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Observations of high energy gamma-rays from winter thunderclouds

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Recently, there is a possibility that thunderclouds and/or natural lightning may accelerate electrons to relativistic velocities in their electric fields. Some dose increases associated with winter thunderclouds have been reported along the coastal area of Japan Sea, however the mechanism is still unknown due to lack of detailed information on the types of radiation, short-term intensity variations, and the energy spectra. In order to study those phenomena in further detail, we started "GROWTH (Gamma-Ray Observation of Winter Thunderclouds) collaboration" since 2006. Our new system, installed at the coastal area of Japan Sea, has been successfully operated for two years. We observed two intense dose increases, with a duration around 1 minutes, associated with winter thunderclouds. The measurement clearly revealed that the increase is caused by high energy gamma-rays with a hard spectrum extending up to 10 MeV.

Keywords: thunderclouds, gamma-ray, electron, particle acceleration

1. Introduction

As recent advances of observational technology, it has been revealed that thunderclouds and/or lightning discharges may produce relativistic electrons in their strong electric field. Aircraft or ballon experiments recorded radiation enhancements in thunderclouds [1][2], a ground-based detector at a high mountain reported high-energy radiations above 1 MeV from lightning discharges [3], and a rocket-triggered lightning experiment also gave X-ray or gamma-ray bursts associated with lightning discharges [4][5]. These observational results suggest that a strong electric field in the thunderclouds or lightning discharges accelerates electrons to relativistic energies, and these relativistic electrons and/or bremsstrahlung photons may be detected.

Actually, in Japan, some dose increase, associated with winter thunderclouds, have been reported from the environmental radiation monitoring posts in nuclear power stations along the coast of the Japan Sea [6]. Short intense radiation bursts have been recorded by ionization chambers or NaI scintillators, with a few minute duration during a passage of a strong winter thundercloud. However the mechanism is still unknown due to lack of detailed information on the types of radiation, short-term intensity variations, and the energy spectra.

In order to investigate these phenomena, we started a new experiment "GROWTH (Gamma-Ray Observation of Winter Thunderclouds) collaboration" at Niigata Prefecture in Japan, which is shown in Figure 1. Because winter thunderclouds in Japan appear at a lower altitude (4–6 km) than summer thunderclouds (8–16 km), and is estimated to have more energetic lightnings, it is expected that the bremsstrahlung photons or electron themselves from thunderclouds are easy to reach the ground despite an atmospheric attenuation. So this location has an advantages for the detection of high energy radiations. For a two year operation since 2006, we have successfully detected two gamma-ray (>10 Mev) burst events [7], which is a direct evidence for electron acceleration in the winter thunderclouds.

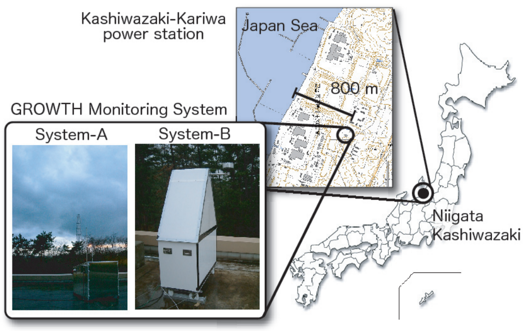

Fig. 1 The location of Kasiwasaki-Kariwa power station, and photons of two radiation detector systems.

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2. Instruments and Observations

GROWTH team designed and manufactured two complementary systems of radiation detectors. System-A (Figure 1 left photo) has a directional sensitivity toward the sky with 40 keV–3.3 MeV energy range, records each event with 10 μsec time resolution. System-B (Figure 1 right photo) has a nearly isotropic sensitivity with wider 40 keV–80 MeV energy range, records spectra every 6 sec, and acquires count rates every 1 sec.

Figure 2 top panel is a cross-sectional view of System-A. Two cylindrical NaI scintillators (3"$\phi\times$3"h) are surrounded by well-type BGO ($Bi_4Ge_3O_{12}$) active shield scintillators (a typical thickness of $\sim$0".5), in order to exclude environmental background radiations from the ground (mainly below 2.6 MeV) with an anti-coincidence method. When the background event came from the ground or from side-way, we can distinguish the background one, if NaI was triggered just after after Compton scatterings at the BGO scintillator. Using this method, we can eliminate the contaminating event from NaI event data with a efficiency of $\sim$60%. This concept of an active shielding is adopted from the Hard X-ray Detector on board the 5th cosmic X-ray astronomy satellite *Suzaku*. As a consequence, System-A achieves a directional sensitivity toward the sky. Furthermore, a plastic scintillator (thickness of 5 mm) was installed above these NaI and BGO scintillators, in order to discriminates charged particles from X-ray/gamma-ray photons.

On the other hand, System-B comprises spherical NaI and CsI scintillators (3" radius) which has a almost isotropic sensitivity. Some other environmental sensors such as optical light sensors, a sound sensor, and a electrical field sensor was utilized in System-A and System-B.

We installed these detector systems in the Kashiwasaki-Kariwa nuclear power station in late December 2006. Two systems are placed with a separation of $\sim$10 m at the rooftop of one building. These two system have been successfully operated until now during the winter month for two years since 2006. Figure 3 shows long-term count rate histories of BGO active shield of System-A, recorded for the first two week just after the install. Long-term dose increases in Figure 3 are mainly due to fallouts atmospheric radons associated with rainfall or snowfall, which are recognized by a characteristic nuclear line spectra decaying in several hours.

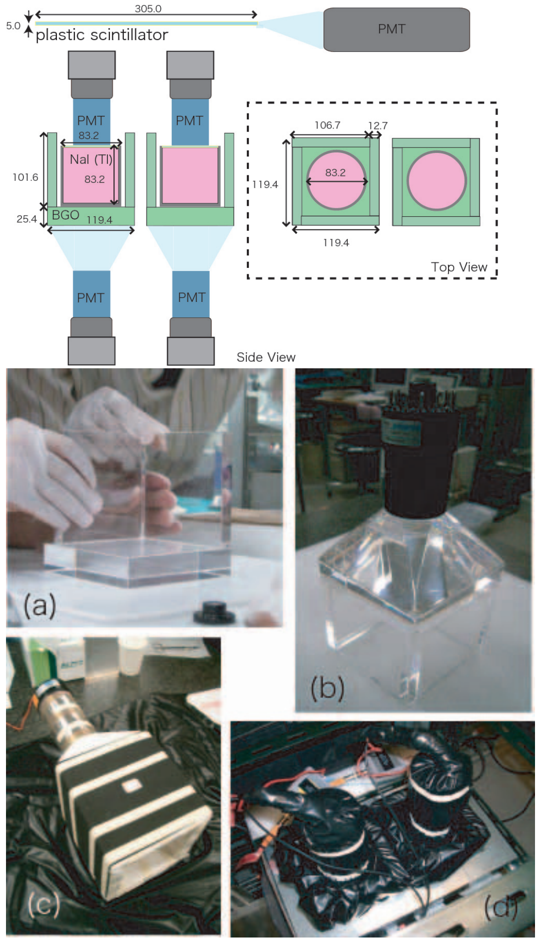

Fig. 2 (Top) Cross-sectional view and top view of our radiation detector System-A (mm scale) [7]. (Bottom) Manufacturing of the well-type BGO active shields of System-A.

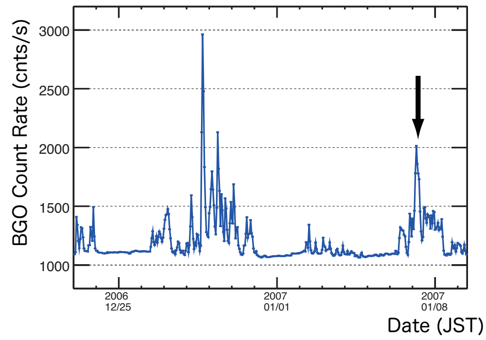

Fig. 3 Long-term count rate (per 1 second) histories of the BGO active shield of System-A, recorded for two weeks. An arrow in the figure shows the arrival time of gamma-rays from thunderclouds.

3. Gamma-ray Burst Events

Nearly two weeks later after the start of the observation, two low pressure systems united above the Japan Sea into a intense one from January 6th to 7th (JST [1]) in 2007. Corresponding constant pressure charts are shown in Figure 4 top panels. During this strong thunderclouds activity, we have success-

[1] JST (Japan Standard Time) precedes UT at nine hours.

fully detected a clear dose increase, which is shown in in the Figure 3 as a arrow. This event was not associated with the radon fallout but with an thundercloud activity.

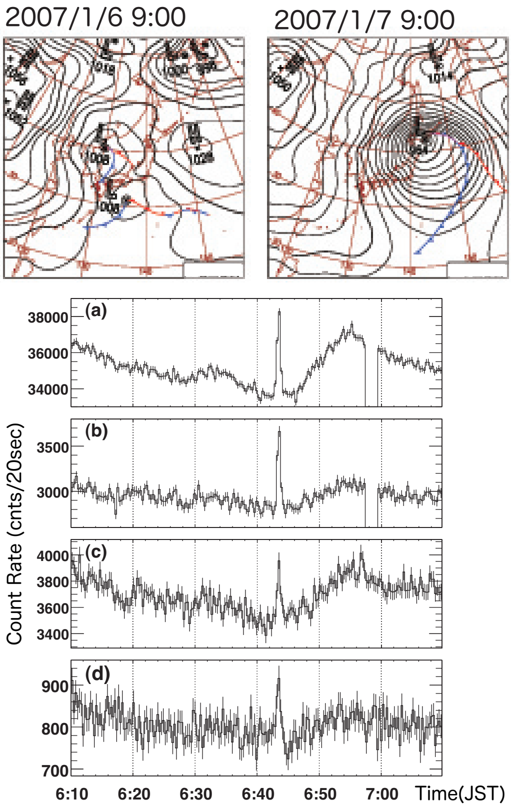

Fig. 4 (Top) Constant pressure charts around the first gamma-ray event from a webpage of Japan Meteorological Agency. (Bottom) radiation count rates around the first gamma-ray event [7]. (a) Count rate of the BGO active shield of System-A (above 40 keV). (b) that of the NaI scintillator of System-A (above 40 keV). (c) that of the NaI scintillator of System-B (above 40 keV). (d) that of the CsI scintillator of System-B (above 600 keV).

Figure 4 bottom a-d panels illustrate count rates for one hour acquired by four individual detectors, the NaI and BGO of System-A, and NaI and CsI of System-B. The short enhancement, or "burst" event was recorded by all the scintillators lasting for ~1 minutes with an enough significance. The occurrence time is January 7 6:43 on 2007 (JST).

Figure 5 a and b are detailed radiation count rates between 6:40 and 6:50 (JST) around the burst, for NaI (>3 MeV) of System-A, and for NaI/CsI (3–10 MeV) of System-B. High energy radiation above 3 MeV prominently detected during the burst, the excess counts above 3 MeV around the burst (36 sec) of NaI/System-A became ~130 and ~43, without and with BGO anti-coincidence, respectively. While that became ~74 and ~53 counts in 3–10 MeV for NaI and CsI of System-B, respectively. Count rates of the plastic scintillator (Figure 5 e) did not exhibit significant enhancement during the burst, so this event is dominated by photon rather than charged particles (e.g. electrons). In addition, at ~70 second after this burst, the optical and electric field sensors recorded 5 lightning discharges signals (Figure 5 c–d), we can confirm an enhanced thunder activity during this period.

Figure 6 demonstrates background-subtracted energy spectra acquired by System-A and System-B. The gamma-ray spectra had no nuclear line feature originating from environmental radiation, and extended up to ~10 MeV, with a typical power-law photon index of Γ=1.7±0.1 determined in the 0.6–10 MeV range of System-B.

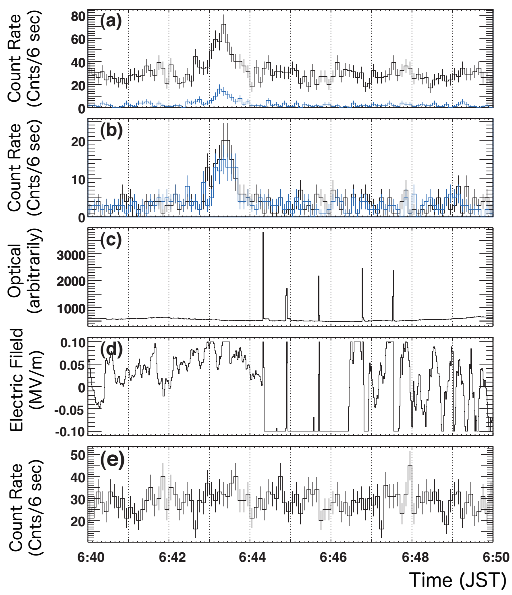

Fig. 5 Radiation count rates and environmental sensor variations around the first gamma-ray event on 2007 January 7 (JST) [7]. (a) NaI count rate of System-A above 3 MeV (black) and that after anti-coincidence by the BGO active shield (blue). (b) NaI (black) and CsI (blue) count rates of System-B in the 3–10 MeV band. (c) Intensity of the optical sensor in the arbitrary unit. (d) Count rate of the plastic scintillator of System-A, which is more sensitive to particles than photons.

In addition to this gamma-ray detection, during next year observation, we detected one more gamma-ray event on December 14th in 2007. A constant pressure chart at this event, resembling that of the first event, had a intense low pressure system above the Japan Sea. The gamma-ray burst lasted for ~66 sec, its spectrum extended up to nearly 10 MeV. Lightning discharges were recorded ~130 second before the gamma-ray burst, which is different from the first event. Nearest two monitoring posts in the nuclear station also detected this radiation enhancement a few minutes later after our detection of the burst, which

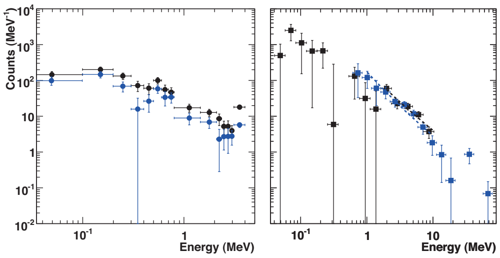

Fig. 6 Energy spectra of the first gamma-ray event from a winter thundercloud on 2007 January 7 (JST) [7]. (Left) Acquired by NaI scintillator of System-A, without (black) and with (blue) the anti-coincidence by the BGO. (Right) acquired by NaI (black) and CsI (blue) of System-B.

delay may be due to moving thunderclouds.

4. Discussion

What is a radiation mechanism of these high-energy gamma-rays up to 10 MeV? It is considered that the developed winter thunderclouds usually has a three charged layer structure like Figure 7 [9]. Strong electric fields seem to emerge in the bottom part of the cloud. Cosmic rays, going through this region, induces some high energy seed electrons to drop out from the air molecules, and these electrons can be accelerated up to relativistic energies by the strong electric fields, through a process known as an avalanche amplification (relativistic runaway electron avalanche model) [10][11]. A runaway region of these relativistic electrons are shown in Figure 8 (energy loss curve of an electron in the 1 atmosphere). Decelerating by the atmosphere, these relativistic electrons radiate bremsstrahlung gamma-rays, which can reach the detectors on the ground. Because the bremsstrahlung photons may be beamed toward the forward direction of electron motion, a beam-like radiation cone is expected to sweep the ground. The duration of enhancement may be explained by the motion of this cloud above our detectors, with a typical speed of the thundercloud. The subsequent lightning discharges may be produced by this strong electric field.

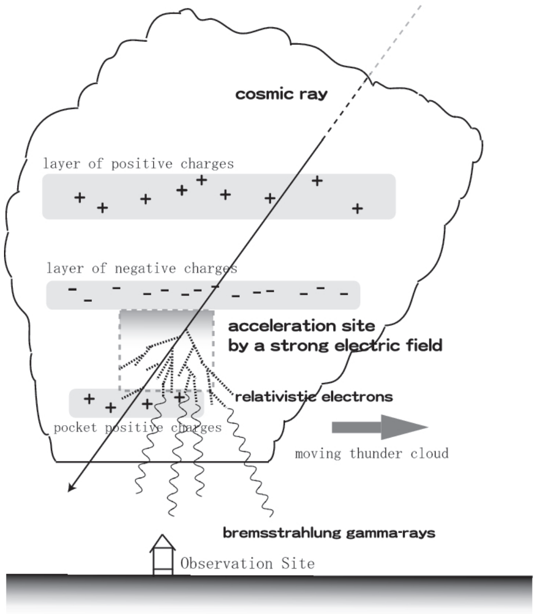

Fig. 7 Imaginary picture for the generating mechanism of the gamma-rays.

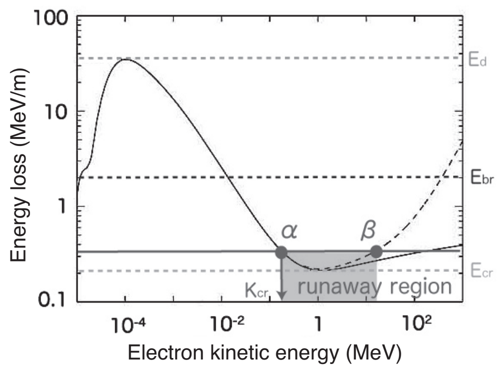

Fig. 8 Energy loss of an electron in the 1 atmosphere, modified from a figure in [8]. A solid line shows only an ionization loss, while a dashed line shows an additional bremsstrahlung effect.

Acknowledgements

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