PROCEEDINGS OF SCIENCE

Lightning Mapping as a Probe of Electron Accelerator in Thunderclouds

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Strong electric fields inside thunderclouds can accelerate electrons to relativistic energies. Gamma-ray glow is a high-energy atmospheric phenomenon originating from bremsstrahlung of the accelerated electrons. Since they originate from electric fields inside thunderclouds rather than lightning flashes, gamma-ray glows are not usually coincident with lightning flashes. On the other hand, gamma-ray glows are sometimes terminated with lightning flashes as lightning flashes can discharge the electrified region. Therefore, lightning mapping observation is useful to investigate how the electrified region is depleted by lightning flashes. On December 18, 2018, we detected a gamma-ray glow at Kanazawa University in Japan during a wintertime thunderstorm. Winter thunderstorms along the coast of the Sea of Japan are an ideal target for observing gamma-ray glows as their charge center is lower than summer thunderstorms and hence high-energy particles are less attenuated before reaching the ground. The gamma-ray glow was terminated by a lightning flash that was monitored by the Fast Antenna Lightning Mapping Array. Combining the gamma-ray and lightning mapping observations, we discuss the charge structure of the thundercloud that produced the gamma-ray glow.

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1. Introduction

Interactions between electric fields in thunderstorms and high-energy particles are getting attention, and are establishing a new interdisciplinary field called high-energy atmospheric physics [1]. Gamma-ray glows, also referred to as thunderstorm ground enhancements [2] or long bursts [3], are one of the high-energy atmospheric phenomena associated with thunderclouds [4–7]. It is considered that gamma-ray glows originate from electron acceleration and multiplication by strong electric fields inside thunderclouds, which may be driven by the relativistic runaway electron avalanche (RREA) scheme [8].

While the discovery was made in 1980s [9, 10] and observational evidence has been accumulated [7, 11], gamma-ray glows are still poorly understood as it is difficult to investigate charge structures inside thunderclouds. Besides high-energy measurements, lightning mapping is becoming a useful tool to investigate gamma-ray glows. In general, gamma-ray glows are not associated with lightning flashes themselves. On the other hand, a gamma-ray glow can terminate with a lightning flash, which can be monitored by the radio-frequency band [6, 12–14]. In this paper, we present an example of the termination of a gamma-ray glow detected in Kanazawa, Japan, and discuss the charge structure of the thundercloud with a lightning mapping observation.

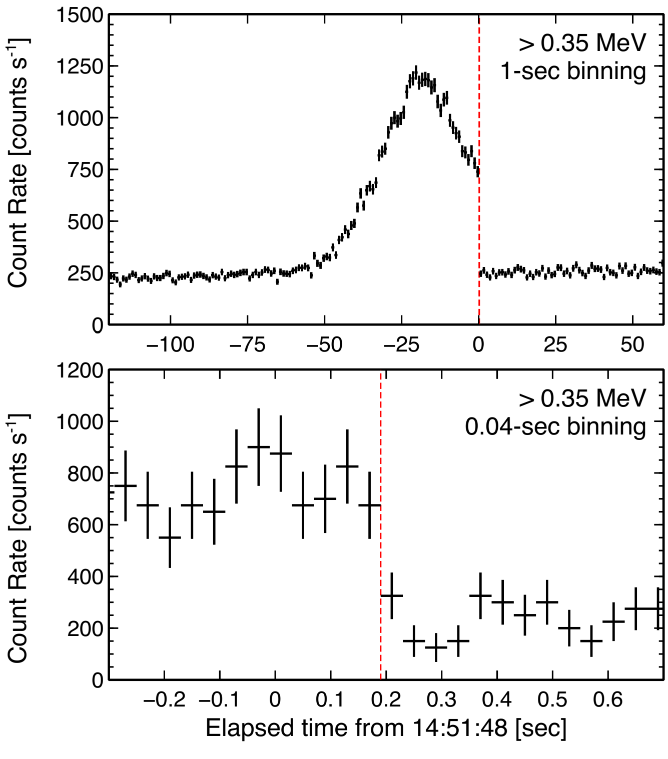

Figure 1: The count-rate history of the gamma-ray glow on December 18, 2018, with a 1-sec binning (upper), and its expansion around the termination (lower). The red-dashed lines show the timing of the glow termination.

2. Observation

We have performed an observation campaign of high-energy atmospheric phenomena during winter thunderstorms in Kanazawa, Japan. Winter thunderstorms in coastal areas of the Sea of Japan have quite different characteristics from summer thunderstorms. In particular, a low-charge-center structure of thunderclouds can facilitate the detection of high-energy photons at sea level. In the present paper, we analyze a gamma-ray glow detected at Kanazawa University on December 19, 2018. The glow was detected by a portable radiation monitor equipped with a $25 \times 8 \times 2.5$-cm BGO scintillation crystal [15]. The count-rate history of the glow is shown in Figure 1. The glow suddenly stopped at 14:51:46.190 UTC. The termination is as quick as 40 ms

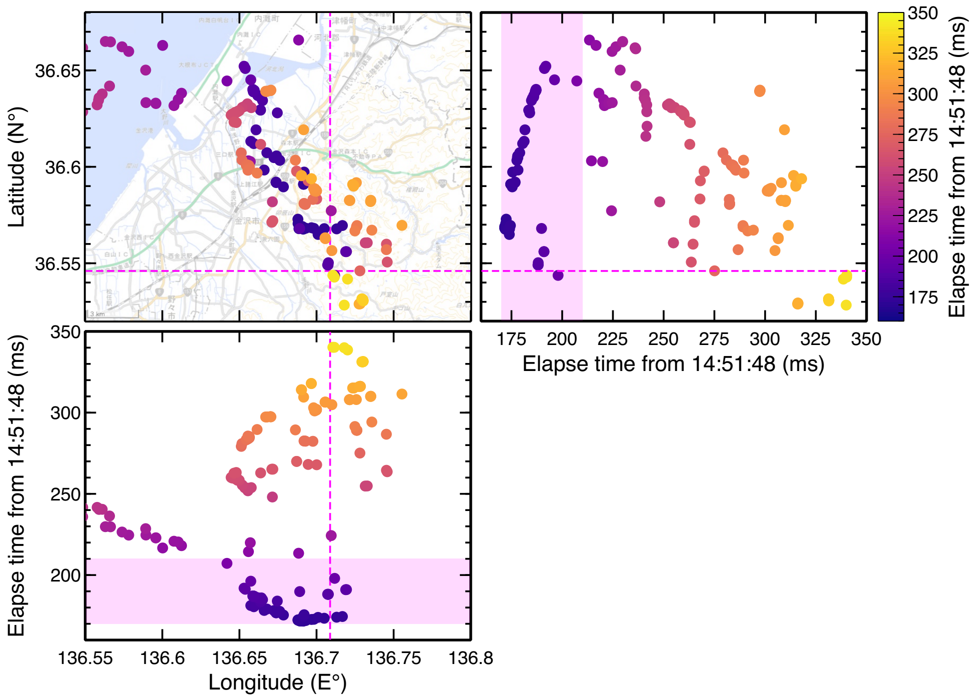

Figure 2: Location and timing of low-frequency pulses detected by FALMA. The magenta dotted lines show the position of the gamma-ray monitor. The magenta area indicates the time window of the glow termination.

At the moment of the termination, a lightning flash was also detected. The lightning flash was monitored by the fast antenna lightning mapping array (FALMA), operated by Gifu University [16]. FALMA consists of fast antennae sensitive to broadband low-frequency (LF) band of 1–500 kHz, and two-dimensionally locates LF pulses of lightning flashes by the time-of-arrival technique.

Figure 2 shows the result of lightning mapping by FALMA. The lightning flash initiated at the northwest of the detection site of the gamma-ray glow, Then, an eastward leader and a north-westward leader were detected. Most of the LF pulses of both leaders have the same polarity as positive cloud-to-ground (CG) strokes, and hence they are probably negative upward leaders (NLs). After the two NLs (NL1 for eastward and NL2 for north-eastward), several LF pulses were located close to the observation site. The closest one has the same polarity as positive CGs and was located

0.36 km from the radiation monitor. Its peak current is estimated to be +3.6 kA.

3. Discussion

FALMA located several pulses close to the detection site, which are also coincident with the time window of the glow termination. Therefore, these pulses are probably associated with the termination of the gamma-ray glow. When gamma-ray glows are detected at the ground, an upward electric field should exist, and electrons should be accelerated downward. Considering a conventional tripolar charge structure [17], gamma-ray glows can be produced between a main negative charge layer and a lower positive charge layer. If an in-cloud current occurs between the two layers to cease gamma-ray glows, the polarity of the current should be the same as negative CGs. However, the observed LF pulses are the opposite, the same as positive CG.

Figure 3 shows a vertical cross-section of the thundercloud that produced the gamma-ray glow, and a possible scenario of the charge structure. A convective echo region was detected by the Noumi X-band weather radar operated by the Japan Ministry of Land, Infrastructure, Transport and Tourism, The echo region with reflectivity larger than 40 dBZ suggests the existence of negatively charged graupel particles, and hence a negative charge region is suggested around the 2-km altitude.

The lightning flash initiated with two upward negative leaders. It is considered that two negative leaders initiated in the negative charge region, then went upward to an upper positive charge. On the other hand, a positive leader can be simultaneously produced with NL1 and NL2. Although it is difficult to detect the progression of positive leaders in the LF band, positive leaders can be detected by a recoil leader. We conjugate that the LF activities detected around the detection site are associated with a positive leader progression and/or a subsequent recoil leader. In this case, the positive downward leader could have proceeded to the glow-producing region, reduced negative charges above the observation site, and then terminated the gamma-ray glow.

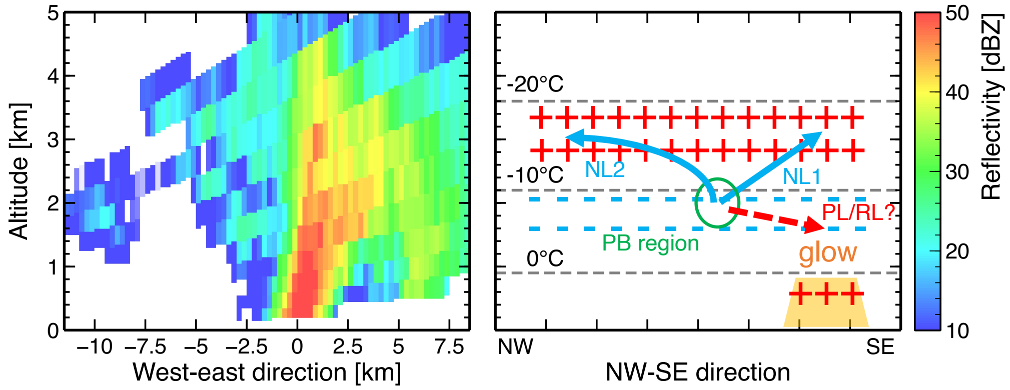

Figure 3: Left: A vertical cross-section of radar echoes detected by the Noumi X-band weather radar. Right: A schematic of charge structures in the thunderstorms.

In conclusion, we detected the termination of a gamma-ray glow at Kanazawa University on December 18, 2018. The lightning flash associated with the glow termination was monitored by FALMA. Combining the timing, location, and polarity of LF pulses detected by FALMA, it is possible that a positive downward leader proceeded toward the strong electric-field region where electrons were accelerated and multiplied, reduced negative charges, and then terminated the gamma-ray glow. Although direct measurements of charge structures inside thunderclouds are quite difficult, combination of radiation and lightning mapping observations is a powerful tool to investigate glow-producing thunderclouds.

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