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Lightning flash started near the electron acceleration region in the thundercloud

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The interaction between cosmic rays and thunderclouds has attracted much attention in recent years. Cosmic rays have been considered as one possible cause of the trigger of lightning flashes: e.g., a possible correlation between the number of observed lightning and cosmic ray flux (e.g.,Themis G. Chronis, journal of Climate,2009). In thunderclouds, electric fields are thought to cause relativistic acceleration of electrons as an interaction with cosmic ray air shower and emit bremsstrahlung photons, known as gamma-ray glows. One unresolved is that such electron acceleration, and thus gamma-ray glows, may be related to initiating lightning flashes. To verify this hypothesis, we conducted winter thundercloud observations using mapping radiation measurements in Japan. At 04:06–04:08 JST on December 30, 2021, five radiation detectors recorded a gamma-ray glow, terminated with the lightning flash recorded by two lightning mapping systems (FALMA and DALMA). Our multi-location observation revealed that the gamma-ray glow region had a horizontal size of about 2 km×2.5 km. The XRAIN radar observation showed that the high reflectivity area, presumably corresponding to the electron acceleration region, reaches more than 2 km above the gamma-ray detected radiation detectors. The initiation of this lightning discharge started from 1.6 km altitude from the ground around the gamma-ray glow region [1]. This result indicates that the lightning flash began in the vicinity of the electric field region and a possible connection between the cosmic ray interaction with the electric fields in thundercloud and the triggering of the lightning flash.

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1. Introduction

The mechanism of lightning discharge generation is not yet understood. The classical breakdown threshold in the air of ~3 MVm^{-1} [2] is required for lightning discharges to occur. However, the electric field actually observed in the atmospehere is more than one order lower than this threshold [3]. Cosmic rays are considered to be one of the candidates for triggering the lightning flashes: e.g., a possible correlation between the number of observed lightning and cosmic ray flux [4]. The developed thundercloud and lightning are known to emit gamma rays. One such high energy atmospehric phenomena is "gamma-ray glow". This is radiation enhancements in the MeV range for a duration of tens of seconds to minutes during thnuderstorm passages detected in ground experiments [5–7]. Gamma-ray glow thought to be bremsstrahlung from relativistic electrons accelerated via Relativistic Runaway Electron Acceleration (RREA) process when the high energy electrons such as cosmic ray pass through the strong electric field in thundercloud. Because gamma rays attenuate in the atmosphere, it is necessary to aim at low altitude thunderclouds in order to observe them on the ground. In winter, the Sea of Japan coast is reached by cold dry air from the Siberian continent and the Tsushima warm current, which brings short clouds. Therefore, it is one of the most suitable locations in the world for ground-based observation of gamma-ray glows. To verify the relationship between lightning flashes and cosmic rays, we conducted winter thundercloud observation using mapping radiation measurement in Japan.

2. Method and observation

2.1 Citizen science "Thundercloud project"

In 2018, we launched the citizen science "Thundercloud project" for mapping observation of gamma-ray glow. To construct the multi-point observation network, we developed the Compact Gamma-ray Monitor "Cogamo" and every winter, we mail the Cogamo detectors to citizen supporters who live along the Japan Sea coast area and have them installed in their yards. In FY2021, about 58 cogamo detectors were installed [1] (Figure 1a).

2.2 Cogamo detector

Cogamo detector is a small and lightweight radiation detector using CsI scintillator (5*5*15 cm) coupled with a Silicon Photomultipliers (MPPC) as a photon sensor (Figure 1b). Cogamo detectors acquire the energy deposit of and arrival time of each radiation event and get the information on GPS status, temperature, humidity, and optical luminosity, recorded on the micro SD card and also sent to the web server.

2.3 FALMA and DALMA

The Fast Antenna Lightning Mapping Array (FALMA) and Discone Antenna Lightning Mapping Array (DALMA) are lightning mapping systems working in the low-frequency band (0.5–500 kHz) and median-frequency band (1.5–12.5 MHz), respectively. In 2021, 10 FALMA sites and 12 DALMA sites were deployed (Figure 1a). The localization accuracies of FALMA and DALMA are estimated to be about 200 and 50 m [8, 9], respectively.

2.4 XRAIN metrological radar

In this analysis, the eXtended RAdar Information Network (XRAIN) operated by the Ministry of Land, Infrastructure, Transport and Tourism of Japan is used to determine the movement of the thundercloud. We used the data of XRAIN Nomi radar, which is located 15 km away from Kanazaa City (Figure 1a). The original data set of XRAIN can be obtained from the DIAS service (https://diasjp.net, which was supported by JAMSTEC)

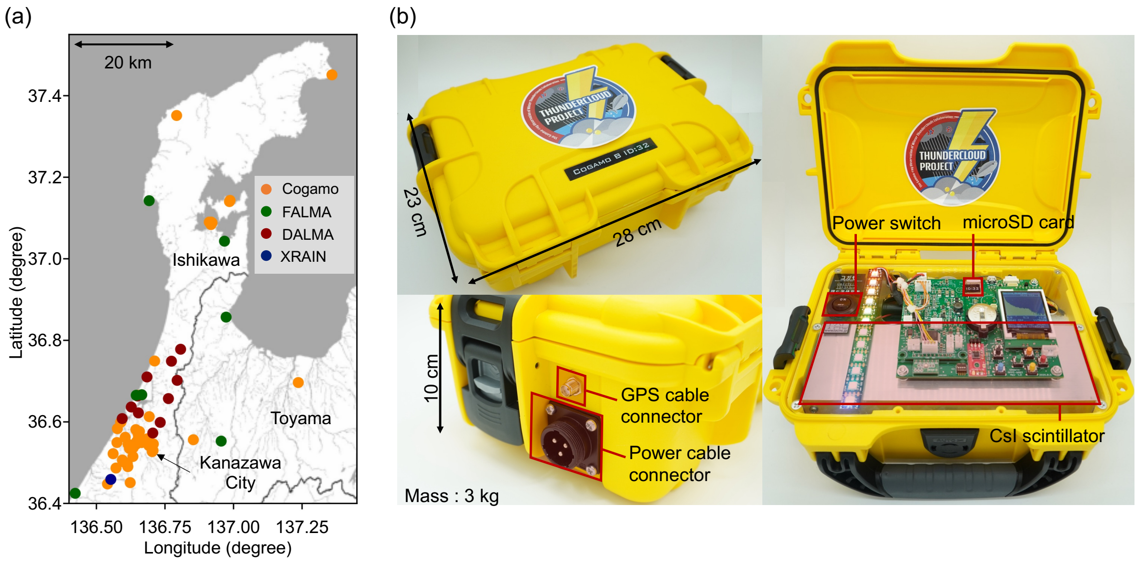

Figure 1: (a) The orange, green, red, and blue circles show, in this observation site map, the locations of Cogamo detectors, the FALMA sites, DALMA sites, and the XRAIN Nomi Radar site, respectively. (b) The portable Cogamo radiation detector (see the details in Tsurumi et al., [1]).

3. Data analysis and result

On December 30, 2021, 5 cogamo detectors (ID 63, 23, 33, 53 and 15) recorded the gamma-ray glow from one thundercloud [1]. These cogamo detectors were installed every few hundred meters at Kanazawa City, Ishikawa prefecture whose location shows the Figure 3a. Figure 2a shows 8-s-binned count-rate histories in the 3-10 MeV band. We set the gamma-ray glow threshold at the count rate bins exceeding the 3.5 sigma significance calculated by the average and standard deviation of 1 hr count rate histories. The duration of gamma-ray glow is calculated the exceeding this 3.5 sigma threshold is shown in red in Figure 2a. FALMA and DALMA recorded the lightning flash at the same time, and the gamma-ray glow recorded by 2 of 5 cogamo detectors was terminated coinciding with this lightning flash (Figure 2b).

Figure 3a shows the rainfall intensity maps every minutes for a period of 04:06-04:09 JST, calculated from the radar reflectivity data. The high-intensity area passed over the cogamo detectors which detected gamma-ray glow during this period. We estimated the on-ground horizontal size of the gamma-ray glow (gamma-ray glow region) by multiplying the duration of the event $T_{3.5}$ and wind speed estimated using XRAIN data (Figure 3b). The wind speed and direction at this glow were 21.2±0.8 ms^{-1} and the westerly, respectively. The size of gamma-ray glow region horizontality (east-west direction) and perpendicular (north-south direction) to the wind direction was estimated to be 2.0 km and 2.5 km, respectivly.

The FALMA and DALMA recorded the lightning flash starting at 04:08:34.8565 JST at the same time of gamma-ray glow. The lightning flash started in the vicinity of the glow event and developed northeastward and then sourthestward (Figure 4a). Figure 3b shows the compearing the location of the cogamo detected glows, glow region and the first three and four discharge signals of FALMA and DALMA, respectively. There ocurred roughly 420 m and 540 m to the east-northeast of Cogamo ID 62. Considering the horizontal error (~50 m for FALMA and ~200 m DALMA), the lightning flash started inside or in the vicinity of the glow region. The low-frequency radio waveform and the altitude of lightning discharge (Figure 2b) indicate that the lightning flash started with a downward negative leader with a large speed of about 3×10^6 ms^{-1}.

Figure 5a shows the rain-fall intensity maps for a wide area. The high rainfall-intensity area was extended from northwest to southeast for a distance of 11 km, while the glow was detected only in the northwest area. To compare the thundercloud of the detected area and non-detected area, we analyzed the vertical cross-section of the corrected reflectivity factor (Figure 5b) and the particle identification (Figure 5c) along the axis of interest indicated in Figure 5a. In the glow region, high reflectivity exceeding 40 dBZ was found under 2 km, and the wet graupels appeared up to the altitude of 2 km above the glow region.

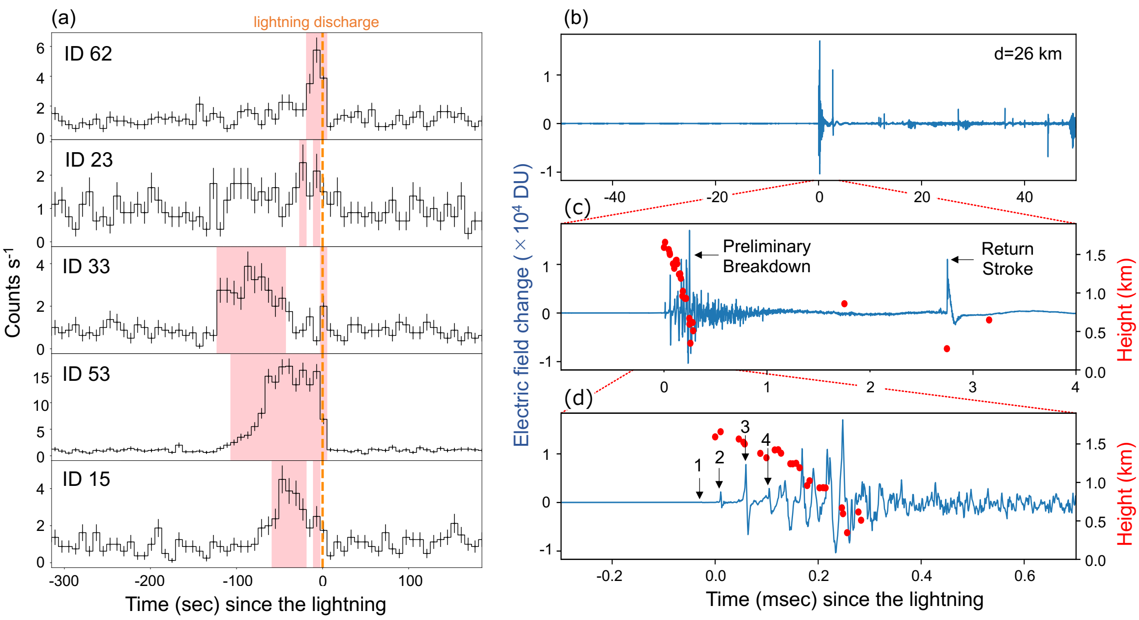

Figure 2: (a) The 3-10 MeV and 8-sec binned radiation count rates recorded by five Cogamo detectors. Error bars are statistical 1σ. The time origin is 04:08:34.8565 JST on 30 December 2021, which corresponds to the initial lightning discharge signal recorded by FALMA and DALMA. Data bins with detection significance exceeding 3.5σ are marked in red. (b–d) Preliminary breakdown radio pulses recorded by FALMA (blue lines, the left vertical axis) and their heights mapped by DALMA (red markers, the right axis). The time origin is the same as panel (a). The indicated numbers are used for the location shown in Figure 4 [1].

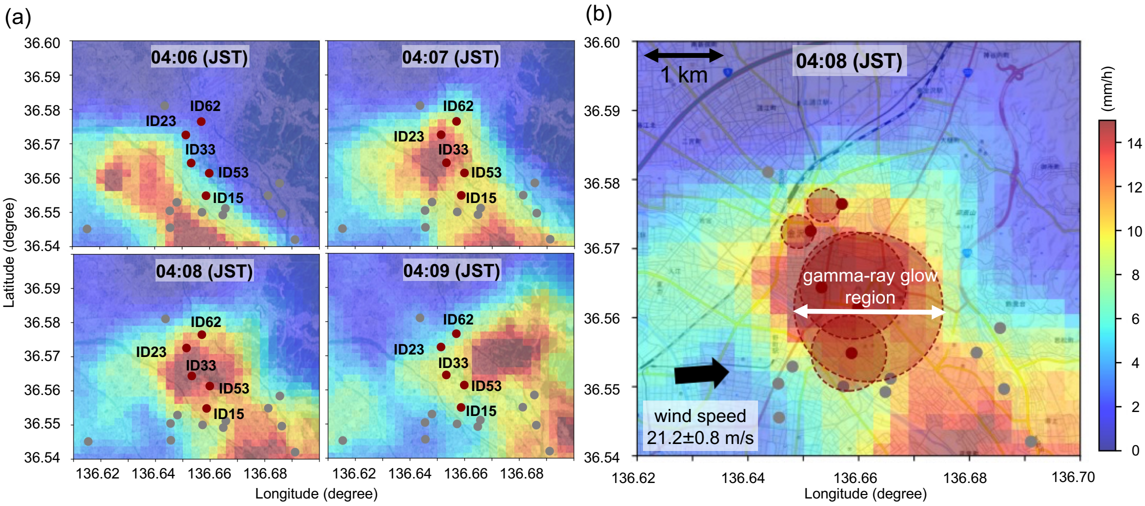

Figure 3: (a) XRAIN radar rainfall intensity maps at every minute between 04:06–04:09 JST on 30 December 2021. Red and gray circles show detectors with and without the gamma-ray glow detections, respectively. The overlaid topographic map is taken from the Geospatial Information Authority of Japan. (b) Same as panel (a) at 04:08 JST, but our estimated regions of gamma-ray radiation are overlaid.

4. Discussion&Conclusion

According to the riming electrification [10], in the developed thundercloud, tripole structure is formed by upward winds. From Figure 4b, the lightning flash started in or the vicinity of gamma-ray glow region. The gamma-ray glow is considered to radiate from between the negatively-charged middle layer (wet graupel) and the positively-charged lower layer (wet graupel and cristal). In this case, the high reflectivity (>40 dBZ) of the thundercloud reached 2 km in altitude (Figure 4b) and wet graupels found in the lower layers (Figure 4c) in the glow region, and it is suggested that there was a strong electric field region at this altitude. The lightning flash started at an altitude of 1.6 km and propagated downward, ending at 0.5 km in altitude. The leader speed at the preliminary breakdown stage is about one order of magnitude higher than those in the previously reported lightning flashes [11–13]. This result suggests the strong electric field regions initiating the lightning discharges and relativistic electron acceleration for the gamma-ray glow existed in the same space. All these results are published in Tsurumi et al., [1].

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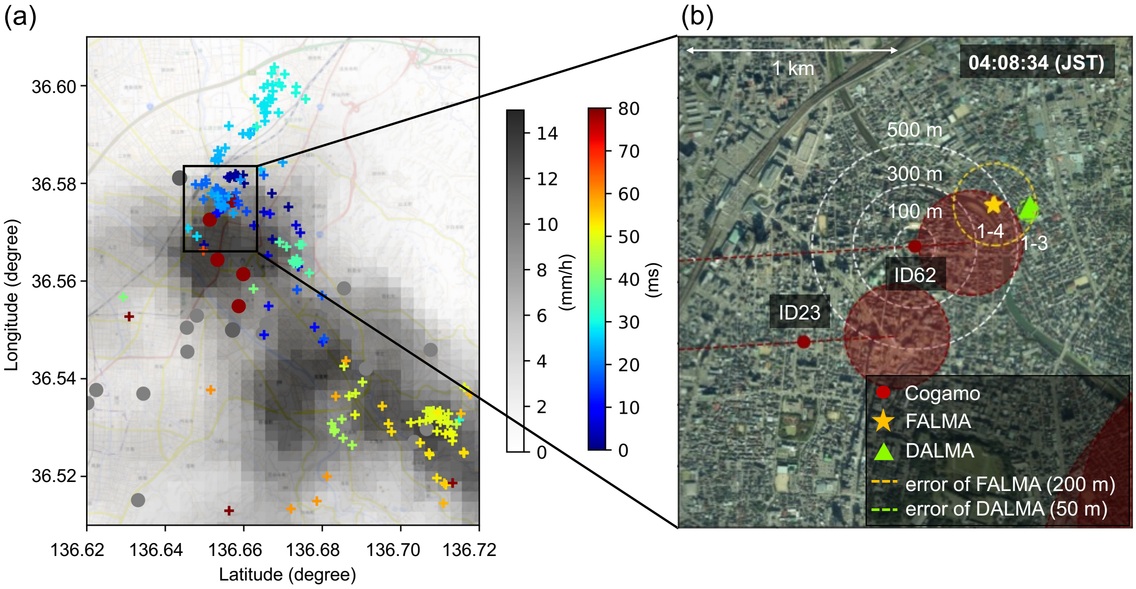

Figure 4: (a) Locations of FALMA-detected lightning discharges (cross marks) compared with the Cogamo locations (circle marks) and rainfall intensity (background in grayscale). The time origin of colors of the cross marks is 04:08:34.8565 JST (right-side color bar). (b) Zoom-up figure at 04:08:34 JST around the initial stage of the lightning flash. The location of initial FALMA and DALMA signals with corresponding error circles (see the legend). The red-filled circles indicate the estimated gamma-ray glow regions [1].

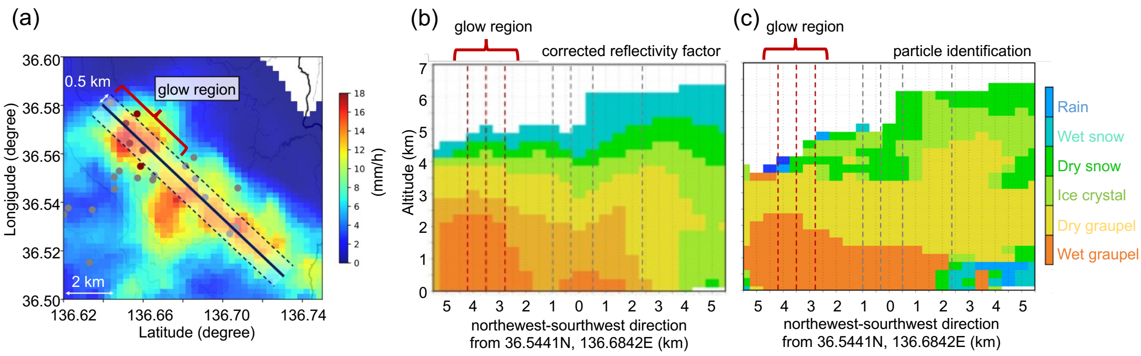

Figure 5: (a) The wide area rainfall intensity map at 04:08 JST. The blue solid line and dotted lines indicate the vertical cross-section to be used in panels b and c. (b) Vertical cross-sectional view of the corrected reflectivity factor. Red vertical dotted lines and gray dotted lines indicate the locations of Cogamo detectors with and without gamma ray detections, respectively. (c) Same as Panel (b), but for the particle identification [1].

Infrastructure, Transport and Tourism and retrieved from the Data Integration and Analysis System (https://diasjp.net). The background image in Figures 1, 3 and 4 was provided by the Geospatial Information Authority of Japan.

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