Compton Camera Imaging of a Gamma-Ray Glow From a Thunderstorm

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Abstract Gamma-ray glows associated with thunderclouds have been observed since the 1980s, however it remains unclear how, and at which thunderstorms gamma-ray glows are generated in dense atmospheres. In this study, we report the first Compton camera imaging of a gamma-ray glow from a winter thundercloud. On 14 January 2022, using two identical Bi$_4$Ge$_3$O$_{12}$ scintillators in energy range of 0.05–5 MeV, we detected two gamma-ray glows lasting ~4 min in a mountain area 25 km from the Japan Sea and 410 m above sea level. The same events were also observed by the Compton camera, where the first glow we observed suggested statistically significant (4.0 and 5.9 $\sigma$ level) signals of two enhanced concentrations in gamma-ray photon images in a range of 0.15–1.5 MeV. These concentrations were most clearly observed in a time window of $\Delta t = 50$ s around the peak intensity of the gamma-ray glow.

Plain Language Summary Observations of gamma rays from thunderclouds started in 1980s, leading to intensive studies in the last 40 years. However, the question of where and how such gamma rays are produced in thunderstorms remains unclear, as no gamma-ray images have been obtained to date. This paper presents the first successful gamma-ray imaging of a thundercloud in a winter of Japan. In particular, we installed a Compton camera of 10 × 10 cm$^2$ in size, that is a compact but high sensitivity camera originally developed in the field of astronomy to observe gamma-ray sky. At the peak of a gamma-ray emission, we detected significant enhancements in the gamma-ray photon image. The image provides the source position and beam pattern of the gamma-ray emission, thus may be connected to highly electrified region and electron acceleration inside thunderclouds.

1. Introduction

The study of radiation associated with thunderclouds began with the suggestion that charged particles accelerate in electric fields, reported in 1925 (Wilson, 1925). Since the 1980s, high-energy gamma-ray bursts related to lightning discharges and thunderclouds have been observed. These observations were mainly accomplished using satellites (Fishman et al., 1994; Smith et al., 2005), aircrafts (Kelley et al., 2015; Parks et al., 1981), and balloons (Eack et al., 1996). However, ground-based observations have also been reported (Chilingarian et al., 2013; Chilingarian et al., 2020; Moore et al., 2001; Torii et al., 2002). Although ground-based observations generally require high altitudes, because of the attenuation of gamma rays, in some cases, these high-energy events can be monitored at sea level when the base of thunderclouds is low, as with winter thunderstorms in Japan.

Observed gamma-ray bursts associated with thunderclouds can be classified into two types: terrestrial gamma-ray flashes (TGFs) and gamma-ray glows. TGFs typically last for only a few milliseconds and are thought to be produced during lightning discharges. Although only a few physical processes related to TGFs are known due to their short duration, recent observations suggest a photonuclear reaction is triggered by lightning discharges (Enoto et al., 2017). By contrast, gamma-ray glows typically last from a few seconds to more than several minutes. Thus, they have been the focus of intensive observations since the 2000s. Importantly, these glows are not typically attributed to lightning discharges (Torii et al., 2011). During the winter season in Japan, observations of these glows have been reported many times, particularly since the 2010s. Thus, the details of these bursts have been discussed and are relatively well known (e.g., Tsuchiya et al., 2011). Specifically, the altitude of the radiation source and the

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relationship between gamma-ray glows and weather conditions have been discussed (Torii et al., 2011; Wada, Enoto, et al., 2021).

Although many issues associated with gamma-ray glows have been discussed, the question of where and how such glows develop in clouds remains unclear, as no gamma-ray images have been obtained to date. Gamma-ray imaging of sub-MeV to several MeV is generally difficult, but high-sensitivity Compton cameras have been developed for use in the fields of medicine, astrophysics, and even for environmental surveys (e.g., Hosokoshi et al., 2019; Kataoka et al., 2013; Koide et al., 2018; Omata et al., 2020, 2022; Schonfelder et al., 1984). In this study, we provide the first challenge of direct imaging of gamma-ray glows using a Compton camera during 2021–2022 winter in Japan.

2. Experiments

We installed our detector system at a facility in Matsudai, Tokamachi City, Niigata Prefecture, Japan (37°9’42.99N, 138°37’44.47E). As Figure 1a shows, the observation site was located approximately 25 km from the coast of the Japan Sea and approximately 410 m above sea level. The detectors were placed on the third floor of a building, or approximately 10 m above ground. We operated and monitored the system remotely from our laboratory at Waseda University in Tokyo.

Our detector system consists of (a) gamma-ray spectrometers based on scintillators coupled with a photomultiplier tube (PMT) and (b) a gamma-ray imager using a Compton camera. All detectors were placed at a window on the floor of the building.

We prepared two identical sets of scintillation detectors as gamma-ray spectrometers to cover the possibility of detecting a wide variety of gamma-ray events (e.g., Wada, Enoto, et al., 2021). Each set consisted of four types of scintillation detectors: Bi₄Ge₃O₁₂ (BGO; 120 × 50 × 30 mm³), CsI(Tl) (100 × 40 × 40 mm³), GAGG(Ce) (25 mm diameter, 40 mm length), and LYSO (30 × 30 × 50 mm³).

All of these scintillators were optically coupled with a PMT assembly with a 25.4-mm diameter (R7889EG-PMT-ASSY), which has high quantum efficiency, is water-proof, and requires only a small applied voltage (+12V) to achieve high voltages up to +1,250V (Kataoka et al., 2005). Because the BGO scintillators are the largest and most suitable for detecting gamma-ray glows, we focused solely on data derived from the BGO scintillator in this study. The output signals from each PMT assembly were fed into a charge-sensitive amplifier (CSA: ClearPulse 5022) with a feedback capacitance $C_f = 100$ pF and a resistance of $R_f = 10$ kΩ. CSA outputs were then fed into a quad digital multi-channel analog-to-digital converter (CAEN N6781) with four independent channels, and the time and energy for each event were acquired after appropriate trapezoid filters for each scintillator were applied. The dynamic range of each scintillator was set to 0.05–5 MeV, and the triggered time of each gamma-ray photon was stamped with a resolution of 10 ns.

In addition to these spectrometers, we installed a Compton camera to visualize possible gamma-ray enhancement in thunderclouds. The Compton camera utilizes Compton-scattering kinematics to constrain the incident direction of gamma rays and consists of two layers of detectors, namely, a scatterer and an absorber. When a gamma-ray photon is scattered in the front detector (i.e., the scatterer) and absorbed in the rear detector (i.e., the absorber), the incident energy of the gamma rays $E$ and the scattering angle $\theta$ can be calculated as follows:

$$E = E_1 + E_2$$

$$\theta = \cos^{-1}\left(1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E}\right),$$

where $E_1$ and $E_2$ are the energy deposits in the scatterer and absorber, and $m_e c^2$ is the rest mass energy of the electron, respectively (e.g., Schonfelder et al., 1984). Thus, for a given event, the incident direction of a gamma ray can be constrained to lie somewhere on a cone-surface, that is, on the so-called “Compton cone” with a half opening angle $\theta$. After the events are accumulated, the position of the radiation source is specified as an enhancement of the image. However, cone-like artifacts sometimes remain in the image, particularly when event statistics are relatively low.

A schematic of the Compton camera installed in the proposed system is shown in Figure 2. The overall dimensions of the Compton camera were approximately 100 × 100 mm², where the distance between the scatter and...
absorber was fixed at 50 mm. Both the scatterer and absorber consist of 2 × 2 arrays of fine-pixelized GAGG(Ce) scintillator arrays (45 × 45 array of either 1 × 1 × 3 mm³ or 1 × 1 × 5 mm³ for scatterer and absorber, respectively) optically coupled with 16 × 16 multi-pixel photon counter (MPPC:S13360-3050) arrays of 3 × 3 mm² square. The output signal from each MPPC array is read out through a resistive charge division network and fed into a dedicated analog circuit to record the position and energy of each gamma-ray photon.

Due to the limited thickness of the GAGG(Ce) scintillator, the maximum energy that can be imaged with the Compton camera is limited to 1.5 MeV. In addition, gamma rays below ~0.15 MeV cannot be imaged because these photons are mostly absorbed within the scatterer. The energy resolution of the Compton camera is 9.7% full-width half-maximum (FWHM) with an angular resolution of 6.2° (FWHM), as measured with 0.662 MeV gamma rays. Here we define the field of view (FOV) of the Compton camera as ±70°, in which the detection

Figure 1. (a) Location of observation site (star mark) in Niigata Prefecture, Japan, which is based on a published map of the Geospatial Information Authority of Japan. (b) Radar map during the observed glow-1 (14 January 2022, 06:13:00 JST) and glow-2 (14 January 2022, 11:51:00 JST). The star mark in the center indicates the observation site, and the arrow to the north-west indicates the direction of the Compton camera. The dotted line indicates the field of view of the Compton camera. Color indicates refractive index in dBZ.
efficiency is larger than 20% of that measured in the pointing center. Configuration of detectors in the observation room and field view of the Compton camera captured with a fish-eye camera is shown in Figure 2b. Note that, together with ground surface, there exists boundaries of mountain and forest that shadow the bottom half of the FOV of the Compton camera.

3. Results

Gamma-ray glows associated with thunderclouds were detected twice on 14 January 2022. The first glow was started at approximately 06:13 a.m. (hereafter “glow-1”) and the second was at approximately 11:51 a.m. (hereafter “glow-2”). Note that the time is given in Japan Standard Time (JST). Figure 1b shows an X-band polarimetric RAdar information network (XRAIN) map.

XRAIN provides precipitation maps covering urban areas of Japan every minute with a range resolution of 150 m and an azimuth resolution of 1.2°. As Figure 1b shows, for glow-1, the thundercloud was located immediately above the detector; whereas for glow-2, the detector was inside a thundercloud, but its center was ∼5 km away to the west-northwest direction. Figure 3 shows the count rate histories of glow-1 and glow-2 recorded by the BGO scintillators, as measured below 1.5 MeV, above 1.5 MeV, and above 3.0 MeV. It should be noted that sharp increases and decreases in gamma-ray flux within a timescale of a few minutes were seen in all energy bands, but a gradual decrease (glow-1) and increase (glow-2) lasting more than 30 min were also apparent in the counting variation due to the increase in natural radiation such as radon fall triggered by rain clouds. Also, the energy spectra of each gamma-ray glows are shown in Figure S1 of Supporting Information S1.

A significant increase in the gamma-ray count rates was also observed with the Compton camera, as shown in Figure 4. Thus, we extracted gamma-ray images for various durations (Δt = 50, 100, 200 s) around the peak intensity at 06:15:00 (defined hereafter as T = 0) for a detailed comparison. For image reconstruction, we applied the following selection criteria: (a) time difference between the scatterer and absorber was less than 0.8 μs; (b) the energy deposit in the scatterer (E₁) was 0.05 MeV ≤ E₁ ≤ 1.5 MeV; and (c) the total energy deposit in both the scatterer and absorber (E = E₁ + E₂) was 0.15 MeV ≤ E ≤ 1.5 MeV. Figure 5a shows example gamma-ray images extracted under Δt = 50 s around the peak of glow-1. Note that the central image, extracted from 06:15:00 − 06:15:50 (T = 0 − 50 s)
on 14 January, exactly matches the time window of glow-1 highlighted in yellow in Figure 4. Figure 5b shows that the enhancement of the gamma-ray image appeared to have two separate regions, defined as area-1 and area-2. Number of photons extracting the central image, corresponding to 06:15:00 06:15:50 ($T = 0 - 50 \text{ s}$) is 72. The elevations and azimuth angles of area-1 and area-2 were $\theta_1 = 30^\circ$, $\phi_1 = -36^\circ$, and $\theta_2 = 66^\circ$, $\phi_2 = -14^\circ$, respectively. It seems that a weak concentration of area-1 already appeared in images starting from 06:13:20 and 06:14:10 ($T = -100 \text{ s}$ and $-50 \text{ s}$), whereas a much stronger enhancement in area-2 suddenly appeared in the image starting from 06:15:00. Both concentrations completely disappeared in the image starting at 06:16:40 ($T = 100 \text{ s}$). The gamma-ray spectra of the coincidence events between the scatterer and absorber are shown in Figure 5b under various $\Delta t$.

To examine whether these enhancements could be attributed to the gamma-ray glow and not to statistical fluctuation, we constructed 860 gamma-ray maps using the archive data of Compton images taken on 14 June and other days randomly sampled when no thunderstorms or rain were observed. We then integrated pixel values over

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**Figure 3.** Count rate history of gamma rays as measured with Bi$_4$Ge$_3$O$_{12}$ (BGO) scintillators around glow-1 (left: 14 January 2022, 5:55 to 6:35 JST) and glow-2 (right: 11:33 to 12:13 JST). The top, middle and bottom figures show counting rates below 1.5 MeV, above 1.5 MeV, and above 3 MeV, respectively. Counts obtained with both BGO scintillators are summed.
exactly the same regions (20° × 20°) as defined by area-1 and area-2 to evaluate the distribution of values. The statistical significance of observing these concentrations in area-1 and area-2 as seen in glow-1 were 4.0 and 5.9 σ respectively, when the distribution was modeled by a Gaussian function. The expectation value of observing this concentration within our datasets (number of trials = 860) was 2.1 × 10 −1 for area-1 and 2.5 × 10 −5 for area-2. For a more conservative estimation, we created a modified color map in which values in area-1 and area-2 were normalized with the total number of Compton events used for image reconstruction, which resulted in the 2.5 and 4.0 σ statistical significance.

We examined whether a gamma-ray source situated around the corner of the FOV can be actually imaged with our Compton camera as suggested in area-2. We placed a point source of 137Cs that emits 0.662 MeV gamma rays at exactly the same position with area-2 (θ2 = 66°, φ2 = −14°) then reconstructed an image by using only 72 events. Owing to low photon statistics, circular artifacts extending from the source toward the lower part of the image is seen, but concentration of area-2 was robustly detected with more than 10 σ level. Such artifact often happens because the geometrical size of scatterer and absorber are limited and thus Compton events with large scattering angles are more difficult to be captured in the detector. In such cases, we tend to see a virtual concentration in the opposite region against the true source connected with an arc-like structure, that is also clearly seen in the forest/mountain area of observed image in Figure 5.

We also examined other choices of Δt = 100 and 200 s, which resulted in a detection significance of 3.6 σ for area-1 in both cases. For area-2, detection significance decreased, specifically to 4.1 σ and 3.3 σ, for Δt = 100 and 200 s, respectively, which confirmed that the concentrations in area-2 had shorter life spans than that of area-1. Finally, we performed the same analysis for glow-2 to find a possible excess in the gamma-ray image. However, no significant enhancement exceeding a 3.0 σ level was found for glow-2.

4. Discussion and Conclusion

In this study, we reported the detection of two independent gamma-ray glows in a mountainous area 25 km from the Japan Sea and 410 m above sea level. Both events could be regarded as gamma-ray glows associated with
passages of thunderclouds because a significant increase in gamma rays was observed above 3 MeV, which was not affected by radon-decay-chain background variations, and the observed time scale was typical of gamma-ray glows reported (Wada, Matsumoto, et al., 2021). This is the first detection of gamma-ray glows in a mountainous area during winter near the Sea of Japan.

Specifically, gamma-ray emission from thunderclouds was successfully imaged with a Compton camera for the first time for glow-1. We detected two possible enhancements of 4.0 and 5.9 $\sigma$ levels in the gamma-ray images of glow-1, but no such enhancement was found at least above a 3.0 $\sigma$ statistical significance in glow-2. This was interesting because both glows seemed to have nearly identical intensities and durations, yet the direction to the center of the thunderclouds, as indicated by the radar map, was quite different (see, Figure 1b). The Compton camera observed the thundercloud in the forward direction for glow-1, whereas it was almost backward for glow-2. Thus, the cloud was situated just near the edge of the FOV of the Compton camera in the case of glow-2, which made the imaging more difficult as compared with that of glow-1. Also in the case of glow-1, area-2 was detected around the corner of the FOV, but the Compton camera still has more than 20% of detection efficiency of that in the pointing center, thus the detection of gamma-ray concentration in glow-1 is robust.

Regarding glow-1, the Compton events used for image reconstruction were widely distributed between 0.3 and 1.5 MeV (Figure 5b), but we confirmed that the concentration on the image was mostly due to high-energy gamma rays $\geq$0.5 MeV. We note that the efficiency of the Compton camera decreases as energy increases, although the FOV retains almost the same. Considering the energy spectrum of glow 1 shown in Figure 5 and Figure S1 of Supporting Information S1, gamma-ray photons mainly contributing to the obtained Compton camera image is 0.5 − 1 MeV. Because gamma rays above sub-hundred keV are less affected by scattering in the atmosphere, and because the contamination from the ground was negligible when observations were made from the third floor of the building, the Compton camera likely caught a part of the gamma-ray glow directly from the sky. In addition, the elevation angles of area-1 ($\theta_1 = 30^\circ$) and area-2 ($\theta_2 = 66^\circ$) as derived from the image could be explained by the gamma-ray glow emission model in thunderclouds.

Figure 5. (a) Gamma-ray images of glow-1 obtained with the Compton camera in an energy range of 0.15–1.5 MeV. Each panel corresponds to images reconstructed every 50 s around the central epoch of glow-1. The time on top of each panel indicates the starting time used for image reconstruction. The gray shadow at the bottom of each image corresponds to the boundaries of mountains, forest, and horizon as seen in Figure 2b. (b) left: Close-up of image captured at 06:15:00–06:15:50 and excess regions of area-1 and area-2, where the event extraction region was $20^\circ \times 20^\circ$ (dashed square). The color bar indicates relative intensity of gamma rays, that is the value added to each image pixels after accumulation of Compton cones. right: gamma-ray spectra of the coincidence events between the scatterer and absorber, which were used for image reconstruction. Spectra around the peak of glow-1 are shown for $\Delta t = 50, 100, 200$ s as compared with the background shown in the black histogram. The background spectrum is an integrated average of events extracted from 30 min before and after glow-1.
Moreover, it is interesting to note a time difference between the appearance of area-1 and area-2 in glow-1. From the XRAIN maps, rain clouds were moving toward the east-southeast direction with a wind velocity of ~15 m/s. Assuming the height of gamma-ray emission site in thundercloud is 1 km corresponding to an elevation angle of $\theta = 66^\circ$, such a wind velocity would make $\pm 20^\circ$ spread on the image for a time duration of $\Delta t = 50$ s. Actually, the observed image shows some extension along the $\phi$ direction, which is consistent with the direction of wind. Moreover, the fact that area-1 firstly appeared in the image then area-2 subsequently appeared, may suggest that both areas may be closely related to each other, and are moving along the wind direction.

In general, gamma-ray emission from a thundercloud is thought to be boosted along the electric field in the cloud; therefore, it is nearly perpendicular to the ground surface. However, angular spread may arise because of the leakage of accelerated electrons in the cloud and atmospheric scatterings of gamma rays. This oblique-directional glow component is believed to be the Compton camera enhancement peak. Instead, shear in the thundercloud, as is often seen during winter in Japan, may account for this angle of incident gamma-ray direction. When we use a Compton camera under different sky viewing angles, we expect to distinguish these different beam pattern scenarios. These observations provide the source position and information about the beam pattern of the gamma-ray emission, which is directly connected to the structure of the electric field and particle acceleration in thunderclouds.

### Data Availability Statement

The radar map shown in Figure 1b is provided by an X-band polarimetric RAdar information network (XRAIN) which is available at: [http://apps.dias.jp.net/xband/](http://apps.dias.jp.net/xband/). All the data presented in this paper is available from [https://doi.org/10.17632/p6hydmnx1zb.1](https://doi.org/10.17632/p6hydmnx1zb.1). Sub-directories of the above DOI contains the light curves of glows taken with the PMT and BGO (Figure 3), light curves (Figure 4), and the images (Figure 5) taken with the Compton camera.

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