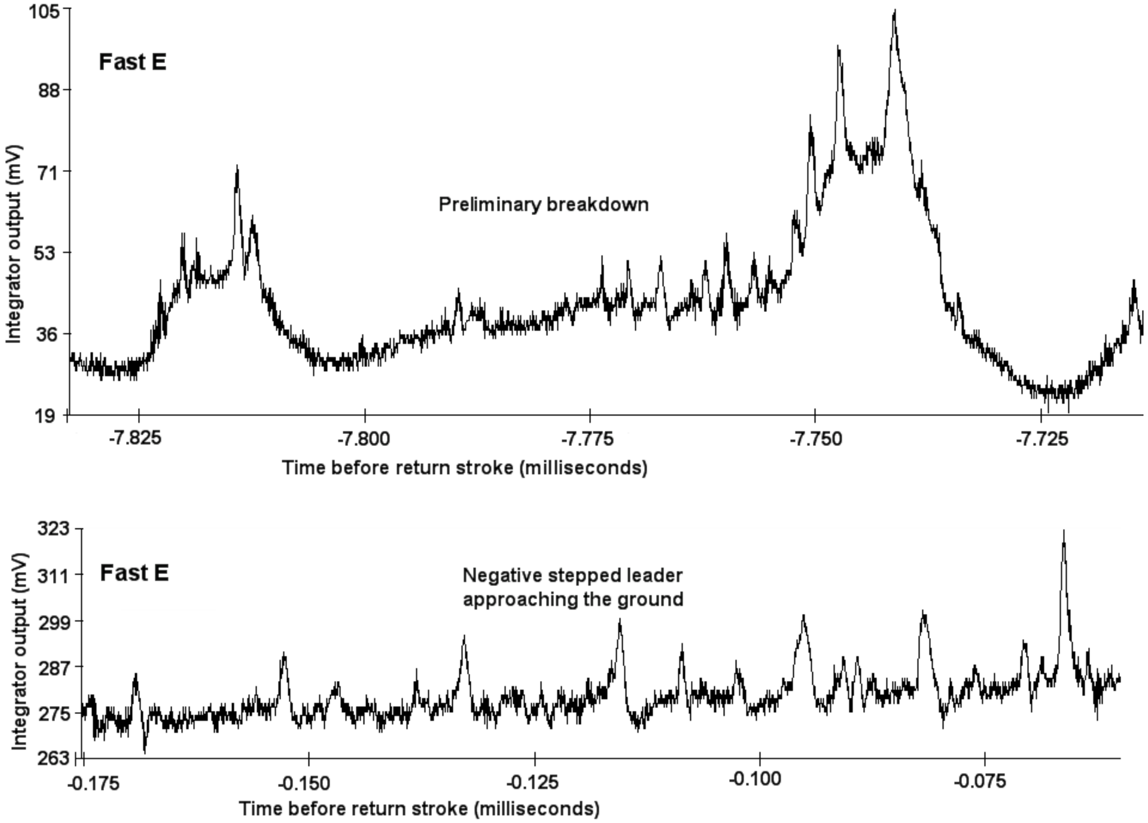

Figure 6 Close-up view of the fast electric field waveform during the preliminary breakdown phase (upper graph) alongside a similar view of the fast electric field waveform immediately prior to the return stroke as the descending negative stepped leader approaches ground (lower graph). Of note is the bimodal distribution of pulse widths during preliminary breakdown, with short duration pulses on the order of 1 µs superimposed onto longer duration pulses on the order of 20 - 40 µs. The short-duration pulses during preliminary breakdown are similar to the pulses associated with normal negative stepped leader progression immediately prior to attachment to ground.

Figures 5 and 6 show a distinct bimodal distribution of pulse widths during the preliminary breakdown phase of the lightning flash. The short duration mode has pulse widths on the order of 1 microsecond while the long duration mode has pulse widths on the order of several tens of microseconds.

CONCLUSIONS

The observations presented in the above figures represent perhaps the clearest picture yet of the preliminary breakdown phase of a typical negative cloud-to-ground lightning flash. Pronounced characteristic pulse activity was observed during the preliminary breakdown phase (figures 5 and 6). The characteristic pulses were seen to coincide with the appearance of bright linear lightning channel segments of several hundred meters length (figures 3 and 4). The fast optical waveform data (figure 5) shows bright optical flashes of duration on the order of 100 µs that coincide with bright extensions of the early negative leader channel. This indicates that the bright linear segments shown on the video frames appeared as singular optical events, suggestive of stepwise extension. Under such an interpretation, it would appear that the preliminary breakdown was characterized by extremely large stepwise extension of the negative end of a lightning leader with step lengths often exceeding 200 meters. The structure of the fast electric field characteristic pulses suggests a bimodal distribution of pulse widths, with short duration pulses being more than an order of magnitude shorter than the longer duration pulses. As shown on figure 6, the short duration pulses appear strikingly similar to the pulses generated by a negative stepped leader as it approaches the ground. This suggests that preliminary breakdown includes ordinary negative stepped leader development.

We are thus left with the picture of a bimodal distribution of step lengths during preliminary breakdown consisting of very long steps (200+ meter length) that occur simultaneously with ordinary negative leader steps (10+ meter length). It is possible that the extent of the strong electric field just prior to and during the early stages of a lightning discharge is supportive of space leader formation at great distances ahead of the parent negative leader tip. Such distant space leaders might then develop semi-independently in both directions, undergoing ordinary stepwise negative leader extension in the forward direction (causing the short-duration pulses) while also undergoing positive leader extension in the retrograde direction toward the parent negative leader which may itself be undergoing ordinary negative stepping. As the distant step and the parent step close the gap, the leader currents might rise sharply due to increased corona currents at the leader tips and consequent increase in channel conductivity due to channel heating, thus producing the slowly rising edge of the long-duration “characteristic” bipolar pulses. Upon attachment of the distant space leader with the parent leader (marked by the final and strongest short-duration pulse), rapid redistribution of charge down the 200+ meter-long step and parent leader could account for the strong negative excursion of the long-duration electric field pulse.

The final question raised by the new observations is that of the very first discharge. As seen on figure 5, the very first detectable electric field activity is very weak. No optical activity was observed during this pulse, but this may be due to the daytime illumination overwhelming a weak optical emission. In contrast, significant VHF activity was detected at the same time as the first electric field pulse and continued as a continuous stream of impulsive activity thereafter. This activity suggests the existence of electrical breakdown activity starting at the initial electric field pulse and possibly setting the stage for the subsequent breakdown activity associated with the characteristic pulses.

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