Measurements of x-ray emission from rocket-triggered lightning

J. R. Dwyer, H. K. Rassoul, M. Al-Dayeh, L. Caraway, B. Wright, and A. Chrest
Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, Florida, USA

M. A. Uman, V. A. Rakov, K. J. Rambo, D. M. Jordan, J. Jerauld, and C. Smyth
Department of Electrical and Computer Engineering, University of Florida, Gainesville, Florida, USA

Received 3 October 2003; revised 9 February 2004; accepted 13 February 2004; published 13 March 2004.

[1] We report measurements of the x-ray emission from rocket-triggered lightning, made during the summer of 2003, using four instruments placed between 15 and 40 m from the lightning channels. X-rays were measured 0–80 μs just prior to and at the beginning of 73% of the 26 return strokes observed. The emission was composed of multiple, very brief bursts of x-rays in the 30–250 keV range, with each burst typically lasting less than 1 μs. The x-rays were primarily observed to be spatially and temporally associated with the dart leaders with a possible contribution from the beginning of the return strokes, with the most intense x-ray bursts coming from the part of the lightning channel within ~50 m of the ground. Because triggered lightning strokes are similar to subsequent strokes in natural lightning, it is likely that x-ray emission is a common property of natural lightning. *INDEX TERMS:* 3300 Meteorology and Atmospheric Dynamics; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3324 Meteorology and Atmospheric Dynamics: Lightning; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Dwyer, J. R., et al. (2004), Measurements of x-ray emission from rocket-triggered lightning, *Geophys. Res. Lett.*, *31*, L05118, doi:10.1029/2003GL018770.

1. Introduction

[2] We have previously reported the discovery of energetic radiation from rocket-triggered lightning [*Dwyer et al.*, 2003]. These results along with earlier work by *Moore et al.* [2001] show that the production of energetic radiation is a relatively common feature of lightning. In this paper, we present preliminary results of additional observations made using improved instrumentation. The measurements were made at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL [*Rakov et al.*, 1998] using five instruments designed to operate in the electromagnetically noisy environment near lightning. The instruments were each housed in a heavy aluminum box. The sides of the boxes were 1.3 cm thick, except for a 0.3 cm thick window on the top that allowed x-rays with energies down to about 30 keV to enter. The boxes were welded and RF gaskets and viton O-rings were used on all access doors to prevent RF noise, moisture and light from entering. The five instruments housed a total of 8 NaI(Tl)/photomultiplier tube (PMT) detectors plus two control detectors, identical to the regular detectors, but with no scintillator (NaI). The instruments were battery powered, and switched on and off using fiber optics. The data were transmitted through fiber optic cables to receivers in a shielded metal trailer. The data were then saved to the hard drives of three PCs. Data acquisition was initiated by an external trigger derived from the lightning current, signaling the time of the leading edge of the return stroke current pulse or other large current pulses (threshold ~4 kA). The entire waveforms from seven of the PMT detectors were then digitized with a 0.2 μs sampling interval for 220 ms with 20 ms of pre-trigger sampling. For three detectors the waveforms were digitized with a 10 ns sampling interval for 10 ms with 1 ms of pre-trigger sampling.

[3] The observations made in the summer of 2002 and reported by *Dwyer et al.* [2003] used one 12.7 cm diameter by 7.6 cm thick cylinder of NaI(Tl) mounted to a 12.7 cm PMT detector and one identical control detector (with no scintillator). For the observations made in 2003, seven 7.6 cm diameter by 7.6 cm thick cylinders of NaI(Tl) mounted to 7.6 cm PMT detectors and one control were added.

[4] In this paper, we shall report on two instrument configurations that were used: In the first configuration, 1.7 cm thick tin-bronze (83% Cu, 7% Sn, 7% Pb, 3% Zn) collimators were placed around the NaI and PMTs of the 7.6 cm detectors in order to study the intensity and arrival times of the x-rays as a function of height above the ground. The collimators block energetic electrons below 21 MeV and most x-rays below ~200 keV [*Knoll*, 2000]. The collimators had an opening angle of about ±15° and were pointed in the direction of the lightning channel at 0°, 15°, 30° and 45° from vertical. In the second configuration, the collimators were replaced with tin-bronze attenuators to study the energy spectra and electron and photon components of the energetic radiation. Three of the 7.6 cm detectors and the 12.7 cm detector were left un-attenuated. One detector was covered with a 0.3 cm bronze cap and one detector was covered with a 1.7 cm bronze cap, allowing only x-rays above ~125 keV and ~250 keV to enter, respectively. In addition, all the 7.6 cm PMTs had 1.7 cm bronze collars, covering the PMTs but not the NaI, to prevent lower energy x-rays from scattering up into the NaI, bypassing the attenuators.

2. Observations

[5] The observations reported by *Dwyer et al.* [2003] used signals from the PMT preamplifier bases, derived from the 10th dynode, with an RC-time of 45 μs. The observations made in 2003 and reported here use the signals from the PMT anodes, connected through buffer amplifiers to the

0094-8276/04/2003GL018770$05.00

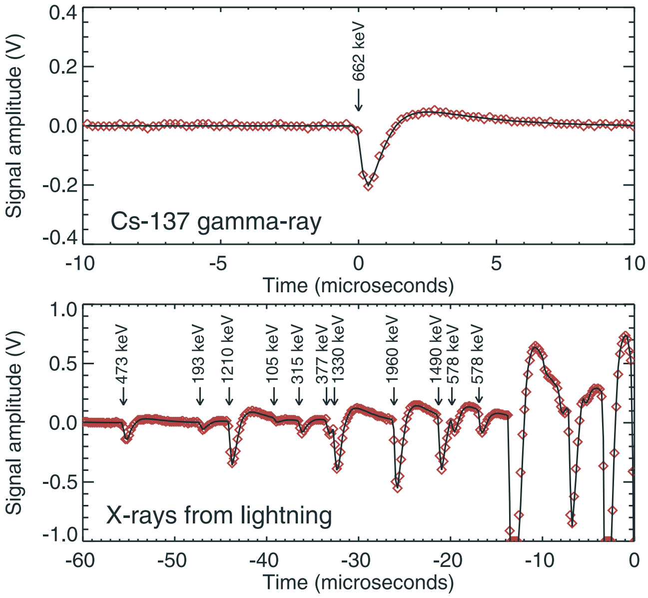

Figure 1. *Top panel*: waveform from one of the NaI(Tl)/PMT detectors for a single 662 keV gamma-ray from a Cs-137 radioactive source placed temporarily on top of the instrument. The red diamonds show the data as recorded by the acquisition system, and the solid line shows the detector response as calculated from the NaI decay-time and the RC-times in the front end electronics. *Bottom panel*: waveform for a time period just prior to a return stroke (at t = 0) of triggered lightning. The detector response (solid line) is plotted over the measured data (red diamonds). The arrows indicate the times and deposited energies of the energetic radiation. The x-ray signals become very large between -14 and 0 μs, as the dart leader approaches the ground, causing saturation.

fiber optic transmitters inside the boxes, giving a greatly improved time resolution of <1 μs. The top panel of Figure 1 shows the response of the instrument to one 662 keV gamma-ray from a Cs-137 radioactive source placed temporarily on top of the box. The solid black curve shows the fit of the response function as derived from the electronics and the 0.23 μs NaI decay-time. The bottom panel of Figure 1 shows x-rays from a (second) stroke of rocket-triggered lightning measured by the 12.7 cm NaI detector, 40 m from the lightning channel, during the dart leader phase. In the figure, the return stroke occurred at time t = 0. The solid black curve is the fit of the response functions with the x-ray's deposited energies and times indicated by the arrows. Note that the x-rays arrive at the beginning of the pulses and the pulse amplitudes are proportional to the energy of the x-rays deposited in the scintillator. Between -14 and 0 μs, very large energetic radiation signals were present, causing saturation in the electronics, with a minimum deposited energy of 30 MeV. The background rate during the 60 μs time window shown in Figure 1 was measured to be 123 counts/s for energies above 100 keV, making the odds less than 1 in 135 that even one pulse was due to background. As will be discussed below, although the waveforms shown in the bottom panel are consistent high-energy x-rays at the times of the arrows, they may also be composed of very brief (≪0.5 μs) bursts of lower energy x-rays.

[6] Figure 2 shows the data from the four collimated detectors placed 20 m from the lightning and pointed in a single vertical plane at increasing heights along the lightning channel, thus measuring emission from the lightning channel at the heights of ≫75 m, 75 m, 35 m and 20 m. In the figure, a signal with a peak of -0.1 V corresponds to 350 keV of deposited energy. The vertical dotted line at t = 0 indicates the instant when the return stroke current exceeds the threshold of about 4 kA. With the collimators, a total of four triggered lightning flashes were observed consisting of a total of 13 strokes. X-rays were measured in association with nine of these 13 strokes. In Figure 2, and in all the events in which x-rays were measured, the two detectors pointed at the lowest part of the channel detected a larger x-ray flux than the two detectors pointed at the highest part of the channel, showing that most of the radiation does not come from the clouds above. This is most easily seen in Figure 2 for the positive part of the bipolar pulses after time t = 1 μs, which unlike the negative peaks are not saturating. Of the nine strokes in which x-rays were observed, three had emission only at the time of the onset of the return stroke. In five of the six remaining events, all of which had significant emission before the return strokes, the first x-rays were clearly seen by the two detectors pointed at the highest part of the channel, consistent with the downward propagating dart leader front being the source of the x-rays. The one exception to the above was a very intense event with a complicated time-intensity profile that was not easy to interpret.

[7] In the data, individual pulses, just like those in the bottom panel of Figure 1, are frequently seen prior to the return stroke. The signal amplitudes indicate that up to several MeV were deposited in the detectors per pulse. Comparing simultaneous data from several nearby detectors and using the attenuator data, it is found that these pulses are not caused by individual energetic gamma-rays but are instead produced by extremely fast bursts of many x-rays in the 30–250 keV range. This is illustrated in Figure 3 which

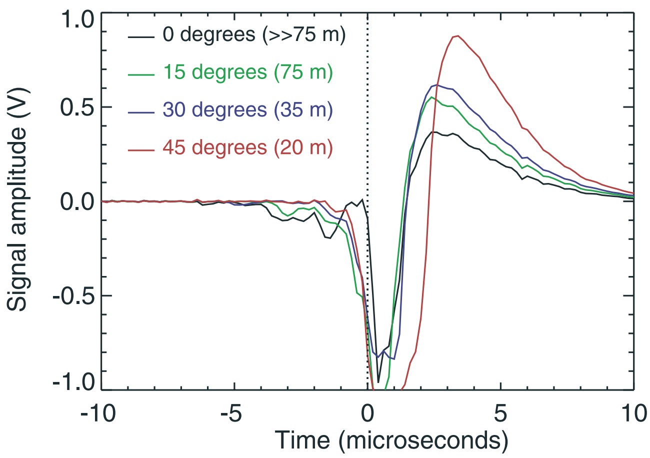

Figure 2. X-ray data from triggered lightning using collimated detectors viewing the lightning channel. The angles that the detectors point are measured with respect to the vertical direction. The vertical dotted line shows the time of the lightning return stroke. The data are consistent with the dart leader and possibly the return stroke being the source of the x-rays.

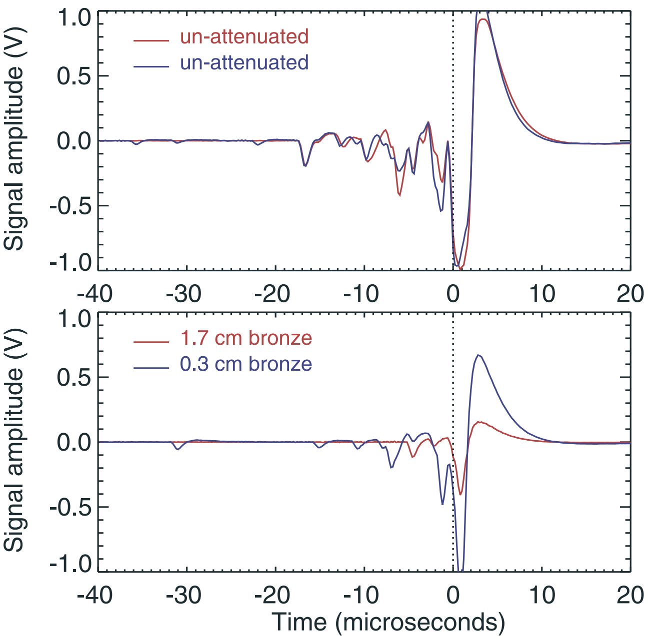

Figure 3. X-ray data from triggered lightning using tin-bronze attenuators over two detectors. A signal with a peak of -0.1 V corresponds to 350 keV of deposited energy. The instruments were all placed side by side and were located about 15 m from the lightning channel. While most of the emission is seen in the un-attenuated detectors, a substantial amount is also seen through the 0.3 cm thick attenuator and some emission is seen through the 1.7 cm attenuator.

shows simultaneous data from the attenuated and un-attenuated detectors, which were placed side by side. Because signals are measured by the two attenuated detectors, the emission cannot be composed of just low-energy x-rays (<100 keV). The possibility that the data are produced by a few high-energy x-rays can also be excluded by comparing the number of pulses and the deposited energies in the un-attenuated and attenuated detectors. If the pulses in the un-attenuated detectors were produced by individual photons then, fitting the response functions to the data between -40 and -0.5 μs, away from the saturation near $t = 0$, an average of 12 x-rays would be measured per detector in the 200–3,000 keV range with an average energy of 1.0 MeV. Using detailed Monte Carlo simulations of the instruments to calculate the effects of photoelectric absorption and Compton scattering with and without the attenuators shows that the detector with the 1.7 cm bronze attenuator would measure 8.9 ± 1.8 photons in the range 100–3,000 keV with a total deposited energy of 7.4 MeV. Instead, only 2 pulses were detected with a total deposited energy of 360 keV. As a result, the possibility that the measured signals were produced by individual high-energy x-rays is excluded at a confidence level of better than the 98% for the data shown in Figure 3. In addition, using the attenuators, three flashes were observed consisting of a total of 11 strokes. Six other events similar to that shown in Figure 3 were measured and the same conclusions were reached for those events as well, making this scenario extremely unlikely. Alternatively, analysis of the data shown in Figure 3, along with that of the other events, indicates that the pulses are instead composed of a few (∼10) medium-energy x-rays and are consistent with emission whose spectrum extends up ∼250 keV.

3. Discussion

[8] All the measurements made to date in the summers of 2002 and 2003 are consistent with energetic radiation being produced in association with the triggered lightning. As can be seen in Figure 1, the measured pulse trains are completely consistent with x-rays producing signals in the NaI(Tl)/PMT detectors, with the pulse shapes determined by the 0.23 μs decay-time of the NaI and the known RC-times in the front-end electronics. The pulse shapes show that the signals originate inside the heavily shielded aluminum boxes, where the detectors are housed. The boxes are many times thicker than the skin depth for frequencies above a MHz, corresponding to the ∼0.5 μs pulse widths. Furthermore, there is no known mechanism that would allow RF noise to produce such signals in the scintillators and PMTs, especially during the dart leader phase prior to the return stroke. Light leaks are also not an explanation, since the individual detectors are themselves light tight and were tested with a bright strobe light before being placed in the heavy Al light-tight boxes. No such signals have ever been observed on the two control detectors. Many independent NaI(Tl)/PMT detectors in separate Al boxes have simultaneously observed the emission, and different combinations of PMTs and electronics have been used, with no change in the conclusions. The effect of the bronze collimators and attenuators on the radiation and the Poisson fluctuations observed when comparing different detectors all point unambiguously to x-ray emission from lightning.

[9] The background due to atmospheric cosmic-rays and radioactivity was measured immediately after the lightning flashes and was found to not exceed 50 counts/s for the 7.6 cm detectors for energies above 100 keV. As a result, the odds that even one of the pulses seen in the lightning data in Figures 2 and 3 was due to background are negligible.

[10] Because the experimental study of triggered lightning using x-ray detectors is presently in its infancy, we are still working to quantify general properties of the emission. The following facts have emerged so far:

[11] 1) The attenuator data show that most, if not all, of the energetic radiation is in the form of x-rays, with no evidence for energetic electrons. Because electrons would lose a minimum of 3.7 MeV when passing through the 0.3 cm attenuator, if there were an electron component, then un-attenuated signals would be much larger than observed. However, because the detectors are shielded by 0.3 cm thick aluminum windows, only electrons with initial energies above 1.3 MeV could make it to the NaI scintillator to be detected. Given that the x-ray emission extends up to ∼250 keV, it is entirely possible that energetic electrons are also present, but have not yet been observed.

[12] 2) The emission in every case begins arriving either during the dart leader phase or the onset of the return strokes of the triggered lightning. Typically, the emission starts ∼20 μs before the return strokes, but has been observed up to 160 μs before the return strokes. The emission intensifies as the dart leaders approach the ground with most of the emission coming from the last ∼50 m of the

channel. In every event measured to date, the largest signals occur immediately before and/or at the beginning of the return strokes. This is possibly due to the movement of the dart leader tip toward the detector and the enhancement of the electric field in the gap between the leader tip and the ground, but also may indicate that the return strokes are intense sources of x-rays as well. In all cases, the emission appears to terminate at most a few microseconds after the start of the return stroke. One observed scenario that is different from the above occurred on 15 August 2003. During this event an intense burst of MeV gamma-rays, lasting 300 μs, with energies extending to over 10 MeV was observed during the initial stage of triggered lightning. This gamma-ray emission appears to be of a different nature than the majority of the x-ray emission observed to date and is the topic of a companion paper [*J. R. Dwyer et al.*, 2004].

[13] 3) The energy spectra of x-rays extend up to ~250 keV, although occasional MeV gamma-rays cannot be completely ruled out.

[14] 4) The x-ray emission is extremely "bursty": rather than being emitted continuously, the x-ray emission is composed of many pulses usually lasting less than 1 μs each. Each pulse is made up of multiple x-rays, with the energy spectrum described above.

[15] 5) Combining 2002 and 2003 data, we observe that x-ray emission occurs in association with 81% of the dart leader/return strokes sequences. Events with the larger return stroke currents are much more likely to produce intense bursts of x-rays.

[16] 6) The fluence (time integrated flux) of the events frequently surpasses 2×10^4 MeV/m^2 per dart leader/return stroke sequence when measured from a distance of about 20 m. Given that the source appears to be the front of the downward propagating dart leader, which is on the order of 10 m across [*Rakov*, 1998] and the duration of the events is typically on the order of 10 μs, peak fluxes of 30–250 keV x-rays likely exceed 10^{12} photons/(m^2 s) at the source.

[17] 7) The x-ray emission appears to be unrelated to the presence of vaporized wire atoms due to the triggering wire explosion, since x-rays are observed in the later strokes of the flashes as frequently as the early strokes.

[18] If the x-ray emission is locally produced by the dart leader, and the emission continues until the time that the dart leader reaches the ground, it will be very challenging for the standard relativistic runaway electron avalanche (RREA) model to explain this emission [*Gurevich et al.*, 1992; *Gurevich and Zybin*, 2001; *Dwyer*, 2003]. The RREA model requires high electric fields that extend over considerable distances (10s to 100s of meters, depending upon the electric field strength). We note that all strokes reported in this paper are negative in the sense that negative charge is lowered to the ground. Previous measurements of the electric fields associated with dart leaders show that the field falls off rapidly with distance, from several hundred kV/m in the immediate vicinity of the channel to about 100 kV/m at 15 m [*Miki et al.*, 2002; see also *Jordan et al.*, 1997], making it difficult for an avalanche of runaway electrons to grow to the required size.

[19] An alternative to the RREA model is the cold runaway electron model [*Gurevich*, 1961; *Sizykh*, 1993; *Chang and Price*, 1995]. For fields about an order-of-magnitude larger than the conventional breakdown field, part of the thermal electron population can run away. For this model, very high electric fields are required in a thin layer at the leading edge of the leader. However, unless the field enhancements occur very quickly, the intense ionization and charge transport will neutralize the field, preventing cold runaway breakdown from occurring. If such high fields can be shown to exist at leader fronts, it would greatly change our view of how large scale discharges occur, affecting, for instance, how lightning discharges are initiated and propagate.

[20] **Acknowledgments.** We would like to thank those at Florida Tech and the University of Florida who assisted in the construction of the instruments and the collection of the energetic radiation data. We also thank Philip E. Krider for his contribution to the interpretation of the return stroke emission. This work was supported in part by the NSF CAREER grant ATM 0133773, NSF grant ATM 0003994 and DOT (FAA) grant 99-G-043.

References

Chang, R., and C. Price (1995), Can gamma radiation be produced in the electrical environment above thunderstorms?, *Geophys. Res. Lett.*, *22*, 1117–1120.

Dwyer, J. R., et al. (2004), A ground level gamma-ray burst observed in association with rocket-triggered lightning, *Geophys. Res. Lett.*, *31*, L05119, doi:10.1029/2003GL018771.

Dwyer, J. R. (2003), A fundamental limit on electric fields in air, *Geophys. Res. Lett.*, *30*(20), 2055, doi:10.1029/2003GL017781.

Dwyer, J. R., et al. (2003), Energetic radiation produced during rocket-triggered lightning, *Science*, *299*, 694–697.

Gurevich, A. V. (1961), On the theory of runaway electrons, *Sov. Phys. JETP, Engl. Transl.*, *12*, 904–912.

Gurevich, A. V., and K. P. Zybin (2001), Runaway breakdown and electric discharges in thunderstorms, *Phys. Uspekhi*, *44*, 1119–1140.

Gurevich, A. V., G. M. Milikh, and R. Roussel-Dupré (1992), Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Phys. Lett. A*, *165*, 463–468.

Jordan, D., V. Rakov, W. Beasley, and M. Uman (1997), Luminosity characteristics of dart leaders and return strokes in natural lightning, *J. Geophys. Res.*, *102*, 2025–2032.

Knoll, G. F. (2000), *Radiation Detection and Measurements*, John Wiley, Hoboken, N. J.

Miki, M., et al. (2002), Electric fields near triggered lightning channels measured with Pockels sensors, *J. Geophys. Res.*, *107*(D16), 4277, doi:10.1029/2001JD001087.

Moore, C. B., K. B. Eack, G. D. Aulich, and W. Rison (2001), Energetic radiation associated with lightning stepped-leaders, *Geophys. Res. Lett.*, *28*, 2141–2144.

Rakov, V. A. (1998), Some inferences on the propagation mechanisms of dart leaders and return strokes, *J. Geophys. Res.*, *103*, 1879–1887.

Rakov, V. A., et al. (1998), New insights into lightning processes gained from triggered-lightning experiments in Florida and Alabama, *J. Geophys. Res.*, *103*, 14,117–14,130.

Sizykh, S. V. (1993), Runaway electron production rate in gaseous discharges, *High Temp.*, *31*, 1–6.

M. Al-Dayeh, L. Caraway, A. Chrest, J. R. Dwyer, H. K. Rassoul, and B. Wright, Department of Physics and Space Sciences, Florida Institute of Technology, Melbourne, FL 32901, USA. (dwyer@pss.fit.edu)

J. Jerauld, D. M. Jordan, V. A. Rakov, K. J. Rambo, C. Smyth, and M. A. Uman, Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL 32611, USA.