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X-ray bursts associated with leader steps in cloud-to-ground lightning

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[1] X-ray and electric field measurements were made during five nearby negative natural lightning strikes in north central Florida during the summer of 2004. The observed X-ray emission typically was detected ~1 ms before the first return stroke, during the stepped-leader phase, and had energies extending up to a few hundred keV. The X rays were produced in discrete, intense bursts emitted in coincidence with the formation of the leader steps, demonstrating unambiguously that the source of lightning X rays is closely related to the stepping process. The X-ray emission from lightning stepped leaders is found to be remarkably similar to that from lightning dart leaders, suggesting that these different types of leaders share a common mechanism. The reported observations have important implications for understanding how runaway breakdown occurs and how lightning leaders propagate. **Citation:** Dwyer, J. R., et al. (2005), X-ray bursts associated with leader steps in cloud-to-ground lightning, *Geophys. Res. Lett.*, *32*, L01803, doi:10.1029/2004GL021782.

1. Introduction

[2] Despite many decades of research, the physics of lightning leader propagation remains poorly understood. Observations have shown that lightning's initial path to the ground is forged by a hot leader that breaks down the virgin air in front of it and allows current to flow in the channel behind the front [*Rakov and Uman*, 2003, p. 111]. This process can continue for great distances, permitting the initially localized breakdown inside the thundercloud to traverse kilometers of air to the ground where it can potentially cause injury to people and damage to property.

[3] Interestingly, the initial leader does not travel to the earth in a continuous manner, but, instead, takes a series of discrete steps [*Schonland*, 1956]. For this reason, the initial leader in natural cloud-to-ground lightning is called the stepped leader. Why or how lightning propagates in this halting manner is not known, but one possible scenario [e.g., *Rakov and Uman*, 2003, pp. 136–137], based upon negative laboratory spark experiments, is that during the stepping process, a new leader channel segment is initiated in a high electric field region some distance in front of the stalled leader. This new segment attaches to the old leader channel, allowing current to rush along the channel and extending its overall length. The leader propagation then stalls and the whole cycle repeats. Because the process of stepping determines the path that lightning takes and the number of branches that develop, understanding how lightning leader steps occur is of great practical interest.

[4] Up until recently most researchers believed that lightning was an entirely conventional, albeit large, discharge that did not involve any high-energy processes that might produce energetic radiation such as X rays. This view radically changed when *Moore et al.* [2001] showed that energetic radiation is produced during natural lightning and when *Dwyer et al.* [2003] demonstrated that rocket-triggered lightning also produces large quantities of energetic radiation. Later measurements by *Dwyer et al.* [2004a] found that the energetic radiation is in fact composed of X rays with energies extending up to about 250 keV and that the emission occurred in short, <1 μs, bursts during the dart leader phase and possibly at the beginning of the return strokes of negative triggered lightning.

[5] These results demonstrate that lightning is not just a conventional discharge but also involves the runaway breakdown process [*Gurevich et al.*, 1992], in which electrons are accelerated to relativistic energies by strong electric fields [*Gurevich and Zybin*, 2001; *Dwyer*, 2003, 2004]. Furthermore, the fact that lightning emits X rays strongly implies that at some point during the discharge the electric field grows to a much larger value than previously inferred [*Bazelyan and Raizer*, 2000]. Unfortunately, where and how these high fields occur has not been clear, and the exact runaway breakdown mechanism for producing the energetic radiation has remained illusive.

[6] In this report, we present new observations of natural negative cloud-to-ground lightning that demonstrate unambiguously that the production of X rays is associated with the stepping of the leader that initiates the first return stroke. This conclusion substantially narrows the candidates for the source of the emission and allows the underlying mechanism to be explored.

2. Observations

[7] The measurements reported here were made during the summer of 2004 at the University of Florida/Florida Tech International Center for Lightning Research and Testing (ICLRT) [*Rakov et al.*, 1998], at Camp Blanding, FL, by eleven NaI(Tl)/photomultiplier tube detectors plus one control detector with no scintillator. The detectors were mounted inside a total of 5 heavy aluminum boxes, designed to keep out moisture, light, and RF noise, and placed at several locations at the facility with a maximum separation of 60 m. The detectors and associated electronics within each box were battery powered and the output signals from the PMT anodes were transmitted via fiber-

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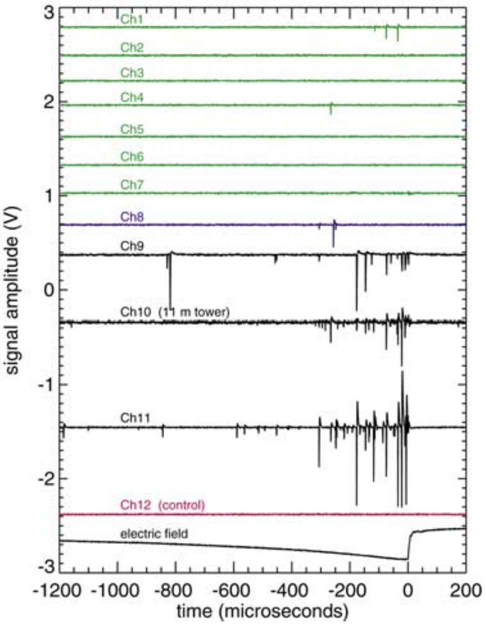

Figure 1. X-ray and electric field waveforms for the 24 August 2004 natural cloud-to-ground lightning flash. Time zero in the plot corresponds to the beginning of the return stroke. Ch1–Ch12 are the raw X-ray waveforms from the PMT anodes, corrected only for slight gain differences between channels. A negative pulse with a magnitude of 0.25 V corresponds to a deposited energy of 662 keV. The electric field (bottom trace) was measured using a flat-plate antenna located 30 m from detector Ch11 and 240 m from the strike point. A −1.0 V deflection on the plot corresponds to a vertical electric field of −82 kV/m. Stepping is not evident in the electric field waveform on the scale shown but is clearly seen with the nearer electric field antenna and the expanded scale in Figure 2.

optic links to a Yokogawa DL750 ScopeCorder, having a sampling interval of 0.1 μs, located in a shielded trailer. Optical measurements were used to trigger the system, generally at the time of the first return stroke, when a nearby lightning strike occurred. The total record length was 2 s, with 0.5 s of pre-trigger data in order to make measurements from the stepped leader phase.

[8] Along with the X-ray detectors, the ICLRT is equipped with instrumentation for measuring optical emissions, electric and magnetic fields, and the time-derivatives of the electric and magnetic fields. These instruments are located at several locations throughout the 1 square km facility. The electric field derivatives, *dE*/*dt*, were measured using aluminum flat-plate antennae, with the data transmitted over fiber-optic links and recorded on a LeCroy LT374 digital storage oscilloscope having a sampling interval of 5 ns and a total record length of 5 ms (4 ms pre-trigger). The upper frequency response of the *dE*/*dt* measurements is about 20 MHz.

[9] During the summer of 2004, a total of 5 natural cloud-to-ground lightning flashes, all of which lowered negative charge to the ground, struck the ICLRT or its immediate vicinity, with significant X-ray emission measured. In this report, we shall discuss two of these flashes, which occurred on 15 July and 24 August 2004. From the point of view of the X-ray observations in 2004 these two events were typical. However, they were unique in the fact that both first strokes terminated on the ground within about 50 m of one *dE*/*dt* sensor, allowing excellent electric field measurements of the initial-leader steps.

[10] Figure 1 shows 1.4 ms of data for all 11 X-ray detectors plus the control detector and electric field data for the flash on 24 August. At the time of the natural lightning observations, seven of the detectors (Ch1–Ch7) were covered by collimators as part of a triggered lightning experiment (not discussed here). The collimators each had a narrow (2° × 20°) field-of-view that happened to be pointed away from the natural lightning strike locations. As a result, X rays from the natural lightning were attenuated by the 0.3 cm thick lead and 1.9 cm thick tin-bronze sides of the collimators. In addition, one detector (Ch8) was shielded by a 0.3 cm thick tin-bronze attenuator cap. The remaining detectors were unshielded except for the aluminum windows on the boxes that contained them. Detectors Ch1–Ch9 were all at the same location, about 300 m from the natural lightning strikes. Detectors Ch11 and Ch12 (control) were collocated about 260 m from the lightning strikes and Ch10 was located on top of an 11 m tall tower, 30 m away from Ch1–Ch9 and about 310 m from the lightning strikes. For this event, the X-ray pulses begin a little less than 1.2 ms before the return stroke and terminate at or near the beginning of the return stroke. No signals are seen on the control detector (Ch12). This behavior is similar to the other 4 natural lightning strikes for which X rays were measured, the average time before the return stroke that the X rays begin being 0.9 ms. This time, corresponding to the last stage of the stepped leader before its attachment to the ground, is about a factor of thirty longer than for the dart leaders in triggered lightning. The difference is likely related to the difference in the leader speeds, since X rays are only observed when the source is within a few hundred meters or so of the ground due to the limited range of X rays propagating through air.

[11] Because the signal amplitudes are a direct measure of the deposited energy in the detectors, a comparison of the attenuated signals with those from the unshielded detectors allows an estimate of the photon energies in the bursts [*Dwyer et al.*, 2004a]. Using a Monte Carlo simulation, it is found that the bronze attenuator cap (Ch8) becomes (>75%) transparent above 150 keV. Therefore, the lack of X-ray pulses on Ch8 compared to the nearby unshielded detectors (Ch9–Ch11) shows that most of the X rays have energies well below 150 keV. On the other hand, less than 25% of 250 keV X rays penetrate the wall of the collimators (Ch1–Ch7), with the transmission dropping rapidly with decreasing energy. The occasional pulses seen in Ch1–Ch7 with relatively small pulses occurring at the same time on the unshielded detectors (Ch9–Ch11) demonstrate that the energy spectrum at times extends up to a few hundred keV, very similar to the dart leader spectrum measured by *Dwyer et al.* [2004a]. The data is consistent with the energetic radiation being composed of X rays, since energetic electrons would lose at least several MeV when passing through the bronze cap or the collimator sides. Such electrons, if they were present, would produce very large signals on the unshielded detectors, which are not observed. The absence of detected energetic electrons is not surprising given the

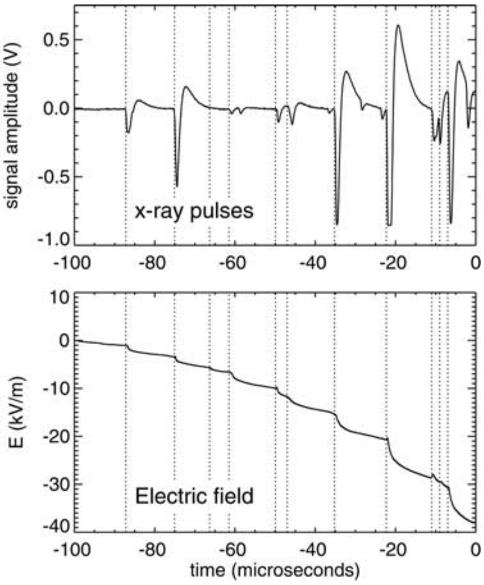

Figure 2. X-rays from detector Ch11 (top panel) and electric field (integrated *dE*/*dt*) waveforms (bottom panel) for the 24 August 2004 natural cloud-to-ground lightning flash. The lightning struck within 50 m of the electric field antenna and about 260 m from detector Ch11. Time zero in the plot corresponds to the beginning of the return stroke. The start times of the eleven final steps are denoted by vertical dotted lines.

large distance to the source and the short attenuation length of electrons in air.

[12] A comparison between the three unshielded detectors, separated by up to 60 m, show that the X-ray emission from the stepped leader, like dart leader emission [*Dwyer et al.*, 2004a], is highly pulsed. For example, for the time period −200−0 μs, of the 5 pulses on Ch9 with deposited energies above 300 keV (larger than 0.11 V in magnitude), all five pulse are also observed simultaneously on Ch10 and Ch11. Since X rays at these energies do not propagate long distances through the air, the X-ray intensities must have been very large in the immediate vicinity of the stepped leader, which was about 300 m away.

[13] Because the entire data record is 2 s long, the background rate is accurately determined and found to be 344 counts/s above 100 keV and 41 counts/s above 1 MeV for the 12.7 cm detector (Ch11) and much less for the other (7.6 cm) detectors. Therefore, there is only about a 1 in 4 chance that one of the smaller pulses seen in Ch11 is due to background and a 1 in 30 chance that one of the larger pulses is due to background. The background rates for the other detectors are substantially lower due to the smaller scintillator sizes and the additional material surrounding them.

[14] Figure 2 shows higher resolution data for the 24 August flash and Figure 3 shows data for the 15 July flash, for the stepped leader phases just prior to the first returns strokes. In Figures 2 and 3, the bottom panels are the integrated *dE*/*dt* waveforms, that is, the electric field changes produced by the stepped leaders as they propagate to the ground. These changes are negative because the leader brings negative charge closer to the ground. The individual steps appear as sudden drops in the electric field waveform. The top panels show the X-ray waveforms from the 12.7 cm detector (Ch11). Note that the finite width of the X-ray pulses (0.8 μs) is due to the detector response and that the X rays arrive at the very beginning of the pulses. The pulse shapes are in excellent agreement with the detector response function [*Dwyer et al.*, 2004a], determined by the front-end electronic circuit and the NaI decay-time, and match the pulse shapes produced by Cs-137 and Co-60 calibration sources. The vertical dotted lines indicate the starting times of the leader steps as determined by the electric field data. We note that time delays and uncertainties in the triggers may produce a small uncertainty, at most 1 μs, in the relative timing between the X-ray and electric field waveforms. As can be seen, the X-ray pulses are very closely associated with the leader steps. Indeed, 13 out of the 14 steps seen in Figures 2 and 3 produce an X-ray burst when measured at a distance of 260 m. In Figure 2 there are a few X-ray pulses that do not have an obvious association with a leader step as seen in the electric field data. It is possible that these X rays originated from leader steps formed by a more distant (from the electric field antenna) stepped leader branch. Indeed, inspection of data from other *dE*/*dt* sensors supports this view.

3. Discussion

[15] The observations reported here confirm the previous findings by *Moore et al.* [2001] that natural negative lightning produces energetic radiation during the stepped leader phase. Although Moore et al. conjectured that the sources of their energetic radiation were the stepped leaders, they did not report an association of the energetic radiation with stepping processes. In fact, their measurements did not

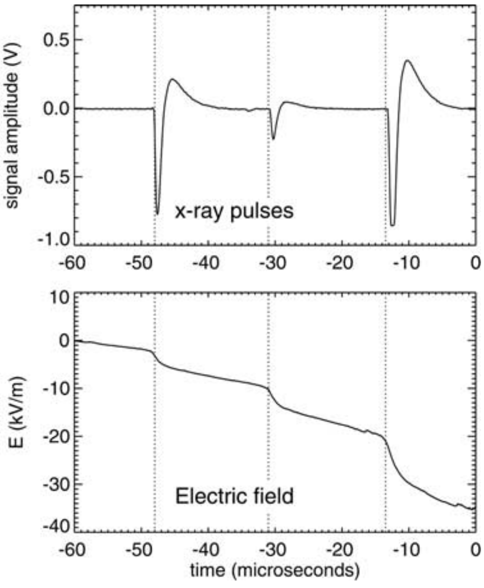

Figure 3. X-rays from detector Ch11 (top panel) and electric field (integrated *dE*/*dt*) waveforms (bottom panel) for the 15 July 2004 natural cloud-to-ground lightning flash. The lightning also struck within 50 m of the electric field antenna and about 260 m from detector Ch11. Time zero in the plot corresponds to the beginning of the return stroke. The start times of the three final steps are denoted by vertical dotted lines.

rule out other sources such as the large-scale electric field produced by the thundercloud. In contrast, in this report we have shown that the stepped leader is the source of the energetic radiation, which is composed of X rays, and that the X rays are produced by the leader stepping process. In addition, our observations indicate that the large pulses observed are not individual MeV gamma rays but are instead intense bursts of X rays with energies typically well below 150 keV but occasionally extending up to a few hundred keV. This conclusion is vital for understanding the underlying mechanism for producing the X rays, since the popular relativistic runaway electron avalanche (RREA) model [*Gurevich et al.*, 1992] is seriously challenged by the absence of higher energy emission, as reported here [*Dwyer*, 2004]. Our observations of X-ray emission from natural lightning stepped leaders is remarkably similar to the X-ray emission from triggered lightning dart leaders previously reported by *Dwyer et al.* [2003, 2004a], implying that both the dart leader and stepped leader X-ray emission share a similar production mechanism. This implies that nearly all dart leaders in fact involve stepping to some degree, but that the steps are so short that they are usually not resolved in optical records. Consequently, it may be possible to unify the different kinds of negative leaders observed in nature, which may appear optically different depending on the conditions along their propagation path [*Rakov and Uman*, 2003], into one basic type, with one underlying mechanism for propagation.

[16] Bursts of X rays and gamma rays have been observed from other atmospheric phenomena as well as lightning. For instance, gamma ray flashes of terrestrial origins have been observed by BATSE onboard the Compton-Gamma-Ray-Observatory (CGRO) [*Fishman et al.*, 1994]. The source of these flashes remains unknown [*Dwyer et al.*, 2004b], but one possibility is that they originate from high altitude discharges called sprites [*Nemiroff et al.*, 1997]. *Pasko et al.* [1998] proposed that the gamma ray emission is produced by runaway breakdown in localized regions of very strong electric fields at the streamer tips of sprites. If this is the case then the process is likely to be very similar to that occurring during cloud-to-ground lightning, and the observations presented here may have a direct application for understanding sprites as well.

[17] In conclusion, large quantities of X rays and hence large numbers of energetic electrons are produced during the formation of leader steps in natural negative cloud-to-ground lightning. Because lightning leader propagation and the stepping mechanism are very poorly understood, these observations should provide both new guidance and powerful constraints on theories to explain the leader phenomenon.

[18] **Acknowledgments.** We would like to thank those at Florida Tech who assisted in the construction of the instruments and the collection of the energetic radiation data. This work was supported in part by the NSF CAREER grant ATM 0133773, DOT (FAA) grant 99-G-043, and NSF grants ATM 0003994 and ATM 0346164.

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