VHF lightning mapping observations of a triggered lightning flash

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Received 22 August 2012; accepted 7 September 2012; published 11 October 2012.

[1] On 3 August 2010 an extensive lightning flash was triggered over Langmuir Laboratory in New Mexico. The upward positive leader propagated into the storm's midlevel negative charge region, extending over a horizontal area of 13 × 13 km and 7.5 km altitude. The storm had a normal-polarity tripolar charge structure with upper positive charge over midlevel negative charge. Lightning Mapping Array (LMA) observations were used to estimate positive leader velocities along various branches, which were in the range of 1–3 × 10^4 m s^{-1}, slower than in other studies. The upward positive leader initiated at 3.4 km altitude, but was mapped only above 4.0 km altitude after the onset of retrograde negative breakdown, indicating a change in leader propagation and VHF emissions. The observations suggest that both positive and negative breakdown produce VHF emissions that can be located by time-of-arrival systems, and that not all VHF emissions occurring along positive leader channels are associated with retrograde negative breakdown. **Citation:** Edens, H. E., et al. (2012), VHF lightning mapping observations of a triggered lightning flash, *Geophys. Res. Lett.*, *39*, L19807, doi:10.1029/2012GL053666.

1. Introduction

[2] Triggered lightning facilitates the study of the electrical breakdown processes of lightning at close range and at a location and time that are more predictable than natural lightning. Triggering a lightning flash is usually accomplished by means of a small rocket that carries a grounded metal wire upward to an altitude of several hundred meters above ground level, at which point a leader may initiate from the rocket to propagate upward into the cloud [*Rakov and Uman*, 2003].

[3] An ascending triggered positive leader produces an initial continuous current (ICC) that lasts a few hundred ms and effectively transports negative charge to ground [*Rakov and Uman*, 2003, p. 267]. After the initial stage one or more dart leaders and associated return strokes may occur along the channel, carrying additional negative charge to ground. The processes occurring after the initial stage are the same as those occurring in a natural negative cloud-to-ground (−CG) flash.

[4] Downward propagating positive leaders in +CG flashes tend to be quiet at RF, unlike the negative leaders of −CG flashes [*Shao et al.*, 1995, 1999]. *Rhodes et al.* [1994] and *Shao et al.* [1995] also observed fast positive leaders occurring immediately after the return stroke in −CG flashes, which originated in the source region of the flash and radiated at least as strongly as negative breakdown. These fast positive leaders are thought to be a consequence of the return stroke introducing ground potential in the cloud, which is strongly positive compared to the potential of the source region. The upward positive leader in triggered lightning would be expected to radiate strongly in RF for similar reasons, but this was not observed [*Krehbiel et al.*, 1994; *Shao et al.*, 1996; *Shao and Krehbiel*, 1996]. More recently, positive breakdown in triggered lightning has been mapped successfully by interferometry [e.g., *Dong et al.*, 2001; *Yoshida et al.*, 2010], indicating that positive leaders do radiate RF at least sometimes.

[5] A positive leader may be accompanied by brief, intermittent optical and RF emissions that propagate backward along the leader channel away from the leader tip. These are referred to in the literature by various names such as recoil streamers [*Mazur*, 1989], K-leaders [e.g., *Shao et al.*, 1995] and recoil leaders [*Mazur*, 2002]. *Shao et al.* [1995] found that K-leaders, dart leaders, attempted dart leaders (dart leaders that do not develop all the way to ground) and M-components in −CG flashes are all a single phenomenon (a fast ionization wave of negative breakdown) and differ only in scale and at what point in time they occur during a flash. In this paper we refer to these K-leaders or recoil leaders as retrograde negative leaders as it is not clear whether they are generated at the very tip of a positive leader by a true recoil-like process, or are a consequence of an increasing potential drop along an aging positive leader channel and initiate some distance back from the advancing leader tip. The word retrograde refers to their backward motion along a positive leader channel, away from the leader tip. Retrograde negative leaders are readily detectable because they radiate strongly in VHF [*Shao and Krehbiel*, 1996] and are optically bright [e.g., *Saba et al.*, 2008].

[6] In this paper we present VHF time-of-arrival lightning mapping array (LMA) observations of upward positive leaders of a triggered flash that developed extensively into the midlevel negative charge region of a storm over Langmuir Laboratory in central New Mexico. From the observations we can estimate three-dimensional velocities of positive leaders, and by identifying leader polarities of naturally

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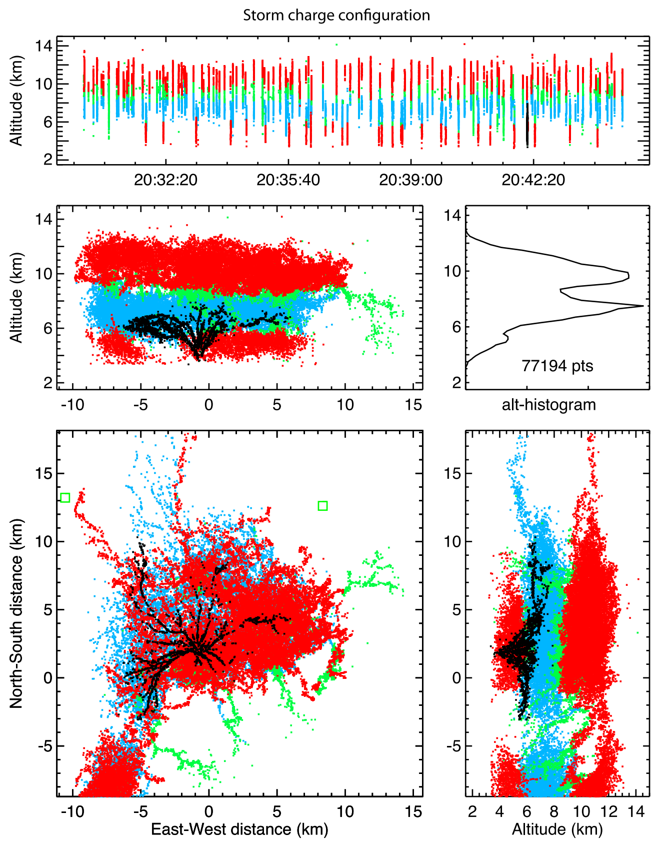

Figure 1. Storm charge structure around the time of the triggered flash, from 20:30 to 20:45 UTC. The charge identification was carried out on all natural flashes in the time interval (see text). The triggering site is located near ($x = -1$, $y = 2$) km. Blue indicates positive breakdown in negative charge, while red indicates negative breakdown in positive charge. Green refers to undetermined space charge. The storm had a normal-polarity tripolar charge structure with the negative charge boundaries near 5.5 and 9.0 km altitude. The triggered flash (VHF sources colored black) initiated under the SW perimeter of the lower positive charge region.

occurring flashes the location of the main charge regions of the storm can be inferred. Also, we show that the LMA can detect and locate VHF emissions from both positive and negative breakdown.

2. Instrumentation

[7] The lightning-triggering facility at Langmuir Laboratory is situated at the summit of South Baldy Peak in the Magdalena Mountains at an altitude of 3.2 km above sea level. To trigger lightning a custom-built aluminum rocket body powered by a G-class model rocket motor tows up a copper-coated steel wire with a diameter of 0.22 mm. The wire unwinds from a bobbin that is fixed at ground level and is electrically grounded. In a sufficiently strong electric field and under favorable conditions an upward leader typically initiates from the rocket when it has reached an altitude on the order of 200 m above ground level.

[8] The LMA deployed around Langmuir Laboratory in 2010 consisted of 16 stations, 13 of which were active at the time of the triggered flash. The array has a diameter of 48 km with 7 of the 16 stations arranged in a compact configuration within a few km of the mountaintop observatory. Each LMA station operates in the 60–66 MHz band (analog television channel 3), recording the time of arrival and peak power of impulsive VHF emissions in successive 10 μs windows [*Rison et al.*, 1999; *Thomas et al.*, 2004]. From the recorded peak-power values the power emitted by a located VHF source can be estimated. The source power detection threshold of the Langmuir Laboratory LMA for VHF sources within the array is on the order of 1 mW.

[9] A set of "slow" and "fast" ΔE antennas were set up at the main laboratory building at a distance of 1.8 km from the triggering site. The slow ΔE antenna has a relaxation time constant of 10 s; the fast ΔE instrument has a time constant of 0.1 ms. One of the LMA stations at the main laboratory provided a logarithmically detected VHF waveform (Log-RF) in the 60–66 MHz band.

[10] A high-speed video camera was operated at the main laboratory building, configured to record 6400 frames per second at an image resolution of 800 $\times$ 600 pixels. Video recordings of the flash discussed here are the focus of a separate study by *Winn et al.* [2012].

3. Observations

[11] The triggered flash occurred on 3 August 2010 at 20:42:09 UTC, in an electric field at the ground of

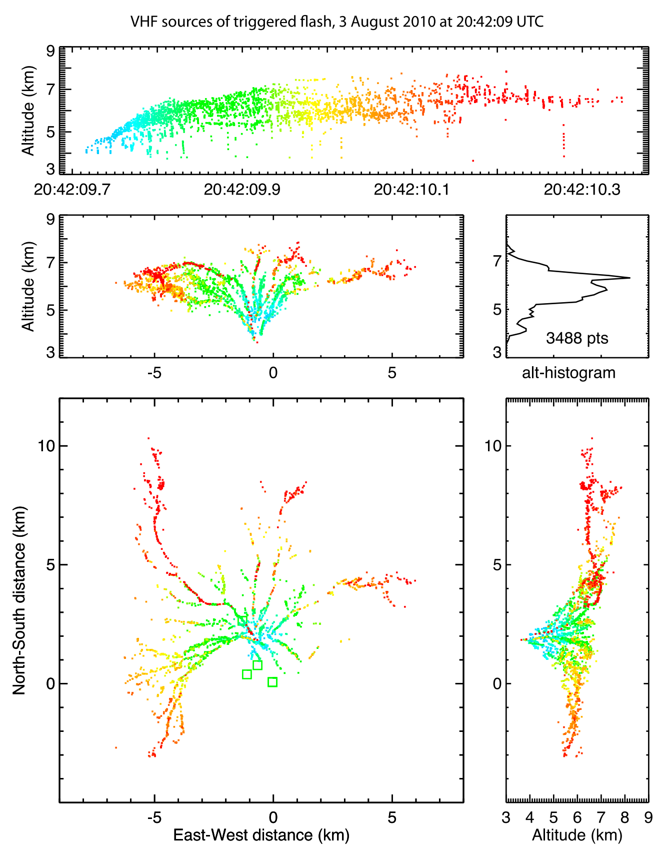

Figure 2. Three-dimensional view of the mapped VHF sources from the triggered flash. Sources are colored by time from blue (earlier) to red (later). The flash lasted 640 ms, reaching up to 7.5 km altitude and extending over a horizontal area of 13 $\times$ 13 km.

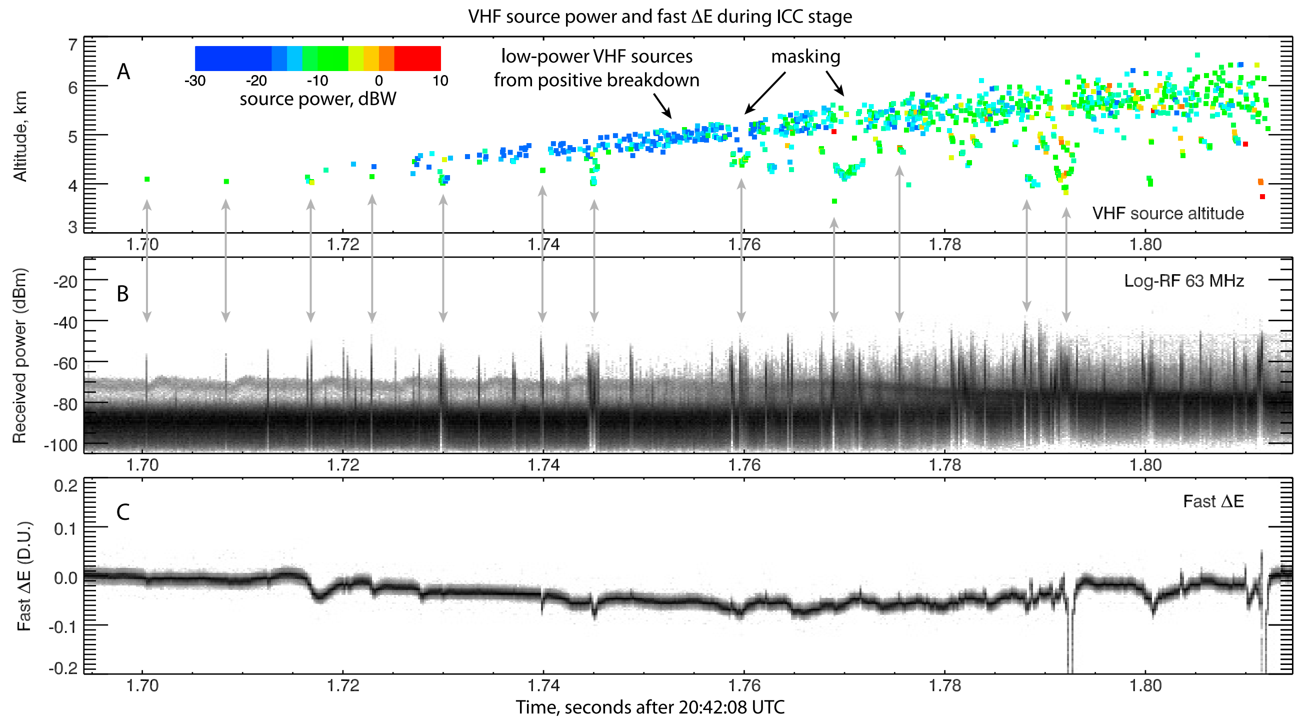

Figure 3. Waveforms and LMA data during the initial 120 ms of the flash, encompassing the ICC stage. (a) VHF source altitude vs. time, colored by power, (b) Log-RF waveform and (c) fast ΔE waveform (using the physics sign convention; D.U. = digitizer units). Several instances of retrograde negative breakdown are indicated by vertical arrows between the VHF sources (Figure 3a) and large-amplitude bursts of VHF emissions (Figure 3b). The bursts correlate in time with dips in the electric field, indicating transfer of negative charge downward. VHF sources associated with retrograde negative breakdown tended to be higher in power than those occurring at a more continuous rate in between bursts, indicating that the latter were associated with positive breakdown (see time interval between 1.74 and 1.76 s). The low-power VHF emissions are occasionally masked by the higher-power VHF emissions from retrograde negative breakdown. Toward the end of the time interval retrograde breakdown became more frequent, and fewer low-power VHF sources were located. Note the V-shape of VHF sources in Figure 3a at 1.77 s, from a downward propagating negative leader that followed part of another branch back upward. The lowest source power detected by the LMA in the time interval was 2.5 mW.

+7.4 kV m^{-1}. At this time the storm's core was displaced about 5 km to the NE of the triggering site. Between 20:30 and 20:45 UTC the storm produced 17 −CG flashes and 95 intracloud (IC) flashes.

[12] *Shao et al.* [1995, 1999] found that VHF emissions from positive breakdown tend to be weaker than those associated with negative breakdown. Source power estimates of VHF sources located by the LMA reflect this [*Thomas et al.*, 2001]. As a result, positive breakdown occurring concurrently in time with negative breakdown is generally not immediately evident in LMA data at the onset of a flash until several ms later, when retrograde negative leaders begin to occur along previously undetected positive leader channels. This gives IC and CG flashes mapped by the LMA a characteristic appearance, from which the leader polarities can be determined and the storm's charge configuration inferred [e.g., *Rust et al.*, 2005; *Weiss et al.*, 2008].

[13] The storm had a normal-polarity tripolar charge structure [e.g., *Williams*, 1989; *Marshall and Stolzenburg*, 1998] with upper positive charge over midlevel negative charge, with a boundary near 9.0 km altitude, and a lower positive charge region below 5.5 km altitude (Figure 1). The triggered flash initiated near the SW perimeter of the lower positive charge region.

[14] Figure 2 shows located VHF sources in three dimensions and time for the triggered flash. The first VHF sources associated with the upward leader occurred at 20:42:09.70 UTC near 4.0 km altitude, about 800 m above ground level. At this time the upward leader channel was about 700 m in length and had split into 5 branches, as determined from high-speed video images. The various branches proceeded upward along slanted paths up to 40 degrees from vertical, changing to mostly horizontal upon entering the midlevel negative charge region of the storm between 6 and 7 km altitude. The flash reached an altitude of up to 7.5 km and extended over a horizontal area of approximately 13 × 13 km. The upward leaders were of positive polarity, as inferred from electric field records.

[15] Figure 3 correlates waveform and LMA data during a time interval of 120 ms, encompassing the ICC stage of the flash. During this stage multiple branches extended upward to 6.5 km altitude into the midlevel negative charge region, causing the electric field to gradually decrease in magnitude over time. Initially, retrograde negative breakdown occurred intermittently in time along the leader channels. The negative breakdown produced relatively strong but intermittent bursts of VHF emissions (Figure 3, Log-RF) that correlated in time with dips in the electric field, indicating transfer of negative charge downward (Figure 3, fast ΔE). Weaker VHF sources

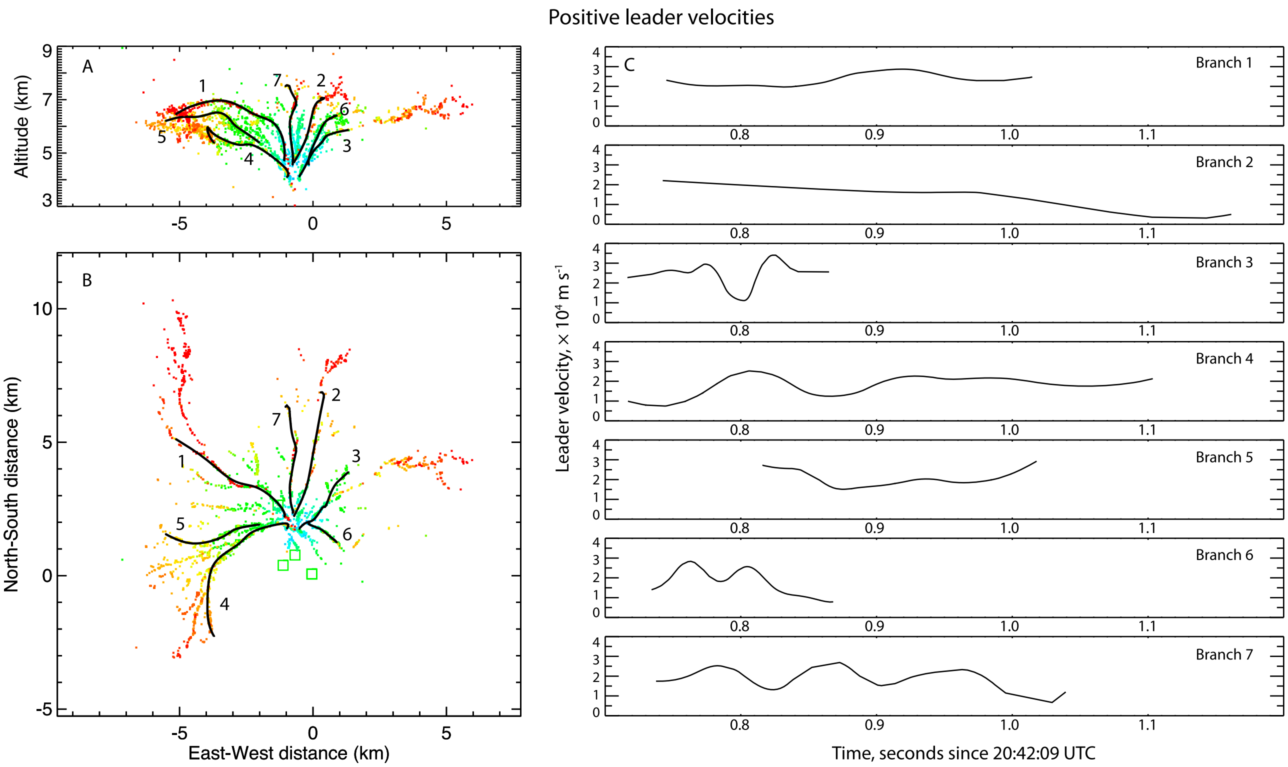

Figure 4. (a) East–west vertical view and (b) plan view of located VHF sources with fitted spline paths overlaid on seven branches, and (c) leader velocities along the seven branches as a function of time. Positive leader velocities are variable in the range of 1–3 $\times$ 10^4 m s^{-1}.

were located by the LMA at higher altitude, closer to the tips of the positive leaders, suggesting that these sources were produced by positive breakdown. When retrograde negative breakdown occurred, the detection of the low-power sources by the LMA was affected: The weak emissions from positive breakdown were masked by the stronger emissions from retrograde negative leaders. This masking effect resulted in gaps in the otherwise continuous "band" of low-power VHF sources associated with positive breakdown (Figure 3, VHF source altitude).

[16] Over time, retrograde negative breakdown occurred at a higher rate along the branches, producing strong VHF emissions that masked the weaker VHF emissions from positive breakdown more often. This can be observed in Figure 3 as a gradual transition from the mostly continuous band of low-power VHF sources to a group of VHF sources that were of higher power and more scattered in altitude. Toward the end of the time interval, when the various branches had entered the midlevel negative charge region, most of the located VHF sources were associated with retrograde negative breakdown, masking weaker VHF emissions from positive breakdown most of the time.

[17] VHF source locations can be used to determine leader velocities. Such a study has been done by *Behnke et al.* [2005] who studied upward negative breakdown at the beginning of IC flashes. By fitting a cubic spline interpolating function to individual leader branches in both the spatial and time domain, leader velocities can be estimated. We used the same fitting procedure to determine positive leader velocities along seven branches of the triggered flash. The spline fitting procedure is more complicated for positive leaders than for negative leaders, due to numerous retrograde negative leaders that may occur close to the tips of positive leaders. It is important to only consider VHF sources from positive breakdown, and for this reason leader velocities of only a few select branches could be determined reliably in the fitting procedure, excluding the most extensive branches.

[18] Figure 4 shows inferred leader velocities along the seven branches. Leader velocities were observed to be in the range of 1–3 $\times$ 10^4 m s^{-1}. No apparent trend of acceleration or deceleration is evident. Positive leader velocities plotted as a function of source altitude (not shown) also do not show a significant trend.

4. Discussion

[19] The triggered lightning flash effectively removed negative charge from the storm's midlevel negative charge region, similar to a natural −CG flash. Although triggered lightning initiates in a different way (with an upward positive leader rather than a downward negative leader), the later stages during which positive leaders extend into negative charge and produce dart leaders and return strokes are the same in both types of flashes.

[20] Reports in the literature on positive leader velocities of triggered lightning are relatively scarce. Most of the estimates of 2D positive leader velocities were made by analyses of streak photographs or high-speed video imagery and range from 2 $\times$ 10^4 to 1.2 $\times$ 10^6 m s^{-1}, with typical values between 10^5 and 10^6 m s^{-1} [*Berger and Vogelsanger*, 1969; *Fieux et al.*, 1978; *Idone*, 1992; *Dong et al.*, 2001; *Biagi et al.*, 2011]. *Yoshida et al.* [2010] estimated 3D positive leader speeds in Florida triggered lightning on the order of 10^6 m s^{-1} using two interferometers. Our 3D estimates of

positive leader velocities in the triggered flash are in the range of $1–3 \times 10^4$ m s^{-1}, which is relatively slow compared to the earlier estimates but agree with those from LMA observations of another triggered flash in a New Mexico storm by *Trueblood et al.* [2011]. Our method of 3D velocity estimates is at least as accurate as the other methods, and inaccuracies in the estimates cannot account for the difference. Positive leaders in triggered lightning do appear to propagate more slowly in New Mexico thunderstorms than in some other regions; it is unclear why.

[21] An important question is whether positive breakdown itself produces locatable VHF emissions, or if all located VHF sources associated with positive leaders actually originate from retrograde negative breakdown, which may occur close to the tips of positive leaders and be short in extent (tens of meters). The results of this study suggest that positive breakdown does produce VHF emissions, but the emissions tend to have low power and are only detectable with time-of-arrival techniques when no concurrent negative breakdown occurs that produces strong VHF emissions.

[22] The LMA started to locate VHF sources from the positive leaders only when they reached an altitude of 4 km, 800 m above ground level. Positive leader channels below that altitude were not mapped. Apparently, the positive leaders initially produced VHF emissions that were either not impulsive or too weak to be detected. The first retrograde negative leaders were observed in video imagery to occur close to 4 km altitude [*Winn et al.*, 2012]. The current associated with a retrograde negative leader is expected to make a leader channel more conductive by heating, and the enhanced channel conductivity may have caused a change in VHF emissions by the positive leaders.

[23] Retrograde negative leaders that frequently occur in both triggered flashes and in natural $-$CG flashes produce strong VHF emissions that tend to mask weaker VHF emissions from positive breakdown. In the initial stage of a $-$CG flash positive breakdown is generally not mapped at all by the LMA due to the VHF emissions from the downward negative leader. Triggered flashes initiate with an upward positive leader without concurrent negative breakdown. Retrograde negative leaders initially occur infrequently and their VHF emissions do not interfere as much with emissions of positive leaders, facilitating the study of positive breakdown processes.

[24] **Acknowledgments.** Major support came from DARPA NIMBUS program grant HR0011-10-1-0057 with additional support from the National Science Foundation, the Lightning Protection Institute, the Irving and Marion Langmuir family, the Geophysical Research Center and the Office of the President of the New Mexico Institute of Mining and Technology, and the United States Forest Service.

[25] The Editor thanks two anonymous reviewers for assisting in the evaluation of this paper.

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