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Full Length Article

High precision spectroscopic observation of gamma rays from thundercloud ☆

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ABSTRACT

High-energy radiation associated with thundercloud activity has been widely studied through observations of gamma-ray glows and terrestrial gamma-ray flashes (TGFs). While previous measurements have primarily focused on temporal behavior and continuum spectral properties, detailed spectroscopic investigations remain limited due to detector energy resolution. In this study, winter thunderstorm observations were conducted in a mountainous region facing the Sea of Japan using a high-purity germanium (HPGe) detector system to explore fine spectral structures in gamma-ray glow emissions. A gamma-ray glow lasting approximately three minutes was successfully detected and confirmed by multiple detectors. The background-subtracted energy spectrum exhibits a clear power-law—like continuum, consistent with bremsstrahlung emission from energetic electrons accelerated in thundercloud electric fields. However, a more detailed analysis based on Monte Carlo simulations revealed several localized deviations from the continuum spectrum. Although these deviations may be regarded as candidate spectral-line features, their statistical significance varied substantially depending on the time interval used to estimate and subtract the background spectrum. Further observations with higher photon statistics are required to determine whether these structures are reproducible features of gamma-ray glow spectra. These results demonstrate the potential of high-resolution gamma-ray spectroscopy for probing detailed spectral structures in thunderstorm-related radiation. Future observations of more intense events with higher photon statistics are expected to clarify the origin of these structures and advance spectroscopic studies of high-energy phenomena associated with thunderstorm.

1. Introduction

High-energy radiation originating from thunderclouds has been extensively studied over the past few decades through observations of terrestrial gamma-ray flashes (TGFs) and long-duration gamma-ray glows [1,2]. Evidence for thundercloud-related high-energy radiation and associated particle acceleration has also been reported in winter thunderstorms in Japan [3]. These phenomena are understood to be produced by energetic electrons accelerated in strong electric fields inside thunderclouds, generating bremsstrahlung gamma rays extending up to MeV energies [3]. Previous observations have successfully established the temporal characteristics and overall spectral properties of gamma-ray glows using scintillation detectors deployed at ground-based and airborne platforms [1,2,4]. These measurements have revealed continuous spectra typically described by power-law—like distributions, supporting models of relativistic electron acceleration in thundercloud electric fields [1,2]. Despite these advances, detailed spectroscopic studies remain limited. The moderate energy resolution of commonly used scintillation detectors makes it difficult to investigate fine spectral structures that may exist on top of the continuum emission. High-resolution spectroscopy has the potential to provide additional observational constraints, but such measurements have rarely been performed in thunderstorm environments, with only limited attempts except for pair annihilation line at 511 keV (e.g., [5]).

In this study, we conducted thunderstorm observations using a high-purity germanium (HPGe) detector to explore gamma-ray glow emissions with high energy resolution. The primary objective is to investigate whether fine spectral structures can be identified beyond the continuum component and to evaluate the capability of HPGe detectors for spectroscopic studies of thunderstorm-related radiation.

2. Experimental setup

The observations were carried out during winter thunderstorms in a mountainous region facing the Sea of Japan, where intense thunderstorm activity frequently occurs during the winter season. The site provides favorable conditions for ground-based detection of high-energy

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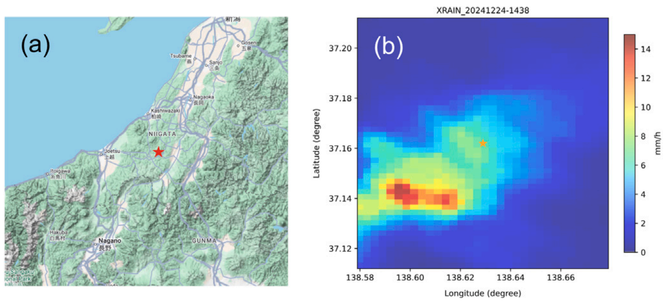

Fig. 1. (a) Geographic location of the observation site (37.162° N, 138.629° E) in Niigata Prefecture, Japan. The red star indicates the detector location. (b) Spatial distribution of precipitation intensity obtained from XRAIN radar data at the time of the event. The color scale represents rainfall intensity in mm/h. The star marks the detector position, showing its location relative to the precipitation cell associated with the event.

radiation associated with thunderclouds. The observation site was located at 37.162° N, 138.629° E, at an altitude of approximately 410 m above sea level. The geographic location of the observation site and the precipitation distribution at the time of the event are shown in Fig. 1. The radar data indicate that the detector was located near an active precipitation region associated with thunderstorm activity.

The primary instrument used in this study was a coaxial high-purity germanium detector (ORTEC, GMX40P4-83). The germanium crystal has a cylindrical geometry with a diameter of 63 mm and a height of 64.6 mm. The detector provides sensitivity over an energy range from approximately 15 keV to 20 MeV, enabling high-resolution gamma-ray spectroscopy over a broad energy domain. The detector was operated continuously during the observation campaign to monitor radiation associated with thunderstorm activity.

In addition to the HPGe detector, a scintillation detector system consisting of BGO, CsI(Tl), and SrI_2 scintillators was deployed at the observation site. The BGO and CsI(Tl) detectors employed rectangular prism crystals with dimensions of 30 mm × 50 mm × 120 mm and 40 mm × 40 mm × 100 mm, respectively, while the SrI_2 detector used a cylindrical crystal with a diameter of 25.4 mm (i.e. 1 inch) and a height of 50.8 mm (i.e. 2 inches). The scintillators were optically coupled to compact photomultiplier tube (PMT) assemblies (R7889EG-PMT-ASSY; [6]), and the output signals were processed using charge-sensitive amplifiers (ClearPulse 5022) and digitized by a multi-channel ADC system (CAEN N6781). Event energies and arrival times were recorded after applying optimized trapezoidal filters, with a time resolution of 10 ns. These scintillation detectors were operated simultaneously with the HPGe detector to monitor count-rate variations during thunderstorm events and to provide complementary measurements of radiation enhancements. [7,8].

3. Data analysis

The data analysis consisted of energy calibration of the detector, construction of background-subtracted spectra to isolate the gamma-ray glow emission, and statistical evaluation of deviations from the continuum spectrum.

Energy calibration of the HPGe detector was performed using environmental gamma-ray lines observed during the measurement period. The calibration employed the 1461 keV line from ^{40}K and the 2614 keV line from ^{208}Tl, which provided stable reference points within the observed energy range. The peak positions of these background lines remained stable to within a few percent across different measurement intervals, indicating no appreciable variation in the energy scale during the observation.

Gamma-ray glow intervals were identified through count-rate enhancements observed during thunderstorm activity in order to construct background-subtracted spectra for subsequent analysis.

To evaluate deviations from the continuum spectrum, the background-subtracted and energy-calibrated glow spectrum was analyzed using a statistical approach based on Monte Carlo simulations, following methods commonly employed in spectral line searches in high-energy astrophysics [9]. A continuum spectral model described by a power-law distribution was constructed to represent the observed glow spectrum. Synthetic spectra were generated by randomly sampling photon energies according to the power-law distribution while keeping the total number of events equal to that of the observed glow spectrum. This procedure was repeated 10,000 times to construct expected statistical distributions for each energy bin. Adaptive binning was applied such that each bin accumulated sufficient counts for statistical evaluation. From the simulated spectra, the mean and variance of counts were obtained for each bin, enabling quantitative evaluation of deviations of the observed spectrum from the continuum expectation.

4. Results

As shown in Fig. 2, a gamma-ray count-rate enhancement lasting approximately three minutes was observed during thunderstorm activity with the HPGe detector. The count rate exhibited a rapid rise followed by a short-duration enhancement before returning to the background level. The sharp temporal variation indicates a sudden change in the radiation environment associated with thundercloud activity. The typical dead time of our multichannel ADC system (CAEN N6781) is less than 100 μs, corresponding to a maximum data acquisition rate exceeding 10 kcps. No evidence of ADC saturation was observed within the count-rate range recorded during the gamma-ray enhancement. Fig. 2 also shows that a coincident increase was observed in the HPGe, BGO, CsI(Tl), and SrI_2 detectors, confirming that the enhancement represents a genuine physical event rather than an instrumental effect. The duration and temporal behavior are consistent with previously reported gamma-ray glow events observed in winter thunderstorms in Japan [1,2], characterized by a minute-scale increase in the gamma-ray count rate followed by a gradual decrease back to the background level.

The glow spectrum was accumulated over an effective exposure time of 180 s, corresponding to the glow interval, whereas the background spectrum was accumulated over a total of 10,000 s using data obtained before and after the enhancement interval. Hereafter, this analysis procedure is referred to as the "normal" analysis condition. The background-subtracted energy spectrum obtained during the glow interval, shown in Fig. 3, exhibits a clear power-law-like continuum over a wide energy range after removal of statistically inconsistent bins used for continuum fitting. As shown in Fig. 3, the spectral shape is well represented by a power-law model, consistent with bremsstrahlung emission from energetic electrons accelerated in thundercloud electric fields, as commonly reported in previous glow observations [1,5]. The best-fit power-law index is $\alpha = 1.76$ in count space. No prominent emission line is immediately visible in the raw spectrum. However, deviations from the smooth continuum become apparent when statistical analysis techniques are applied.

To further investigate possible deviations from the continuum identified in the spectral analysis, the observed spectrum was compared with statistical distributions derived from simulated continuum spectra, as shown in Fig. 4, revealing several localized excesses exceeding the expected statistical fluctuation range. These excesses appear as line-like spectral features distributed within a limited energy region of the spectrum. Several bins exceed the fluctuation levels estimated from simulated power-law continuum spectra, as indicated by deviations beyond the expected statistical bands shown in Fig. 4. These deviations may represent localized spectral-line features, whose peak energies and statistical significance levels are summarized in Table 1. Additional analyses using different event and background intervals — selected

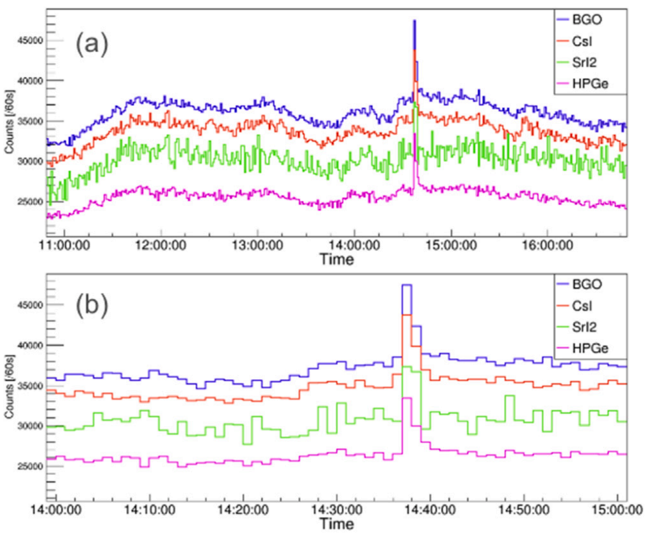

Fig. 2. Time variations of the count rates recorded by the HPGe, BGO, CsI(Tl), and SrI_2 detectors on 24 December 2024 (JST). Panel (a) shows the count-rate variations over a 6-hour period, while panel (b) presents an enlarged view over a 1-hour period around the event. The count rates are shown with a time bin of 60 s. A gamma-ray enhancement lasting approximately three minutes is observed around 14:36–14:39 JST, and simultaneous count-rate increases are detected by all instruments. For clarity, the count rates of the BGO, CsI(Tl), SrI_2, and HPGe detectors are multiplied by factors of 3, 5, 32, and 4, respectively.

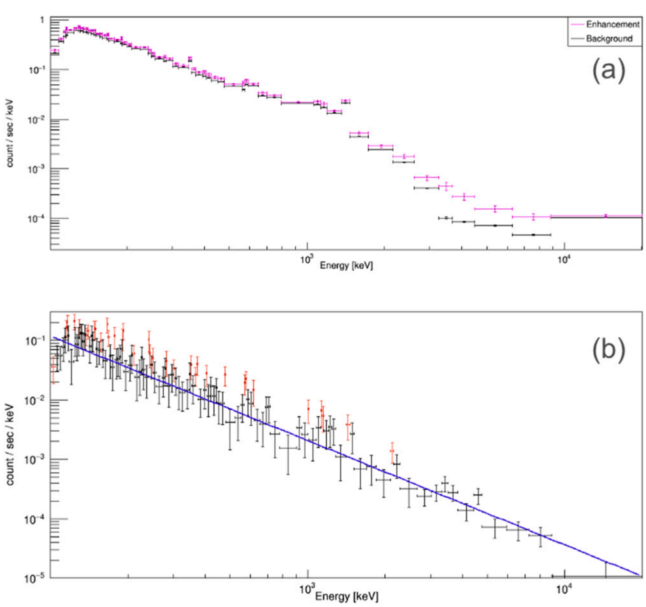

Fig. 3. Energy spectra measured with the HPGe detector during the gamma-ray enhancement event. (a) Energy spectra accumulated during the enhancement interval (magenta, 180 s exposure) and during the surrounding background period (black, 10,000 s exposure). The background spectrum was obtained from data recorded before and after the enhancement interval. (b) Background-subtracted energy spectrum during the gamma-ray enhancement interval together with the best-fit power-law model (blue line). The continuum model was obtained after excluding bins identified as statistically inconsistent with the continuum expectation. Red data points indicate the excluded bins, whose error bars do not overlap with the range of 0.7–1.3 times the initial power-law fit.

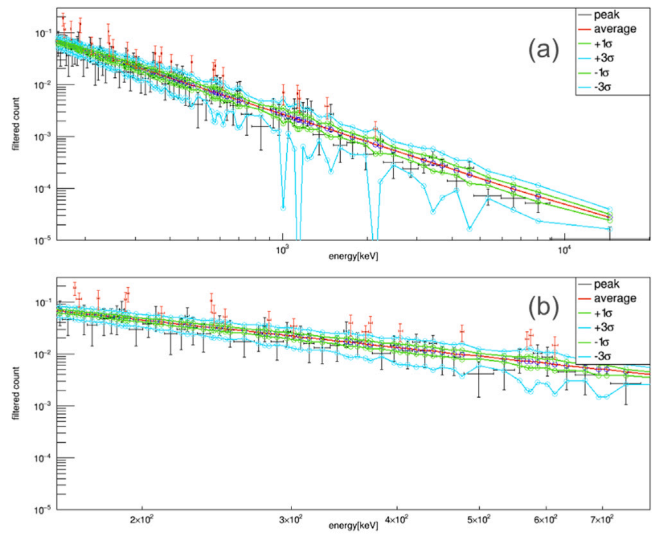

Fig. 4. Statistical evaluation of spectral deviations from the power-law continuum. Panels (a) and (b) show the spectra in the energy ranges of 100 keV–2 MeV and 200–700 keV, respectively. The black points represent the observed spectrum, while the red curve indicates the average spectrum derived from Monte Carlo simulations assuming a power-law distribution with the same total counts and the same exposure time (180 s). The green and cyan curves show the $\pm1\sigma$ and $\pm3\sigma$ confidence regions obtained from 10,000 simulated spectra. Several energy bins exhibit deviations from the expected continuum level, suggesting the presence of line-like spectral structures. The energies and statistical significances of the highlighted candidate features are summarized in Table 1.

Table 1
Candidate spectral features identified through the statistical analysis shown in Fig. 4. The peak energies and statistical significance levels were evaluated using various event and background-estimation intervals in addition to the normal analysis condition.

Peak energy (keV)	Significance (σ)
242	2.44–6.97
372	2.39–6.00
568	1.52–2.81

either before or after the glow interval — revealed excesses in similar energy regions. However, their estimated statistical significance varied from approximately 2σ to more than 6σ, depending on the background interval used. Therefore, these features should be regarded as candidate spectral structures rather than definitive evidence of gamma-ray line emission.

5. Discussion

Gamma-ray glow observations have traditionally relied on scintillation detectors for measuring temporal variations and flux enhancements [1,2]. The present study demonstrates the capability of HPGe detectors for detailed spectroscopic investigation of glow emissions. The identification of deviations from a smooth continuum illustrates that high-resolution measurements allow exploration of spectral structures beyond conventional continuum characterization.

Beyond the instrumental capability demonstrated above, the presence of localized spectral deviations suggests that glow spectra may contain structures not readily observable with moderate-resolution detectors. Even in the absence of a definitive physical interpretation, these observations indicate that additional information may be accessible through high-resolution spectroscopy. Combining monitoring detectors with high-resolution instruments may therefore provide a more comprehensive observational approach to thunderstorm radiation studies.

The present analysis is based on a single glow event with limited photon statistics. Under the nominal analysis conditions, localized spectral features were observed in three energy regions: 242, 372, and 568 keV. These features persisted when different background-selection intervals were used, although their estimated statistical significance varied from less than 2σ to more than 6σ. Therefore, they should be regarded as candidate spectral structures rather than definitive detections of gamma-ray lines. Continued long-term observations using HPGe detectors are expected to accumulate higher-statistics events, enabling more precise spectral characterization. Improved statistics will enhance sensitivity to weak spectral features and clarify whether the observed structures are reproducible characteristics of gamma-ray glow emissions. More intense events with higher photon statistics are expected to reveal these structures more clearly and allow more definitive characterization of their origin.

6. Conclusion

We conducted observations of thunderstorm-associated high-energy radiation using a high-purity germanium (HPGe) detector system during winter thunderstorms in a mountainous region facing the Sea of Japan. A gamma-ray glow lasting approximately three minutes was detected and confirmed by multiple detectors. The measured spectrum exhibited a clear power-law continuum, while statistical analysis revealed several localized deviations from this continuum. These deviations appeared in similar energy regions for different selections of event and background intervals, although their estimated statistical significance varied substantially. Therefore, these features should be regarded as candidate spectral structures rather than definitive detections of gamma-ray lines. This study demonstrates the capability of high-resolution gamma-ray spectroscopy for investigating detailed spectral structures in thunderstorm radiation. Future observations of more intense events are expected to clarify these features and advance spectroscopic studies of thunderstorm high-energy phenomena.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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