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Detection of gamma-rays from winter thunderclouds along the coast of Japan Sea

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Abstract: Recently, it has been revealed that thunderclouds and lightning discharges may produce relativistic electrons and gamma-rays. In Japan, there are a few reports on radiation detections associated with winter thunderclouds along the coast of the Japan Sea. However, little is known about type of the radiation, its duration, and its spectra. In order to better understand the phenomenon, a new experiment has been conducted since late December in 2006 at Niigata Prefecture in Japan. Independent two radiation detectors were set up, one with its sensitivity maximized toward the zenith direction, and the other with an omni-directional sensitivity. Through 5 monthsof observation, an intense burst of gamma-rays was detected by both instruments, on 2007 January 6 UT 21:43. The event lasted for $\sim$1 minutes, preceding lightning discharges by 70 sec. The burst was detected with inorganic scintillators up to $\sim$10 MeV but was undetectable with a plastic scitillator. This implies that the burst consisted mainly of bremsstrahlung gamma-rays from relativistic electrons accelerated by the strong electric fields in the thunderclouds.

Introduction

Along with recent advances of observation technology, it has been revealed that thunderclouds and lightning discharges are an interesting laboratory of high-energy phenomena. Observations with satellites, aircraft, balloons, and ground-based detectors detected high-energy radiation associated with lightning discharges [1] or thunderclouds [2]. Active experiments using rocket-triggered lightning also gave positive results [3]. These results suggest that electrons are accelerated to relativistic energies in the electric fields of thunderclouds and/or lightning discharges, and emit bremsstrahlung photons.

In Japan, such events have been observed by the environmental radiation monitoring posts in nuclear power plants along the coast of the Japan Sea [4]. Ionization chambers and NaI scintillators of these posts recorded short intense bursts with several sec duration, and dose increases for a minute or two, associated with winter thunderclouds. However, at present, little is known about the types of radiation of these phenomena. Detailed time variations, energy spectra, and arrival directions of these events are yet to be clarified as well. In order to address these issues, we have started a new experiment at Niigata Prefecture in Japan. Through 5 months of data taking from late 2006 December, we have successfully detected one event of burst-like gamma-ray emission up to $\sim$10 MeV.

Instruments and a site of observations

We designed and manufactured two complementary types of radiation detectors. One (System-A) has a directional sensitivity toward the zenith, and the other (System-B) has a nearly isotopic sensitivity. Figure 1 (top) shows the appearance of these detector systems.

System-A uses two sets of identical 3”$\phi \times$ 3” h NaI scintillators as main detectors, which operate in 40 keV–3.3 MeV and record each detected event with 10 μsec time resolution. To exclude environmental background gamma-rays below 2.6 MeV mainly from the ground, including in particular those from ^{40}K and ^{208}Tl, the main NaI scintillators are surrounded by well-type active BGO scintillator shields with a thickness of 0”.5 on the side and 1” on the bottom. This concept of active shield is adopted from the Hard X-ray Detector on board the cosmic X-ray astronomy satellite *Suzaku*. Figure 1 (middle) illustrates this well type structure. When an environmental gamma-ray enters the detector from sideways, we can eliminate it from the NaI data with a typical efficiency of $\sim$60%, just using its Compton energy deposit in BGO. As a result, system-A has an enhanced sensitivity toward the zenith. In addition, a plastic scintillator with 5 mm, placed above the NaI and BGO, discriminates charged particles from photons.

System-B utilizes spherical NaI and CsI scintillators both with 3” radius. This system does not adopt the anti-coincidence method, so that it has an almost isotropic sensitivity. These detectors have a wide energy range over 40 keV–80 MeV, and acquire multi-channel spectra every 6 sec. Broadband count rates are also recorded every 1 sec.

In addition to these two radiation detectors, some environmental sensors such as light sensors, a sound sensor, a electrical field sensor can monitor the surrounding environment.

In late December in 2006, we set up these detectors in the Kashiwasaki-kariwa nuclear power plant. Winter thunderclouds along the Japan Sea occur when strong monsoons from high pressure systems covering the Asian continent hit the island of Japan. The produced clouds have much lower altitudes (typically $\sim$5 km) compared to the summer thunderclouds. This low altitude gives an advantage for the detection of their high energy emission, because gamma-rays are strongly attenuated as they pass through atmosphere. In fact, at this site there have been some reports on radiation increase associated with thunderclouds, a few times a year, made by fixed-point observations as a part of nuclear plant operation.

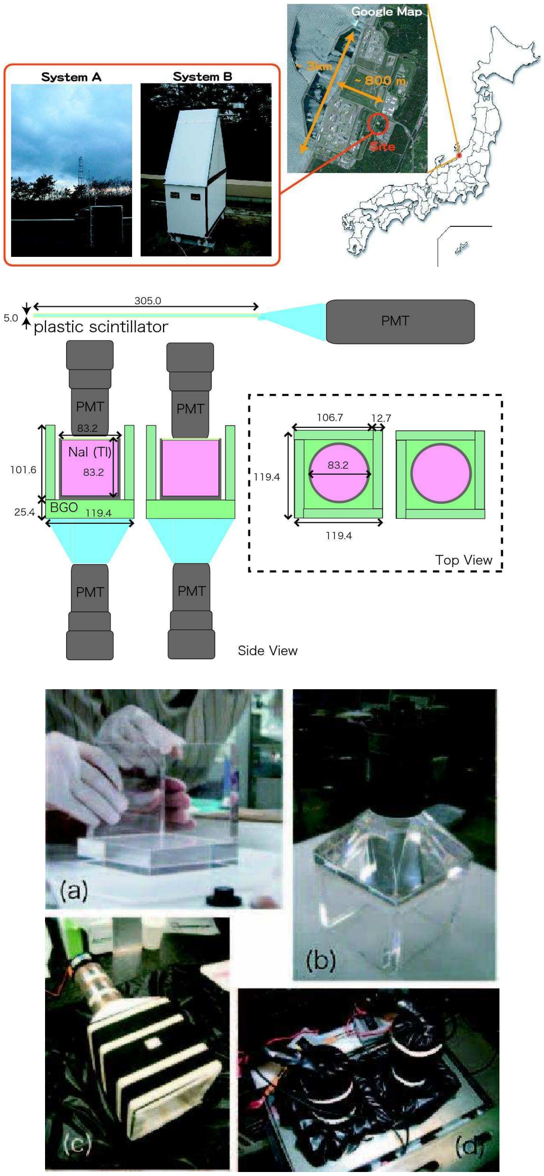

Figure 1: (Top) The location of Kashiwasaki-kariwa in Japan, and the appearance of two radiation detectors. (Middle) Cross-sectional view and top view of the radiation detector System-A. (Bottom) Manufacturing of the well-type BGO active shields of System-A.

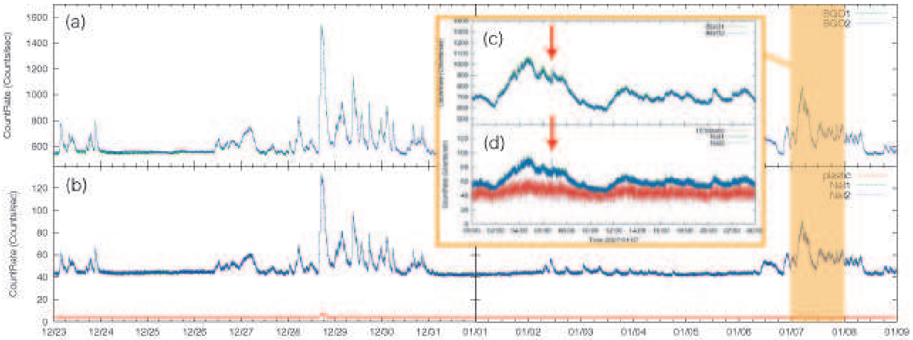

Figure 2: (a) Long-term (16 days) count-rate (per 1 sec) histories of the BGO active shield of System-A. (b) Those of the System-A NaI (blue) and the plastic scintillator (red). (c)(d) Details of panels (a) and (b), focusing on 2007 January 7 (JST). Count rates of the plastic scintillator are multiplied by a factor of 10.

Detection of the gamma-rays

Figure 2 illustrates count rate histories of the NaI, BGO and plastic scintilltars of System-A, acquired in the first 16 days after their install. During rainfalls or snowfalls, fallout atmospheric radons increase the environmental radiation by a factor of 2 or 3, with a characteristic nuclear line spectra which decays in several hours.

During the early one month observation, we have successfully detected a clear dose increase, lasting for $\sim$1 minutes, which is not associated with radon fallouts but with an enhanced thunder activity. The time of occurrence of this event, January 6 21:43 on 2007 (UT) is indicated in figure 2 as a red allow. On this day, two low-pressure systems merged together above the Japan Sea, producing one of the strongest thunder storms in this winter. Figure 3 shows detailed count-rate histories of this event from individual detectors.

In figure 3, all the four scintillators, the NaIs and BGOs of system-A, and the NaI and CsI of system-B, recorded the increases with $\sim$1 minute duration. In addition, at $\sim$70 seconds after this enhancement, the optical and electric field sensors recorded 5 lightning discharges.

The count rate increase is statistically significant, because the hypothesis that the count rate is constant was rejected by a chi-square test with reduced chi-square $\sim$3 for NaI, and $\sim$8 for BGO. The possibility of electrical noise is also rejected, because a reference detector, a photo multiplier tube without scintillator, did not detect any increase. The count rate of the plastic scintillator (figure 3-d) did not exhibit significant enhancement over this period, so the signal is dominated by photons rather than charged particles such as electrons. In addition, the ratio between the NaI and BGO counts during the increase period is higher than those for environmental signals, meaning that the photons came from the sky rather than from the ground.

Figure 4 shows background-subtracted the energy spectra from System-A and System-B. The detected gamma-rays extend up to 10 MeV, with a power-law photon index of $\Gamma = 1.66 \pm 0.13$ in the high energy range.

Discussion and conclusion

How are these gamma-rays produced? It is considered that developed winter thunderclouds have a strong electric field at their bottom. When cosmic rays go through this region, some high energy seed electrons are generated from the air molecules, and are accelerated to relativistic energies by the strong electric fields through a process known as an avalanche amplification (relativistic runaway electron avalanche model) [5]. The observed gamma-rays are likely to be bremsstrahlung radiation from these high energy electrons. Because the bremsstrahlung photons are 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 cone above our detectors, with a typical speed of the thundercloud [6]. The subsequent lightning discharges may be produced by this strong electric field.

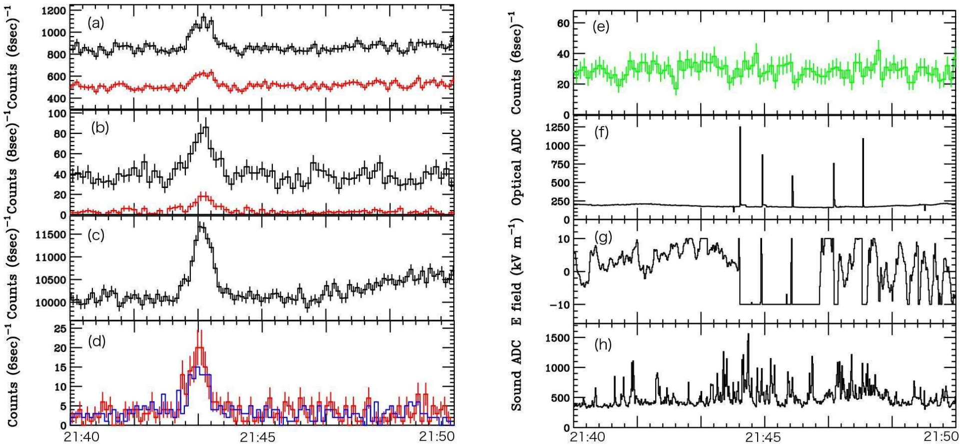

Figure 3: (a) The NaI count rate (>40 keV) of system-A with (black) and without (red) anti-coincidence. (b) The same as panel (a) but in energies above 3 MeV. (c) The BGO count rate (>40 keV) of system-A. (d) The NaI (red) and CsI (blue) count rates in 3-10 MeV of system-B. (e) The plastic scintillator count rate (>1 MeV) of system-A. Panels (f), (g), and (h) are outputs from the optical, electric-field, and sound sensors, respectively.

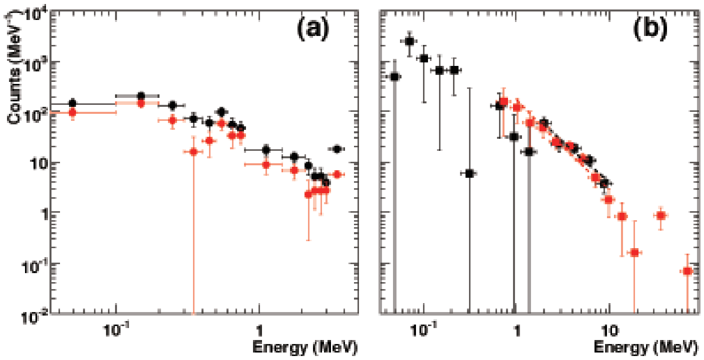

Figure 4: The background-subtracted energy spectra of (a) System-A and (b) System-B, both accumulated over a 36 sec interval around the burst peak.

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