GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 11, PAGES 2141-2144, JUNE 1, 2001

Energetic radiation associated with lightning stepped-leaders

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Abstract. With the use of a NaI scintillation detector, bursts of radiation with energies in excess of 1 MeV were recorded at a mountain-top observatory immediately before three, nearby cloud-to-ground, negative lightning strikes. Coincident recordings of the electric field changes due to the discharges showed that, in each case, the bursts began between 1 and 2 milliseconds before and continued until the onset of the first return stroke. This radiation was associated with approaching stepped-leaders and may have influenced their development.

Introduction

Schonland and Collens [1934] discovered that the early stage of most cloud-to-ground lightning strikes consists of a negative leader that descends from a thundercloud; it "advances in a series of steps, each about 50 yards long, and pauses for about fifty microseconds after each such step, behaving as if it were exhausted and needed time to recuperate. After a pause, the process is repeated with a new step downwards, the new movement involving a rejuvenation of the part of the channel already created by the streamer, which gives out a burst of light along its whole length, though not as brightly as does the new step. Each step is made in a different direction from the previous one, and it is at the start of a new step that the streamer sometimes forms forks or branches, whereupon the leader continually divides along different paths, each itself involving a series of steps." [*Schonland*, 1950]

Stekolnikov and Shkilyov [1965] later studied long, negative sparks in a high-voltage laboratory using an electron-optical converter on negative-rod-to-positive-plane discharges in gaps ranging from one to three meters in length. They discovered that a stepped leader propagates by creating "impulse corona flashes" and "space leaders" ahead of the tip of a negative leader. The "space leader" consists of a new channel forming ahead of the leader with the negative end of the channel moving toward the positive plane while the positive end of the channel propagates backward, toward the tip of the negative leader. Stekolnikov and Shkilyov suggested that when the positive end of the channel connects to the tip of the negative leader, the length of the leader increases by one step and its new tip rapidly assumes the source potential whereupon new space leaders develop in the air ahead of the new tip.

This behavior of the strike-initiating negative leaders; advancing in steps, with the leader changing its direction with each step, with branching occurring during the initiation of a new step, and with the development of new channels out ahead of the leader tip before a step is made, all suggest that the tip of the leader may become a source for ionizing radiation. This radiation, coupled with the strong electric fields near the tip, may be the cause of the new channels ahead of the leader.

After C. T. R. *Wilson*'s suggestion [1925] that strong electric fields in thunderclouds might accelerate free electrons to high speeds thereby generating penetrating radiation as the electrons slowed during collisions with air molecules, there have been many attempts to determine if energetic radiation occurred in and around thunderclouds [*Schonland and Viljoen*, 1933; *Halliday*, 1934; *Hill*, 1963; *Anderson and Few*, 1968; *Fleischer*, 1977; *Susczynsky et al.*, 1996] and others. Such radiation has been detected by *Eack et al.* [1996a,b, 2000] using scintillation detectors carried by free balloons into regions of thunderclouds with strong electric fields. Following *Gurevich et al.* [1992], these investigators interpreted their results as being caused by the acceleration—under the influence of the strong electric fields in thunderclouds—of electrons liberated by cosmic rays which created subsequent energetic electron avalanches. Although a number of other investigators have attempted to determine if ionizing radiation was associated with stepped leaders, none of them has been successful using the detection techniques that were available at the time.

Our experiment

In the course of our continuing study of the responses of lightning rods to nearby strikes [*Moore et al.*, 2000], on May 31, 2000, we installed a NaI (Th) scintillation detector and a control detector (without the NaI crystal) in the vicinity of our lightning rods on the roof of Kiva II, the buried, underground room at the 3288-m high summit of South Baldy Peak in the Magdalena mountains of west-central New Mexico. To record the analog signals that were produced in the detectors by any incident radiation, their outputs were connected to computer-controlled digitizers located within the Kiva, immediately below the detector.

Instrumentation

Scintillator description

Two Bicron NaI scintillation detectors used earlier in a ground-based search for X rays generated by thunderstorms [*Susczynsky et al.*, 1996] were loaned to us by Los Alamos National Laboratory for this study. Each detector consisted of 63.5-mm-diameter, 63.5-mm-thick NaI crystal, a coupled photomultiplier tube with a 75-mm-diameter photocathode and a high-gain preamplifier which was a-c coupled to the

Paper number 2001GL013140.
0094-8276/01/2001GL013140$05.00

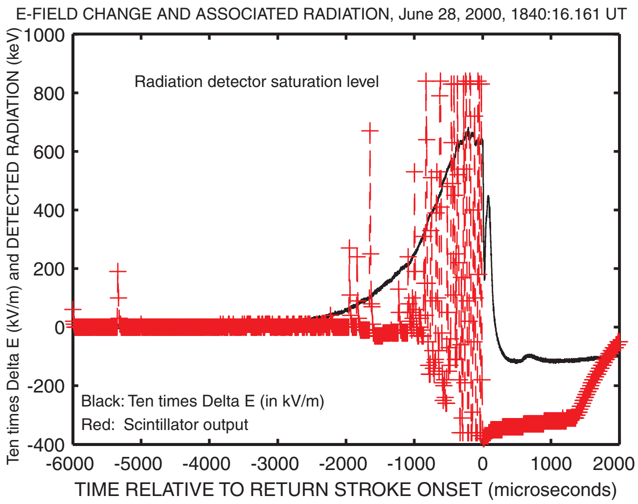

Figure 1. Plot of the change in the strength of the atmospheric electric field and of the associated radiation that was detected when lightning struck near the radiation sensor on South Baldy Peak at 1840:16.161 UT, June 28, 2000. The lightning strike closest to the peak during this storm struck a pine tree that was located 34-m NNE of the radiation sensor.

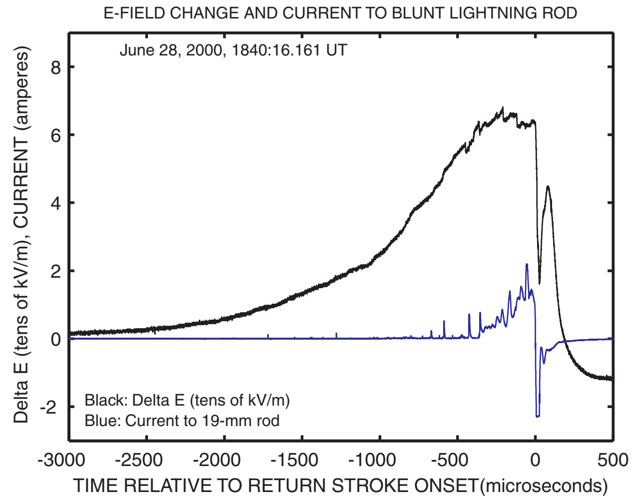

Figure 3. Plot of the change in the strength of the atmospheric electric field and of the current that flowed to a 19-mm-diameter blunt lightning rod mounted on a 6-m high mast over the radiation sensor on South Baldy Peak when lightning struck nearby at 1840:16.161 UT, June 28, 2000. The lightning strike closest to the peak during this storm struck a pine tree that was located 34-m NNE of the radiation sensor.

photomultiplier output. The detector windows were covered by a foil of 0.25-mm-thick aluminum.

The NaI crystal was replaced in one of the Bicron sensors with a non-scintillating plastic material. This device was then used as a "control"; its output served as a detector of any spurious radiation indications produced by radio-frequency inputs or by displacement currents caused by nearby lightning.

The active detector was reported to be sensitive to X rays in the 15 keV to 2 MeV energy range at a 60% efficiency cutoff, and to electrons with energies greater than 200 keV. During our measurements, the output from the preamplifier on the active detector saturated at indicated energies of 1.2 MeV. The signal output from the preamplifier on this scintillator had a measured rise time of about 1 μsec and a fall time to half value of 8 μsec.

Digitizer description

A two-channel Gage Lite digitizer was used to record the amplitudes of the output signals from the scintillator photomultipliers. The digitizer was activated by a trigger signal generated by the rapid intensification of the ambient electric field caused by the approach of a stepped leader. The electric field change sensor consisted of an electrode which was exposed to the ambient electric field but shielded from any rain; the signals produced by the displacement currents flowing to the electrode under the influence of changing electric

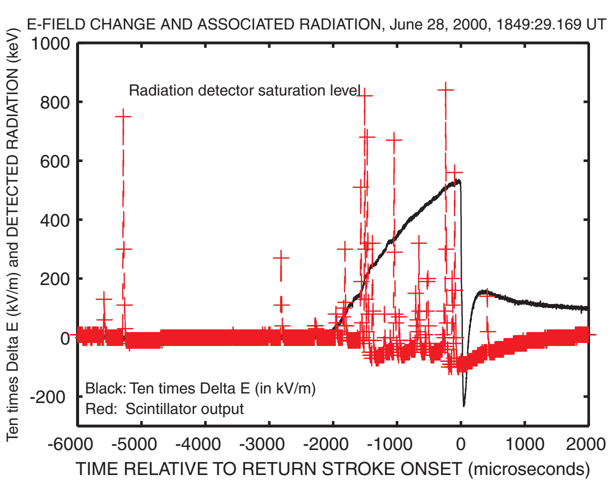

Figure 2. Plot of the change in the strength of the atmospheric electric field and of the associated radiation that was detected when lightning struck near the radiation sensor on South Baldy Peak at 1840:16.161 UT, June 28, 2000. During this storm, lightning also struck a spruce tree that was located 44-m NE of the radiation sensor.

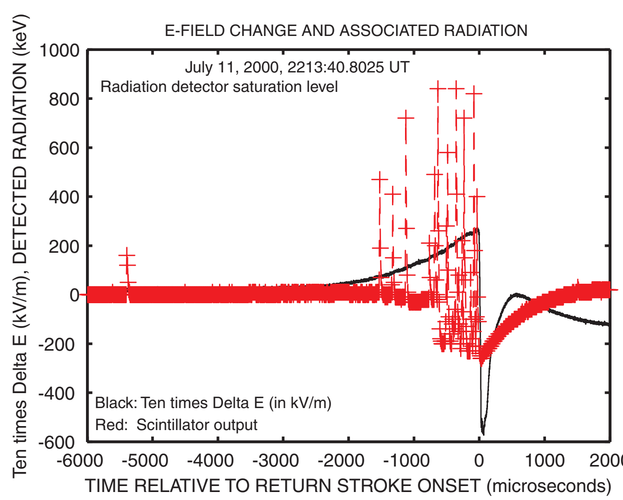

Figure 4. Plot of the change in the strength of the atmospheric electric field and of the associated radiation that was detected when lightning struck somewhere near the radiation sensor on South Baldy Peak at 2213:40.8025 UT, July 11, 2000.

fields were differentiated and passed to a comparator that generated a trigger pulse whenever the electric field changes were sufficiently strong for the initiation of a strike nearby. After the digitizer received a trigger, it wrote the recorded data to hard disk then re-armed itself waiting for the next trigger.

Two other digitizers, each operating at a 5 MHz sampling rate, were activated by the same trigger to record the electric field changes and the currents that flowed from the Earth to the tips of three lightning rods in a continuation of the measurements described by *Moore et al.* [2000]. During the 2000 study, the lightning rods under test were a UL-listed, sharp-tipped Franklin rod, a 19-mm diameter, hemispherically-tipped blunt rod and a high-tech French air terminal alleged to emit early streamers.

For these studies, the digitizer recording the scintillator outputs was set to record the input signals once every 10 microseconds with 6066 samples pre-trigger and 2126 samples post trigger. All three digitizers employed in the 2000 study collected data while unattended.

In late August, the digitization rate was increased with a sample being taken every microsecond. On July 21, we installed a fourth high speed digitizer that recorded the output of the active scintillator once every 40 ns.

The radiation detectors were calibrated by use of ^{137}Cs sources which emit 511 keV β-rays and 662 keV γ-rays. When those sources were placed near the detectors, the peak output signals from the digitizers were increased by about 67 bits from which we infer that a radiation energy of 10 keV was required to produce an output level change of 1 bit.

Results

The plots in Figures 1, 2 and 4 depict the active scintillator's photomultiplier amplifier output for each sample taken during the recordings. Each pulse in the plot indicates the detection of a single radiation event or of multiple events if they occurred between successive samples. The output of the control scintillator (which was a duplicate of the active one in all respects except that it did not contain a sodium iodide crystal) showed no indication of any response during any of the three nearby strikes for which we obtained recordings. The noise level of its output was at the one-bit level; this level was not exceeded during these strikes. From this we infer that the signals from the active detector were not influenced by radio-frequency pickup or by other spurious inputs.

June 28, 2000

An air-mass thunderstorm formed over South Baldy Peak just after local noon on this day when there were no observers in the Kiva. The electric field discontinuities caused by the lightning in this storm were recorded both by the digitizers and on a strip chart. The outputs from the two scintillators were digitized, tagged with the GPS times of occurrence and stored on the computer hard drives.

During our next visit to the Kiva on July 7, we discovered that two nearby lightning strikes had activated the recording system on June 28 and that the active scintillator had detected radiation associated with these two strikes. Plots of the electric field changes and the outputs of the active scintillator during these strikes are shown in Figures 1 and 2. A plot of the currents flowing from the exposed lightning rods mounted above the scintillators shows, in Figure 3, that the 19-mm-diameter blunt rod emitted a peak current of 2 A about 50 μsec prior to the onset of the first return stroke at 1840:16.161 UT on June 28. This large burst of current and the electric field change of 68 kV/m indicate that the strike was quite close to the Kiva. The National Lightning Detection Network (NLDN) [*Cummins et al.*, 1998] recorded at this time and at the approximate location of South Baldy Peak a flash with sixteen return strokes, the peak current in the first of which was 88 kA.

The peak current emitted by the blunt rod during the second strike at 1849:29.169 UT was 0.18 A; the peak electric field change was about 54 kV/m. These lesser values suggest that the second discharge was not as close to the Kiva as the first discharge. The peak current in the initial return stroke recorded at 1849:29.169 UT by the NLDN was 80 kA.

Visual examination of the area around the Kiva on July 7 showed that two trees nearby had been struck recently. The closest tree, a pine located 34 meters NNE of the scintillator, had lost most of the pine needles in its upper parts; the needles that remained were brown and soon fell off. The needles around the "crown" of the second tree, a spruce at a distance of 44 meters NE of the scintillator, had all turned brown.

July 11, 2000

Another strike near the Kiva occurred on July 11 at 2213:13.170 UT, when again, there were no observers present. Plots of the electric field changes and the scintillator outputs during this strike are shown in Figure 4. The location spot on the Earth for this strike could not be found; there was no indication of damage to the local vegetation. The peak current measured by the NLDN for this stroke was 76 kA.

Later measurements

In a subsequent effort to determine the horizontal extent of the radiation associated with a strike, we installed two additional scintillators at distances of 5 meters and 44 meters from the first set and led their outputs through shielded cables to another pair of computer-controlled digitizers within Kiva II. All four devices operated until October 4, after the end of the thunderstorm season but no nearby strikes occurred during the remainder of the season after July 11. Distant strikes did occur during this late summer period but there was no indication of energetic radiation associated with them.

The two trees struck by lightning just north of South Baldy Peak were located within 40 meters of the exposed lightning rods. However, none of the three lightning rods competing for strike reception were struck by lightning during the year 2000 thunderstorm season.

Concluding remarks

The inferred peak energies of the incident radiation at 1840:16.16 UT on June 28, 2000 (during the closest strike) were in excess of 1.2 MeV, the level at which the detector saturated, however, with our digitizers it was not possible to determine if multiple photons arrived during the 10 microsecond interval between samples. The obvious question is "What is the source of the energetic radiation bursts that produced the scintillations in our detector?" Since they occurred in close association with negative stepped leaders initiating cloud-to-ground lightning strikes, it is likely that they originated in the leaders around the tips of which very strong electric fields have been inferred [*Bazelyan and Raizer*, 1997]. It is possible that this electric field combined with a cosmic ray shower produced an avalanche of energetic electrons that in turn produced the radiation we detected [*Gurevich et al.*, 1999]. Conventional breakdown involves electron energies on the order of 10 eV [*Bazelyan and Raizer*, 1997] and cannot produce such energetic radiation. Therefore, the production of this radiation during the development of negative stepped leaders warrants further investigation.

Acknowledgments. Support was provided by the NSF through grant ATM-0075730. We thank David M. Suszcynsky at Los Alamos National Laboratory for the loan of the radiation detectors. We also thank East Coast Lightning Equipment, Inc., A-C Lightning Security, Robbins Lightning, Inc., Advanced Lightning Technology, Inc., Maxwell Lightning Protection of Florida Company and Bonded Lightning Protection of Florida Company for the support that made these digitizer studies possible, Richard Setchell, Wisconsin Electric Power Company, for providing the computers used in this study and Franco D'Alessandro of ERICO, Tasmania for the loan of the Gage Lite digitizers that we used to record the outputs from the scintillators.

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(Received March 8, 2001; revised April 20, 2001;
accepted April 25, 2001.)