PROCEEDINGS OF SCIENCE

Observation of a downward terrestrial gamma-ray flash and the flash-induced neutrons

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A downward terrestrial gamma-ray flash (TGF) occurred in association with a lightning discharge in 2017 November 24th. Observations of the downward TGF was made with scintillation detectors located at the Kashiwazaki-Kariwa nuclear power plant in the coastal area of the Japan Sea. Its intensity was so high that the scintillation counters were saturated, and hence the counters failed to correctly detect the downward TGF. After the intense emission of the TGF, high-energy gamma rays lasting for a few hundred ms were successfully observed utilizing the same scintillation counters. A simultaneous detection of neutrons with other scintillation counters was also performed alongside the detection of high-energy gamma rays. The simultaneous detection indicates the occurrence of photonuclear reactions in the lightning.

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1. Introduction

High-energy bremsstrahlung emissions originating from lightning and thunderclouds have been extensively investigated using various detection systems. These include space-borne detectors [1], detectors deployed at high mountain locations [2], and ground-based detectors at sea level [3]. The measured emissions exhibit energies extending to 10 MeV or higher, which provides evidence that lightning and thunderclouds can accelerate electrons beyond the 10 MeV inside their electric fields. However, lightning-related phenomena generally produce too intense emissions on a short time scale of 1 ms or less to clearly detect the emissions from lightning. Thus, the details of the production mechanism of high-energy gamma rays in an early phase of lightning remain less understood.

It had been proposed that high-energy emissions with energies of 10 MeV or higher could produce neutrons via photonuclear reactions with atmospheric nitrogen and/or oxygen. However, until recently, there was no observational evidence for the occurrence of photonuclear reactions. Instead of directly detecting neutrons produced by photonuclear reactions, Enoto et al. [4] successfully detected prompt gamma rays at 10.8 MeV emitted from nitrogen through the capture of photonuclear neutrons generated inside a lightning discharge, with organic scintillation detectors installed at the coastal area of Japan. Additionally, Bowers et al. [5], using plastic scintillation detectors installed at the same coastal region, detected the Compton edge of 2.223-MeV prompt gamma rays resulting from neutron absorption of hydrogen in the plastic scintillators.

The detection of neutrons generated via photonuclear reactions on the ground requires the presence of intense bremsstrahlung emissions. These emissions, known as downward Terrestrial Gamma-ray Flashes (TGFs), frequently occur during the early stage of lightning. Based on results of two papers [6, 7], we present, in this proceeding, observations of high-energy gamma rays and neutrons, and discuss intense gamma-ray emissions related to a lightning flash and the subsequent photonuclear reactions.

2. Experiments

The Gamma Ray Observation of Winter Thundercloud (GROWTH) experiment has been operating at the coastal area of the Japan sea since 2006. The area is famous for its frequent thunderstorms in winter seasons. The GROWTH experiment aims at elucidating how electrons are accelerated to relativistic energies inside lightning and thunderclouds. To this end, we developed radiation-detection systems [8] at the Kashiwazaki-Kariwa nuclear power plant of Tokyo Electric Power Company Holdings (TEPCO). In the present study, radiation monitoring posts (MPs) were utilized together with our radiation-detection systems.

Figure 1 illustrates the spacial arrangement of our detectors and the MPs within the Kashiwazaki-Kariwa nuclear power plant. In order to measure gamma rays, Detector A, B, and C have $Bi_4Ge_3O_{12}$ scintillators with the size of $25\times8.0\times2.5$ cm^2. The energy range for gamma-ray detection is 0.2−18 MeV for Detector A, 0.2−26 MeV for Detector B, and 0.3−15.0 MeV for Detector C. Detector D incorporates an additional gamma-ray detector, but its data is not presented in this proceeding. In addition to the BGO scintillators used for gamma-ray measurement, each of the four systems is equipped with Ge_2SiO_5 (GSO) scintillators to measure neutrons via neutron capture reactions of

Gd isotopes, which have large capture cross sections. At a thermal energy of 0.025 eV, ^{155}Gd and ^{157}Gd have capture cross sections of 6.1×10^4 and 2.5×10^5 b, respectively. The volume of each GSO scintillator is $2.4 \times 2.4 \times 0.5$ cm^3. Light emitted by the BGO and GSO scintillators is collected by photomultiplier tubes and read by our developed data acquisition systems [8].

Figure 1: The positions of Detectors A-D (red circles) and the MPs (blue circles) operated by TEPCO within the Kashiwazaki-Kariwa nuclear power plant. The original map utilized was taken from Google Map.

The radiation dose monitoring in the nuclear power plant is conducted at nine stations as depicted in Figure 1. Each station consists of a ϕ5.1 cm × 5.1 cm height NaI scintillation detector (NaI) and an ionization chamber (IC). The NaI detector is employed for monitoring low-dose radiation levels, capable of detecting doses up to 10 μGy h^{-1} in the energy range of 0.05−3 MeV. On the other hand, the ionization chamber is designed to monitor high-dose radiation levels, with a detection range of up to 100 mGy h^{-1} in the energy range greater than 0.05 MeV. Both the NaI detector and the IC record radiation doses every 30 seconds.

3. Results and discussions

A thunderstorm took place on November 24, 2017, resulting in radiation enhancements at 10:03:02 UT. The count increases recorded by the BGO counters of Detector A-C and the GSO counters of Detector A-D are presented in Figure 2. Concurrently, radio observations conducted at a location approximately 110 km southwest of the nuclear power plant detected low-frequency (0.8-500 kHz) emissions originating from lightning at 10:03:02.282827 UT. The observed LF emission lasted for approximately 400 ms. Consequently, a consistent temporal correlation is observed between the detection time of the radiation enhancements and the occurrence of the LF emission.

After a detailed analysis using pulse shapes acquired by the BGO counters, we found that our detectors were rendered inoperative for the 10 ms from the lightning flash due to the intense radiation emissions. These emissions are believed to originate from bremsstrahlung processes involving

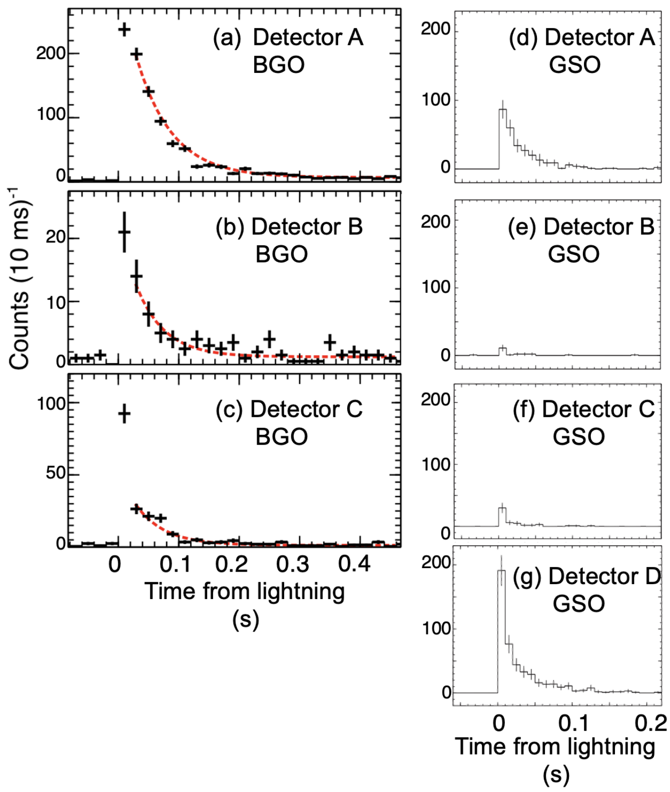

Figure 2: Count histories per 10 ms obtained by the BGO counters and GSO ones. The horizontal axis of each panel represents time elapsed from a lightning discharge, but time duration differs between panels (a)-(c) and panels (d)-(g). Individual red dashed lines in panels (a)-(c) indicate exponential functions derived from the χ^2 fitting. The original figures were sourced from papers of Wada et al. [6, 7], and were subsequently integrated with slight modifications.

electrons accelerated within the lightning flash. While our scintillation detectors experienced saturation because of the overwhelming intensity of the emissions, the ICs of the MPs were sensitive to the intense emission during the early phase of the lightning flash, because their sensitivity to gamma rays is much lower than that of general scintillation detectors.

All ICs of the MPs, with the exception of MP8, demonstrated dose increases accumulated over a period of 30 seconds. Figure 3 presents the doses recorded by the ICs after subtracting the background. The NaI detectors of the MPs also recorded minor does increases, approximately 10^{-4} μGy or less. Extrapolating from the observed dose by the NaI detector of MP9, we estimated a radiation dose up to 10.8 MeV, which correspond to prompt gamma rays emitted from nitrogen after absorbing neutrons, as 2×10^{-3} μGy. This estimated does is less than 1% of the measured IC does by MP9, around 1.4 μGy, implying that similar to the BGO counters equipped with our system, the NaI detector was incapable of correctly recording a full extent of the gamma-ray dose related to the lightning flash. From these measurements, we conclude that a downward TGF occurred in the early phase of the lightning discharge.

As clearly shown in Fig. 3, the ICs situated on the southern side of the nuclear power plant exhibited higher radiation dose enhancements compared to those on the northern side. These IC observations suggest that the origin point of the downward TGF is very likely located on the southern side of the nuclear power plant.

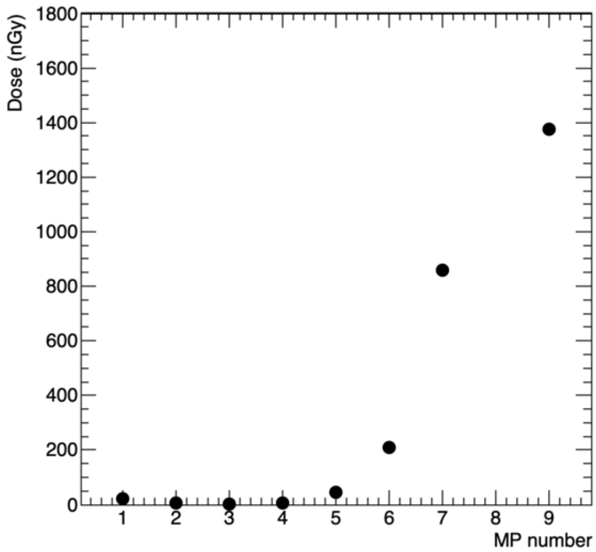

Figure 3: Dose increases obtained by the ICs of MPs except for MP8. The abscissa represents the MP number corresponding to Fig. 1.

As shown in Fig. 2, each radiation enhancement recorded by the BGO counters [panels (a)-(c)] exhibits a rapid onset within 10 ms, followed by an exponential decay characterized by a time constant of 50−60 ms (red lines in Figure 2). The obtained decay constants are in good agreement with those associated with the thermalization processes of neutrons resulting from elastic scattering in the atmosphere [4]. These temporal characteristics provide supporting evidence of the production of neutrons in the lightning flash.

The occurrence times of the count increases obtained by the GSO counters coincide with those of the BGO counters [panels (d)-(g) of Fig. 2]. Furthermore, Figure 4 shows the background-subtracted energy spectra obtained from the GSO counters of Detector A and D. The background was estimated by summing up the data from 10 minutes prior to the downward TGF. The spectra were constructed by the data of 10−200 ms after the occurrence of the downward TGF. A gamma-ray line with an energy of around 80 keV in each spectrum is due to prompt gamma rays emitted by ^{157}Gd. According to the neutron capture tables [10], ^{157}Gd produces 79.5-keV gamma rays via $^{157}\mathrm{Gd} + \mathrm{n} \rightarrow \gamma + {}^{158}\mathrm{Gd}$. The detection indicates that the neutrons arrive at the GSO scintillators within 10−200 ms after the downward TGF. Given these measurements of high-energy gamma rays and neutrons, we conclude that photonuclear reactions occur in this event and produce neutrons with interactions of atmospheric nitrogen and/or oxygen; $^{14}\mathrm{N} + \gamma \rightarrow +^{13}\mathrm{N} + \mathrm{n}$ (threshold 10.55 MeV) and $^{16}\mathrm{O} + \gamma \rightarrow {}^{15}\mathrm{O} + \mathrm{n}$ (threshold 15.66 MeV) [9].

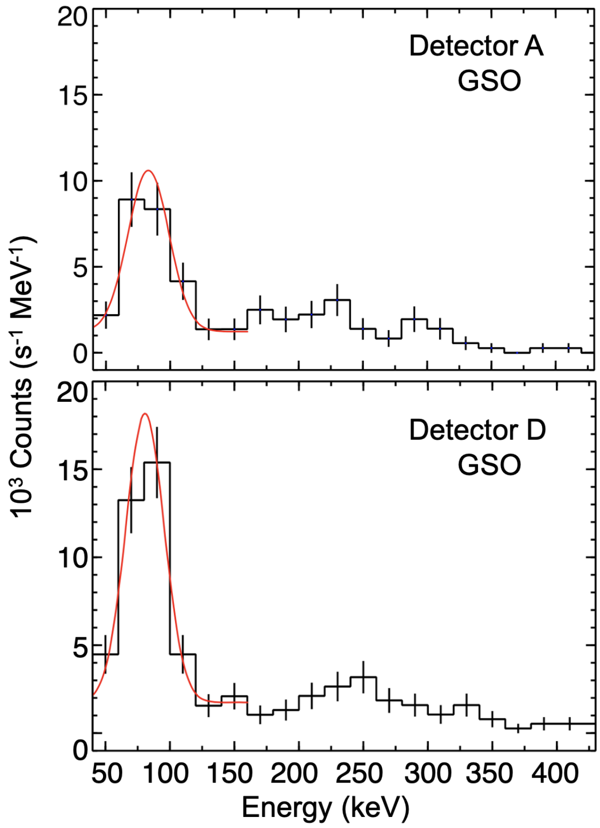

Figure 4: The background subtracted GSO spectra for Detector A (top) and D (bottom). Each red line represents an evaluated line structure by the χ^2 fitting. The original figures were taken from Wada et al. [7] and modified slightly.

4. Summary

During a lightning discharge on 2017 November 24, a powerful downward TGF occurred. Although radiation enhancements were observed by multiple detector systems installed at the Kashiwazaki-Kariwa nuclear power plant, the TGF intensity exceeded the gamma-ray measurement capabilities of the BGO scintillation counters and made them saturated during an period of approximately 10 ms from the TGF beginning. The intense downward TGF triggered photonuclear reactions in the atmosphere and resulted in the production of neutrons. These neutrons underwent moderation through scattering in the atmosphere, and the moderated neutrons were subsequently captured by atmospheric nuclei such as nitrogen. Subsequently, prompt gamma rays emitted from those nuclei were detected by the BGO counters, and neutrons reaching ground were measured by the GSO counters. Additionally, ICs of the MPs operated by TEPCO recorded radiation dose enhancements due primarily to the downward TGF.

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