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A ground level gamma-ray burst observed in association with rocket-triggered lightning

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[1] We report the observation of an intense gamma-ray burst observed on the ground at sea level, produced in association with the initial-stage of rocket-triggered lightning at the International Center for Lightning Research and Testing at Camp Blanding, FL. The burst was observed simultaneously on three NaI(Tl)/photomultiplier tube detectors that were located 650 m from the triggered lightning channel with gamma-ray energies extending up to more than 10 MeV. The burst consisted of 227 individual gamma-rays that arrived over a 300 μs time period in coincidence with an 11 kA current pulse. The burst of gamma-rays had very different characteristics from the x-ray emission frequently seen in association with the dart leader/return stroke sequences of triggered lightning and may represent a new kind of event, likely originating from cloud processes thousands of meters overhead. *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), A ground level gamma-ray burst observed in association with rocket-triggered lightning, *Geophys. Res. Lett.*, *31*, L05119, doi:10.1029/2003GL018771.

1. Introduction

[2] We have reported extensive observations of x-ray emission produced in association with rocket-triggered lightning at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL (*Dwyer et al.* [2003, 2004]; for triggered lightning references, see *Rakov et al.* [1998]). To date, we have observed 63 dart leader/return stroke sequences and have measured energetic radiation in 51 of these events. In almost every case, the emission appeared to be associated with the dart leader, the most intense emission arriving when the dart leader was approaching the ground, with some contribution from the beginning of the return stroke also likely. As reported in *Dwyer et al.* [2004], the energetic radiation from the dart leaders is composed of x-rays with spectra extending up to ~250 keV. For most of the events observed, the emission occurred within about 20 μs before and possible at the beginning of the return strokes. However, occasionally energetic radiation was observed at much earlier times, up to 160 μs before the return strokes. Because for such times, the dart leader tip must have been about 1000 m above the ground, it cannot be ruled out that for these events a gamma-ray (>1 MeV) component also originated from the cloud.

[3] In this paper, we report an unusual event that occurred during the last rocket-triggered flash of the 2003 season. For this flash, an intense burst of MeV gamma-rays was observed from a distance of 650 m from the lightning channel, not in association with the dart leader or return stroke, but in association with a large current pulse (11 kA) occurring during the initial-stage (during the initial continuous current), about 20 ms after the vaporization of the triggering wire. In triggered lightning, the initial-stage is characterized by a steady current, preceding the return strokes, with superimposed pulses up to several kA in amplitude [*Wang et al.*, 1999]. Considering the large distance of the detectors and the high energy of the gamma-rays, it is plausible that the burst originated in the cloud processes, perhaps many thousands of meters above the ground. This result may greatly facilitate the study of runaway breakdown of air inside thunderclouds [*Gurevich et al.*, 1992], since it implies that observations of this phenomenon from the ground at sea level may be practical.

2. Observations

[4] The instruments used for the observations presented here have already been described in *Dwyer et al.* [2003, 2004] and so will only be briefly summarized here. For the events discussed in this paper, two instruments were operating. The instruments were placed approximately 10 m apart and were located 650 m from the mobile rocket launcher used to trigger lightning. The first instrument consisted of one 12.7 cm diameter by 7.6 cm thick cylinder of NaI(Tl) scintillator mounted to a photomultiplier tube (PMT) detector and one identical control detector with no scintillator. The second instrument consisted of two 7.6 cm by 7.6 cm NaI(Tl)/PMT detectors and one identical control detector (with no NaI). The detectors were battery powered and were sealed inside thick aluminum boxes to keep out RF noise, light, and water. Fiber optics were used to transmit the anode signals to a data acquisition system located in a shielded trailer. The signals from the first instrument were digitized with a 0.2 μs sampling interval for 220 ms with 20 ms of pre-trigger sampling. The wave-

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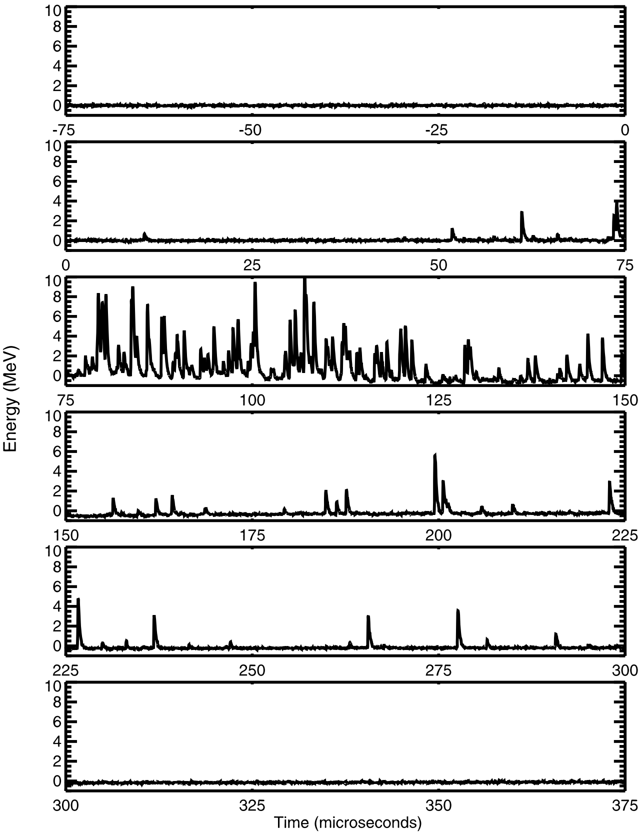

Figure 1. Waveform from the fast detector for the gamma-ray burst associated with a rocket-triggered lightning flash. Each pulse is produced by the detection of a gamma-ray. The raw data have been multiplied by −36 MeV/V so that the energy of the individual gamma-rays can be read. The six panels show the consecutive 75 μs segments of the 450 μs portion of the record.

forms for the second instrument were digitized with a 10 ns sampling interval for 10 ms with 1 ms of pre-trigger sampling. For the second instrument, one NaI(Tl)/PMT detector (hereafter referred to as the fast detector) had its anode signal fed directly into the fiber optic transmitter with a 75 Ω input resistance. This resulted in a very fast pulse with a width determined solely by the 0.23 μs decay-time of the NaI scintillator. The low input resistance also resulted in a much smaller signal than the other detectors, which used buffer amplifiers between the anodes and the transmitters.

[5] On 15 August 2003, three rockets were launched during thunderstorm conditions and produced triggered lightning. All three launches were unusual because very large initial-stage current pulses (5.5, 2.5 and 11 kA) occurred following the triggering wire vaporization, considerably larger than the typical initial-stage pulses of the order of 100 A. The 5.5 kA and 11 kA current pulses for the first and third launches were large enough to trigger the data acquisition (threshold = 4 kA). For the first launch, no energetic radiation was observed. However, for the last launch, a huge burst of gamma-rays was observed in all three NaI detectors in coincidence with the largest pulse superimposed on the initial-stage current. No signals were observed in either of the two control detectors. Figure 1 shows the entire waveform from the fast detector during the gamma-ray burst. The data plotted are the data from PMT anode multiplied by the calibration factor −36 MeV/V, allowing the gamma-ray energies to be read. Each positive spike in the figure is the detection of one gamma-ray. For the entire burst, a total of 370 MeV was deposited in the 7.6 cm diameter detector. The other two NaI detectors, which had higher gains and longer signal widths, completely saturated during the time period of highest intensity. During the early and late stages of the burst, however, the signals from the three detectors could be compared, and it was found that unlike dart leader emission, which consists of many short bursts of x-rays, this event was made up of individual MeV gamma-rays.

[6] Figure 2 shows a close-up of the signal from one such gamma-ray during the time period shown in Figure 1 (at $t =$ 277.49 μs). 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 exponential decay, returning the signal to the baseline, is due entirely to the time structure of the scintillation light signal from the NaI(Tl) crystal. The presence of the NaI decay-time in the data further reinforces the argument that these are indeed gamma-rays being detected and not some kind of spurious signals.

3. Discussion

[7] The background rate was measured to be 26 counts/s for the fast detector for energies above 0.5 MeV at the time of the gamma-ray burst, implying that the background in the 300 μs event was completely insignificant. The burst of gamma-rays was also not consistent with a cosmic-ray shower, since its duration was far too long and no signals consistent with minimum ionizing electrons or muons were detected. A minimum ionizing particle deposits on average 34 MeV in the 7.6 cm thick NaI detector, while the largest signal detected had a deposited energy of only 11 MeV. It is certainly possible that energetic electrons or muons could occasionally produce such small signals, e.g., when clipping the edge of the NaI. However, the chance that 227 consecutive minimum ionizing particles would do so is extremely

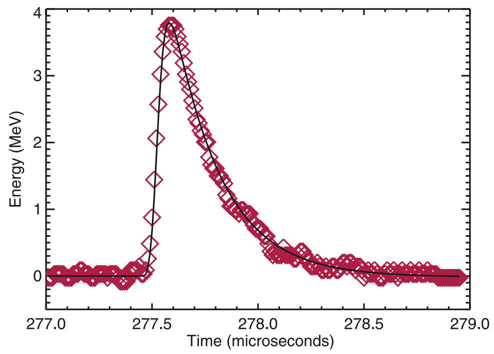

Figure 2. Expanded view of the waveform of one of the gamma-rays seen in Figure 1. The red diamonds show the data as recorded by the acquisition system (multiplied by the constant −36 MeV/V), and the solid line shows the detector response as calculated from the NaI decay-time and the RC-times in the front end electronics. The 0.23 μs decay-time from the NaI scintillator is clearly visible.

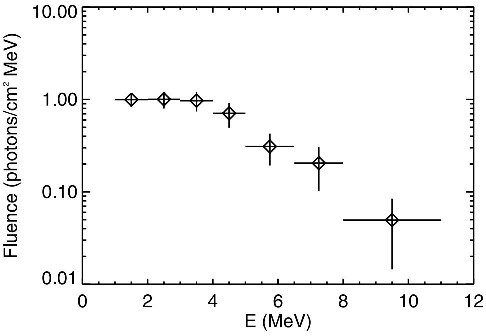

Figure 3. Energy spectrum of the gamma-ray burst. The fluence (time-integrated flux) of the gamma-rays for the entire event is plotted as a function of gamma-ray energy. The data have been corrected for the detector response. The vertical error bars show the statistical errors and the horizontal bars show the width of the energy bins.

remote, making it highly unlikely that the event was a cosmic-ray air shower.

[8] Figure 3 shows the energy spectrum of the entire gamma-ray burst, calculated by fitting the detector response functions to the data in Figure 1 to get the energy of each individual gamma-ray. A Monte Carlo simulation was used to correct the spectrum for the response of the 7.6 cm diameter by 7.6 cm thick NaI scintillator, including the effects of the surrounding material in the instrument. Corrections were also made for the occasional chance overlap of gamma-rays that could not be resolved due to the finite time resolution of the detector.

[9] As seen in Figure 3, the spectrum below 4 MeV is flatter than a locally produced bremsstrahlung spectrum, which must fall off at least as quickly as E^{-1}, regardless of the source spectrum [*Koch and Motz*, 1959]. However, because the Compton scattering cross-section decreases with increasing energy, bremsstrahlung emission can produce such a spectrum after the radiation has propagated over a long distance in the atmosphere. Unfortunately, the energy spectrum alone is not enough to infer the exact distance to the source, since the source spectrum is not known and it is not known whether the emission is beamed towards the detector or not.

[10] The beginning of the burst occurs at about the same time that the upward propagating positive leader, initiated from the top of the rocket and extended triggering wire, would have reached the overhead cloud charge at some kilometers above the ground. This is illustrated in Figure 4, which shows the entire current waveform for the flash. The start of the initial-stage (leftmost arrow) corresponds to the beginning of the upward propagating positive leader from the top of the wire [*Wang et al.*, 1999]. The current drop, 20 ms later, is part of the so-called initial current variation (ICV) and is due to the vaporization of the triggering copper wire. The largest current pulse and the burst of gamma-rays occurred 40 ms after the beginning of the initial-stage and 20 ms after the ICV. The typical speed of upward propagating positive leaders is $1.5-2 \times 10^5$ m/s, which places the upward propagating leader at a height of 6–8 km above the ground when the gamma-ray burst began, the expected range of heights for the cloud charge in Florida. It is possible that when the leader reached this charge, an intense discharge was initiated, producing the gamma-ray burst via the runaway breakdown of air [*Gurevich and Zybin*, 2001]. Although a more local source cannot be excluded, it is not clear what that source would be or where it would be located.

[11] *Wang et al.* [1999] observed five large current waveforms during a triggered lightning initial-stage somewhat similar to the waveforms seen from about 0 to 40 ms in Figure 4. However, their waveforms were characterized by considerably smaller current peaks and charge transfers, 1–2 kA and several coulombs, respectively. Wang et al. attributed their current waveforms to a negatively charged in-cloud leader that intercepted the upward positive leader of the triggered lightning [also see *Rakov*, 2003]. It should be noted that all the triggered lightning events produced on 15 August occurred with relatively clear air directly overhead but also with large negative electric fields at the ground. Although clear air can potentially contain enough charge to support lightning, the positive leaders may have also propagated a substantial horizontal distance to reach the cloud charge.

[12] Figure 5 shows an expanded view of the current data shown in Figure 4, along with the gamma-ray data measured by the other instrument. As can be seen, the gamma-rays began after the current reached a small plateau at about 4.5 kA and continued throughout the pulse, only ceasing after the current dropped to a few kA. For the two launches that produced triggers, many large current pulses occurred during the initial-stage (see Figure 4), but only the largest pulse during the last launch produced gamma-rays. When comparing the current and gamma-ray data, we assumed that both the gamma-rays and the current pulse propagated at the same speed. If the propagation speed of the current pulse is similar to that of an *M*-component wave then we might expect it to be more in the range 10^7-10^8 m/s. A correction for the travel times over 6 km would cause the current pulse to begin earlier, shifting the current waveform in the figure to the left by about 100 μs.

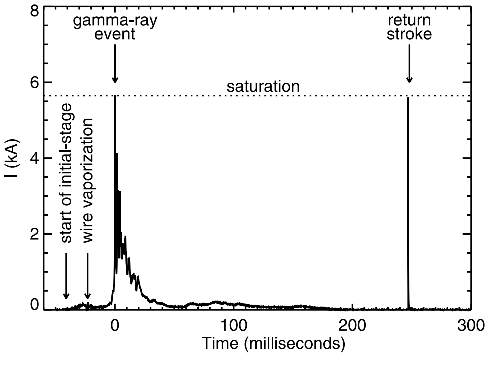

Figure 4. Electric current, measured at the rocket launcher, for the last triggered lightning event on 15 August 2003. The arrows indicate the start of the initial-stage, which corresponds to the beginning of the upward propagating positive leader; the time of the ICV associated with the wire vaporization; the time of the observed gamma-ray burst and the time of the return stroke. During the initial-stage, a total of 57 C was brought to the ground, which is about a factor of two greater than typical values for triggered lightning.

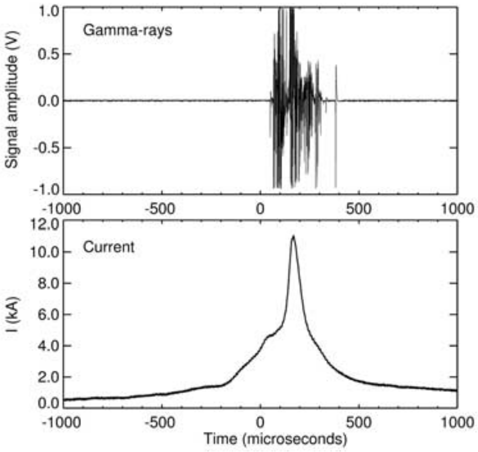

Figure 5. Expanded view of the time period shown in Figure 4. The top panel shows the gamma-ray data as measured by the 12.7 cm detector in the first instrument. The bottom panel shows the electric current data, measured at the lightning channel base.

[13] If the gamma-rays were indeed produced at a height of 6–8 km above the ground, atmospheric attenuation would reduce the gamma-ray intensity on the ground by several million. As a result, the gamma-ray intensity at the source may have been enormous, possibly reaching biologically significant doses. Interestingly, the amount of atmosphere above 6 km is about the same as the amount below that altitude, raising the possibility that similar gamma-ray events might also be observable from space, since the attenuation of the gamma-rays in the upward and downward directions would be the same. Indeed, intense gamma-ray flashes have been reported using BATSE data from the Compton Gamma Ray Observatory (CGRO) [*Fishman et al.*, 1994]. These flashes were inferred to be associated with high-altitude discharges such as red-sprites [*Nemiroff et al.*, 1997], largely because of their correlation with thunderstorms and lightning [*Inan et al.*, 1996].

[14] Because there are some similarities between initial-stage pulses produced during rocket-triggered lightning and the *M* processes observed during continuing currents that follow return strokes in natural lightning [*Wang et al.*, 1999], it is plausible that the burst of gamma-rays reported here may also occur during natural lightning *M* processes as well. Furthermore, upward lightning discharges from tall grounded objects necessarily contain an initial-stage similar to that of rocket-triggered lightning, and so gamma-ray bursts may possibly occur during lightning discharges from tall structures.

[15] Many researchers have reported long duration (a few seconds) x-ray and gamma-ray emission from thunderclouds, but the majority of these observations were made in or near the cloud either using balloons or on top of high mountains [*Brunetti et al.*, 2000; *Eack et al.*, 1996; *Suszcynsky et al.*, 1996]. *Moore et al.* [2001] also reported gamma-ray emission, measured on a high mountain, associated with stepped leaders from nearby lightning strikes. At this point, it is not clear how the gamma-ray burst reported here relates to these earlier observations. However, based upon the duration, energy spectrum and inferred distance from the source, the gamma-ray burst may indeed be a new phenomenon. Furthermore, the observation of an intense burst of gamma-rays on the ground at sea level suggests that the production of energetic radiation by thunderstorms can be studied in locations such as Florida, which has a large number of thunderstorms per year. This can potentially lead to substantial advancement in the study of the runaway breakdown of air, a mechanism that may play an important role in thundercloud and lightning processes [*Gurevich and Zybin*, 2001; *Dwyer*, 2003].

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References

Brunetti, M., S. Cecchini, M. Galli, G. Giovannini, and A. Pagliarin (2000), Gamma-ray bursts of atmospheric origin in the MeV energy range, *Geophys. Res. Lett.*, *27*, 1599–1602.

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.

Dwyer, J. R., et al. (2004), Measurements of x-ray emission from rocket-triggered lightning, *31*, L05118, doi:10.1029/2003GL018770.

Eack, K. B., W. H. Beasley, W. D. Rust, T. C. Marshall, and M. Stolzenburg (1996), Initial results from simultaneous observation of x rays and electric fields in a thunderstorm, *J. Geophys. Res.*, *101*, 29,637–29,640.

Fishman, G. J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, *264*, 1313.

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.

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

Inan, S. U., S. C. Reising, G. J. Fishman, and J. M. Horack (1996), On the association of terrestrial gamma-ray bursts with lightning and implications for sprites, *Geophys. Res. Lett.*, *23*, 1017–1020.

Koch, H. K., and J. W. Motz (1959), Bremsstrahlung cross-section formulas and related data, *Rev. Mod. Phys.*, *31*, 920–955.

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.

Nemiroff, R. J., J. T. Bonnell, and J. P. Norris (1997), Temporal and spectral characteristics of terrestrial gamma flashes, *J. Geophys. Res.*, *102*, 9659–9665.

Rakov, V. A. (2003), A review of positive and bipolar lightning discharges, *Bull. Am. Meterol. Soc.*, *84*, 767–775.

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.

Suszcynsky, D. M., R. Roussel-Dupré, and G. Shaw (1996), Ground-based search for x-rays generated by thunderstorms and lightning, *J. Geophys. Res.*, *101*, 23,505–23,516.

Wang, D., V. A. Rakov, M. A. Uman, M. I. Fernandez, K. J. Rambo, G. H. Schnetzer, and R. J. Fisher (1999), Characterization of the initial stage of negative rocket-triggered lightning, *J. Geophys. Res.*, *104*, 4213–4222.

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