# Hardening and Termination of Long-Duration $\gamma$ Rays Detected Prior to Lightning

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We report the first observation of 3–30 MeV prolonged gamma-ray emission that was abruptly terminated by lightning. The gamma-ray detection was made during winter thunderstorms on December 30, 2010, by the Gamma-Ray Observation of Winter Thunderclouds experiment carried out in a coastal area along the Sea of Japan. The gamma-ray flux lasted for less than 3 min, continuously hardening closer to the lightning occurrence. The hardening at energies of 3–10 MeV energies was most prominent. The gamma-ray flux abruptly ceased less than 800 ms before the lightning flash that occurred over 5 km away from the experimental site. In addition, we observed a clear difference in the duration of the 3–10 MeV gamma rays and those >10 MeV, suggesting that the area of >10 MeV gamma-ray emission is considerably smaller than that of the lower-energy gamma rays. This work may give a manifestation that a local region emitting prolonged gamma rays connects with a distant region to initiate lightning.

*Introduction.*—Prolonged gamma rays emitted from thunderclouds were observed during the 1980s and 1990s by detectors onboard an airplane and a balloon [1,2]. High-mountain experiments [3–9] and sea-level measurements [10–13] also observed thundercloud-related gamma rays that lasted for a few seconds to ~10 min, and even 40 min on rare occasions. However, we do not fully understand the causes of the differences in duration and the temporal variations of the individual thundercloud-related gamma-ray events. Better understanding of these parameters would provide valuable information on the charging mechanism of thunderclouds as well as the electric-field acceleration that occurs in natural accelerators.

Unlike prolonged gamma rays, short-duration ones are related to natural lightning [14–16] and artificial lightning [17]. These lightning-related gamma rays last for a millisecond or less. Although there are distinct differences between thundercloud- and lightning-related gamma rays, especially in duration, they are considered to have a common viable mechanism based on the relativistic runaway electron avalanche models [18–20]. These models explain the generation of a large amount of nonthermal photons by ambient electrons as follows. Energetic electrons, possibly seeded by, e.g., cosmic rays, will run away when the gained energies from the field are sufficiently high to exceed the ionization loss in air. Then those electrons will produce a detectable flux of bremsstrahlung photons. Presently, a large number of electrons produced by electron avalanches may cause the lightning initiation through an enhancement of the electric fields and the conductivity of the atmosphere [21].

Contrary to the general characteristics of prolonged gamma rays, a few observations have provided a possible association with lightning occurrence. Airplane- [1] and balloon-based measurements [2] showed that x-ray flux at energies of 1–100 keV suddenly ceased at lightning occurrence. In addition, a high-mountain experiment [4] demonstrated that the particle count increased at energies of >30 MeV then quickly returned to the background level when lightning occurred. These events suggest that electrons are continuously accelerated to relativistic energies until just before the lightning strike. However, it is still unclear whether runaway electrons producing long-duration gamma rays are the same as those related to lightning initiation. Here we present the results of a measurement of one prolonged gamma-ray event with the finest time resolution of 0.1 ms and compare it with previous observations of long-duration gamma-ray events.

*Experiment.*—The Gamma-Ray Observation of Winter Thunderclouds (GROWTH) experiment has been operating successfully at the Kashiwazaki-Kariwa nuclear power plant since December 22, 2006. The experimental site is located in the coastal area of the Sea of Japan where winter lightning is common. The data acquisition system, daq1, was installed on the roof of a building on December 2,

2010. It is arranged in a northeast to southwest direction 780 m apart from the original system, daq0. Detailed information on daq0 can be found in Tsuchiya *et al.* [11,13]. Thus, we provide an outline of the daq1.

Daq1 has a cylindrical $\phi 7.62 \times 7.62$ cm$^2$ NaI scintillator equipped with a photomultiplier (HAMAMATSU R1306). Above the NaI counter, a thin plastic scintillator with a thickness of 0.5 cm and an area $30 \times 30$ cm$^2$ is placed. The plastic scintillator is wrapped in thin aluminum foil with a thickness of 15 $\mu$m and then covered with a black 100-$\mu$m-thick sheet. The plastic scintillator is connected to a photomultiplier (HAMAMATSU R1306) by a light guide. It is utilized to reject charged-particle background (mostly muons) by the anticoincidence method.

The signals of the NaI and plastic scintillators are fed to a 12-bit analog-to-digital converter (ADC) chip (AD7862-10) incorporated in a self-triggering electronics system and recorded as ADC values corresponding to the energy deposits in the individual scintillators. The arrival time of each event is determined by the global positioning system synchronized with a 10 kHz frequency. Daq1 observes an energy range of 0.04–30 MeV with a time resolution of 0.1 ms. Because daq0 also employs a global positioning system to determine the recording time, the time of the two GROWTH systems coincides. Moreover, daq1 has an optical sensor with a Si photodiode (HAMAMATSU S1226-8BK) for wavelengths of 320–1000 nm, having a peak of 720 nm. The output signal of the photodiode is fed to a peak-hold ADC, and the peak value per second is recorded as the ADC value.

In addition to the two systems of daq0 and daq1, nine monitoring posts (MPs) are operated by the Tokyo electric power company to monitor environmental radiation doses (circles in Fig. 1 of [13]). Each MP consists of a cylindrical $\phi 5.1 \times 5.1$ cm$^2$ NaI scintillation counter and an ion chamber. The former covers the energy range 50 keV–3 MeV, and the latter measures for those >50 keV. The time resolution of the two detectors is 30 s. MPs are widely distributed in the premises at intervals of 300–400 m.

*Results.*—Figure 1 shows 30-s count rates of the NaI scintillators obtained from daq0, daq1, and MPs 7–9 (Fig. 2 here, Fig. 1 of [13]) obtained over the period of 13:20–13:50 universal time (UT) on December 30, 2010. For comparison, the count rates of daq1 (upper crosses in the top panel) show results from the NaI scintillator without anticoincidence. The background level of daq1 was ∼1.4 times higher than that of daq0 (lower crosses in the top panel) because the effective volume of daq1 was 1.5 times larger than that of daq0. The counts increased from 13:32 UT until 13:36 UT, over a time scale which is typical for prolonged thundercloud gamma-ray emission [10–13]. However, at 13:35:55 UT, the counts suddenly dropped to the background level. Such a sudden termination of the gamma-ray emission was never observed during previous long-duration GROWTH events [11,13].
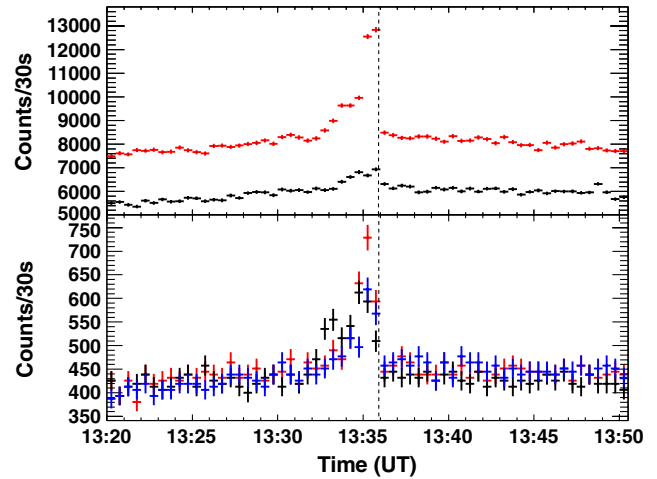


FIG. 1 (color online). Count histories per 30 s of daq0, daq1, and MPs 7–9, obtained during 13:20–13:50 UT on December 30, 2010. (Top) The count rates for >40 keV from the NaI scintillators of daq0 (black) and daq1 (red) without anticoincidence. (Bottom) The 0.05–3 MeV count rates from the NaI scintillators of MPs 9 (black), 8 (red), and 7 (blue). The vertical error bars indicate the 1$\sigma$ standard deviation. The vertical dashed line shows the occurrence time of the lightning flash (13:35:55 UT).

From the optical sensor and electric field mill data it can be seen that lightning occurred at 13:35:55 UT, which coincided with the gamma-ray termination. The lightning event is assumed to have occurred at a distance of >5 km from the experimental site. No lightning within 5 km of the site was recorded over the period between 13:05 and 14:05 UT by the Japan Lightning Detection Network system (operated by Franklin Japan Co. Ltd.), which has a lightning detection efficiency of >90%. One intracloud discharge occurred 1.7 km southeast of the site, but it was at 13:39:25 UT, much later than the gamma-ray termination. Such a low occurrence of lightning in winter is relatively common in this region [22].

The most intriguing aspect of this gamma-ray event is how its sudden termination is related (or unrelated) to the distant lightning. This can be investigated by estimating the horizontal spread of the gamma-ray emitting region. Using the 30 s count data at energies between 50 keV and 3 MeV, we first calculated the count increases (in percent) and the statistical significance of data from all the detectors measured between 13:34 and 13:36 UT. Then using the count increases and positions of each detector, an ellipse-image fitting was performed according to a method that was originally developed for higher-energy gamma-ray observations [23]. The fitting evaluates the major and minor axes of an ellipse. In this Letter, the major and minor axes represent the root mean square spread of the radiation in directions along and perpendicular to the axis, respectively, connecting the center of the ellipse and the detector position with the maximum count increase at each time
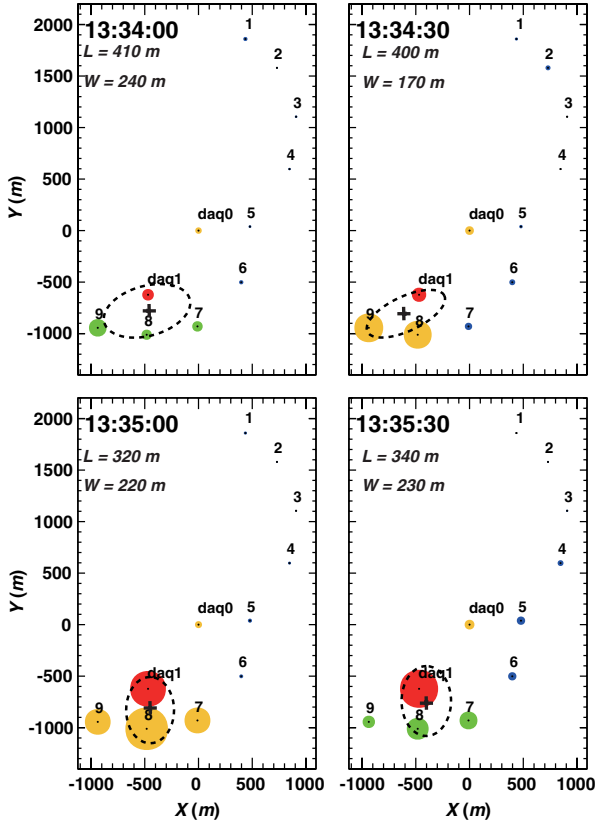
FIG. 2 (color online).   Distributions of count enhancements for all detectors in four time intervals. The values 1–9 represent the MP location. $L$ and $W$ in each panel are the lengths of the major and minor axes of the ellipses (dashed lines), respectively. The crosses show the center of the ellipses. Colors of circles indicate statistical significance obtained by individual detectors. Blue, green, orange, and red represent those $<2\sigma$, $2$–$5\sigma$, $5$–$10\sigma$, and $>10\sigma$, respectively.

interval. Since small amplitude signals measured by distant detectors may distort the estimated image, we did not use individual count increases with statistical significance $<2\sigma$. In practice, MPs 1–6 showed no count increases with statistical significance $>2\sigma$ during 13:34–13:36 UT. Table I lists the numerical values used in the evaluation.

Figure 2 shows the count-intensity distributions along with the radiation spread determined by the above method.

The diameters of the circles correspond to the individual count increase (in percent). Thus, larger diameters correspond to higher count increases. Though probably affected by using a small number of detectors, the horizontal extent was at most ~800 m, which is consistent with other observations [10,12,13]. In addition, the illuminated region appeared to move slowly from southwest to northeast and approach daq1 and MP8. Such movement of a gamma-ray emitting region was previously reported without performing an ellipse fitting. [10,12,13]. As seen from Fig. 2 and Table I, daq1 was the closest detector to the gamma-ray source in the thunderclouds between 13:35:30 and the time that the lightning occurred.

Figure 3 shows data from the NaI scintillator with anti-coincdence measured by daq1, and we can conclude that the observed count increases were attributable to gamma rays. In addition, it is found that the count histories of daq1 exhibited more significant enhancements in two energy bands than the data from daq0. Particularly, the count increases in the 3–10 MeV band are the most prominent. The net count increases of daq0 and daq1 obtained during 13:33:12–13:35:55 UT for the 3–10 MeV band are $140 \pm 15$ ($9.3\sigma$) and $950 \pm 30$ ($32\sigma$), respectively. Here, background levels per 6 s for the 3–10 MeV energy band were estimated to be $2.88 \pm 0.12$ and $2.53 \pm 0.12$ for daq0 and daq1, respectively, using a constant fitting of the data obtained excluding the above period. Furthermore, count rates for $>10$ MeV from daq1 with anticoincidence (bottom of Fig. 3) provided a remarkable net count increase of $57 \pm 8$ over the period 13:35:19–13:35:55 UT above the background level of $2.18 \pm 0.11$, while that of daq0 exhibited a net count increase of $17 \pm 7$, which was not statistically significant, during the same time interval, with a background level of $6.1 \pm 0.2$. The statistically significant $>10$ MeV gamma rays were first detected from sea-level observations.

The top panel of Fig. 4 shows time variations of the energies of individual photons recorded by daq1. Several horizontal stripes can be observed at the 0.3–3 MeV band, corresponding to the natural environmental gamma-ray lines including 609 keV ($^{214}$Bi), 1.46 MeV ($^{40}$K), and 2.62 MeV($^{208}$Tl). Clearly, the number of photons with energies of $>3$ MeV dramatically increased before the lightning occurrence. We applied a waiting time function

TABLE I.    30-s-count increases in percent and the corresponding statistical significance during 13:34–13:36 UT.

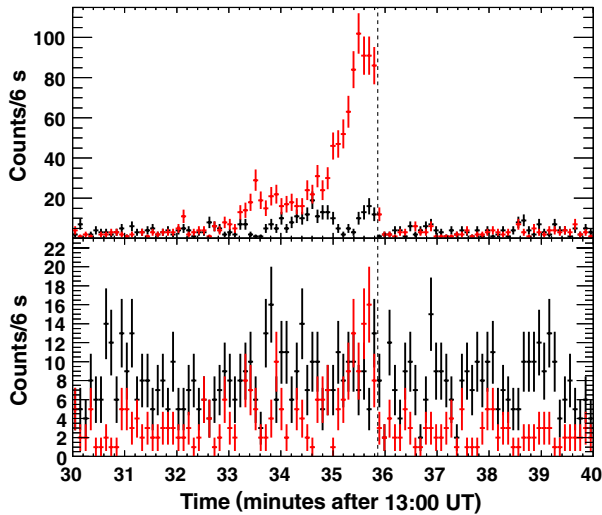| Time[a] | Detector | | | | |
|---|---|---|---|---|---|
| | daq0 | daq1 | MP9 | MP8 | MP7 |
| 13:34:00 | 9.4% ($6.8\sigma$) | 17% ($10\sigma$) | 26% ($3.5\sigma$) | 15% ($2.2\sigma$) | 15% ($2.2\sigma$) |
| 13:34:30 | 13% ($6.8\sigma$) | 21% ($13\sigma$) | 42% ($5.6\sigma$) | 41% ($5.6\sigma$) | 11% ($1.6\sigma$) |
| 13:35:00 | 10% ($5.5\sigma$) | 52% ($30\sigma$) | 37% ($5.1\sigma$) | 62% ($8.1\sigma$) | 38% ($5.2\sigma$) |
| 13:35:30 | 14% ($7.7\sigma$) | 55% ($32\sigma$) | 18% ($2.5\sigma$) | 32% ($4.4\sigma$) | 26% ($3.7\sigma$) |

[a]Start time.

FIG. 3 (color online). Count histories per 6 s for radiations observed at daq0 (black) and daq1(red), obtained during 13:30–13:40 UT. (Top) Count histories of 3–10 MeV of the NaI scintillators of daq0 and daq1 with anticoincidence mode. (Bottom) Same as that of the top panel, but for >10 MeV. Vertical error bars represent $1\sigma$ standard deviation. The vertical dashed line shows the occurrence time of the lightning (13:35:55 UT).

of $r\exp(rt)$ to the data of 0.04–0.3, 0.3–3, 3–10, and >10 MeV during 13:33:12–13:35:55 UT and derived $r = 330 \pm 2$, $230 \pm 2$, $9.0 \pm 0.4$, and $1.4 \pm 0.3$, respectively. Here, $r$ represents the average arrival rate of photons (per s). For comparison, we calculated $r$ for data outside the burst interval as $250 \pm 1$, $170 \pm 1$, $1.42 \pm 0.11$, and $0.40 \pm 0.05$ for the same four energy bands. Dividing by the individual arriving rates of the background levels, the individual rates during the count increases were enhanced by a factor of 1.3, 1.4, 6.4, and 3.5, respectively. Consequently, the count increases for the two higher energy bands were much greater than those for the two lower-energy bands prior to the initiation of lightning, implying that the gamma-ray energy spectrum became harder before lightning.

As shown in the bottom panel of Fig. 4, the >3 MeV gamma-ray hardening abruptly ceased within 0.1 ms or less, 800 ms before the lightning. No >3 MeV gamma rays were detected by daq1 for ~1 s from the time 800 ms before the lightning. Unlike the photons with >3 MeV, those with <3 MeV had no clear gap around the lightning flash. These results suggest that the thundercloud electric fields stopped accelerating the electrons toward the ground at least 800 ms prior to the lightning flash.

*Discussion.*—The authors of [1] and [4], who conducted an airplane observation and a high-mountain experiment, respectively, observed similar events to those under discussion. Unlike these two past observations, the current results, employing one photon counting with a time resolution of 0.1 ms, demonstrate that 3–30 MeV gamma rays clearly terminate 800 ms prior to the lightning
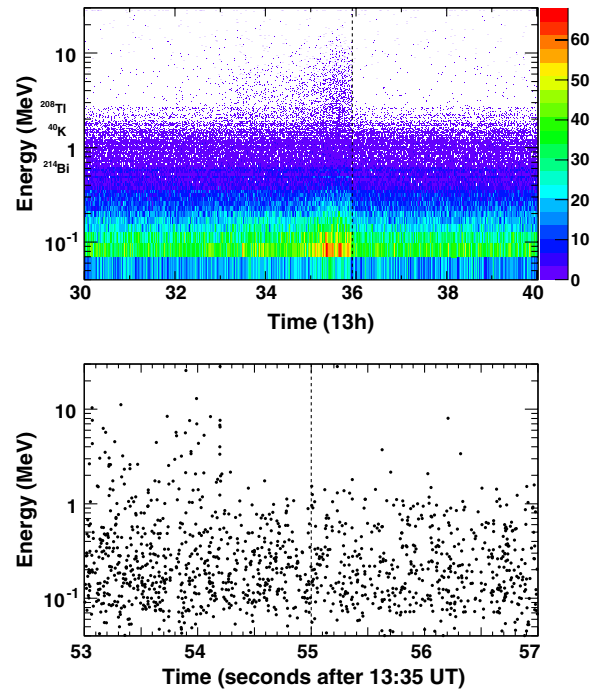


FIG. 4 (color online). (Top) Photon energies recorded by the NaI scintillator of daq1 with anticoincidence mode during 13:30–13:40 UT. A time resolution is 1 sec. Vertical and horizontal axes show the energy in MeV and minutes after 13:00 UT, respectively. The vertical dashed line shows the occurrence time of the lightning, 13:35:55 UT. The color bar denotes counts in each bin; as the color approaches red, the number of photons recorded increases. (Bottom) Same as that for the top panel, but for the interval of 13:35:53–13:35:57 UT, with a time resolution of 0.1 ms.

flash (Fig. 4). In actuality, this time scale of 800 ms agrees generally with the total discharge duration, which is a few hundred to 700 ms, of intracloud discharges [24].

In addition, the present event and the two past observations did not detect any energetic x-ray radiation associated with lightning, mainly its stepped leaders. Therefore, the lack of detection of such x-ray energetic radiation may be a common feature, implying that the source of short-duration x-ray bursts is either different or far from that of the precursory prolonged emission. Alternatively, the lightning-related x rays may not have been beamed toward the detectors. In that case, these events also imply that a local electric field gradually (a few seconds to a minute) enhances. Babich *et al.* [21] recently showed via numerical simulations that such an electric-field enhancement that can potentially generate lightning can last for a relatively long duration of ~10 s via electron avalanches caused by a steady flux of secondary cosmic-ray electrons. Thus, the present temporal behavior prior to the gamma-ray termination (Fig. 3) might indicate such an effect.

Hence, we may interpret the lack of gamma-ray detection during this time interval in the following manner.

Through a process as proposed by Babich *et al.* [21], the field strength of the acceleration region was enhanced, for a prolonged period, until its strength was high enough to produce the observed gamma rays. Then, certain lightning processes, such as stepped leaders, emerged from the acceleration region to initiate an intracloud discharge. As described in the Results section, the observed lightning occurred more than 5 km away from our detectors. Thus, as often observed [25], the stepped leaders would, either horizontally or in an upward direction, propagate over the distance towards another charged region of the thundercloud. This would be possible because lighting paths can extend over 2–8 km (e.g., [26]). Consequently, a connection between the acceleration region and the other charged region could neutralize the acceleration region ∼800 ms before the optical flash was observed, resulting in the termination of the electron acceleration. Then, the field region might not recover to a high enough level to accelerate electrons to relativistic energies, at least until the end of the intracloud lightning event.

Another interesting observation, in addition to the relationship with the lightning flash, was that the measured duration of the present event, 163 s, is 2–4 times longer than that observed by other GROWTH events [11,13]. This could be due to the fact that our detectors, especially daq1, were facing the central region of the gamma-ray source for an extended period (Fig. 2). This favors the detection of >10 MeV gamma rays by daq1. In this event, the flux of >10 MeV gamma rays was the highest energy part of the bremsstrahlung photons that are emitted by electrons accelerated to a few tens of MeV. As known from the bremsstrahlung cross section, such photons, with energies close to that of primary electrons, are projected forward in a narrow cone. In addition, such high energy photons undergo less Compton scatterings than lower energy photons that tend to be spread over a wide area. Therefore, it is likely that the extent of the >10 MeV gamma rays observed in this event almost equals that of the whole acceleration region.

The 36 s duration of the >10 MeV gamma rays detected by daq1 was approximately one fifth of that of the lower energy photons, 163 s. From the <3 MeV observations, we found that the extent is at most ∼800 m (Fig. 2); hence, the extent of >10 MeV gamma rays can be inferred as being ∼180 m, which is almost equal to the acceleration region in the thundercloud. This is smaller than the region of a positively charged layer located at the base of an electrically active phase of winter thunderclouds [27], which can extend a few kilometers, suggesting that only a small part of the electric field is sufficient to give the electrons energies of a few tens of MeV.

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