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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 on 2006 at Niigata Prefecture in Japan. Independent two radiation detectors were set up, one with its sensitivity maximized toward zenith direction, and the other with an omni-directional sensitivity. During half a year observation, an intense burst of gamma-rays were 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, implying 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 may produce high energy radiation. Observations with satelllites, aircraft, balloons, and ground-based detectors detected high-energy raditaion associated with lightning discharges [5] or thunderclouds [2]. Active experiments using rocket-triggered lightning also gave positive results [1]. 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 [6]. Ionization chambers and NaI scintillators of these posts recorded short intense bursts with several sec duration, and dose increses for a minute or two, associated with winter thunderclouds. However, at present, little is known about the types of radiation of these phenomena. Detailded time variations, energy spectra, and arrival directions of these events are yet to be clarified as well. In order to solve this mystery, 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 has a directional to the zenith direction (System-A), and the other has a nearly isotopic sensitivity (System-B). 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 paticular those from ^{40}K and ^{208}Tl, these main NaI scintillators are surrounded by well-type active BGO scintillator shields with 0.5” side thichkness and 1” bottom thickness. This concept of active sheild scintillator is adopted from the Hard X-ray Detector on board 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 such events from the NaI data with a typical efficiency of ~60%, just using its Compton energy deposite in BGO. As a result, system-A has an enhanced sensitivity toward the zenith. In addition, a plastic scintillator with 5 mm thickness was placed above the NaI and BGO, discriminates charged particles from photons.

System-B utilizes spherical NaI and CsI scintillators with 3” radius, and a spherical plastic scintillator with 25 cm radius. This system does not adopt the anti-coincidence method, so that it is 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 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 surrouding environment.

Late December in 2006, we set up these detectors in the Kashiwasaki-kariwa nuclear power plant. Winter thunderclouds along the Japan Sea occurs when strong monsoons from high pressure systems covering the Asian continent hit the island of Japan. Therefore, the clouds have much lower altitudes (typically ~5 km) compared to the summer thundercloud. 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 increse associated with thunderclouds, a few times a year, made by fixed-point observations as a part of nuclear plant operation.

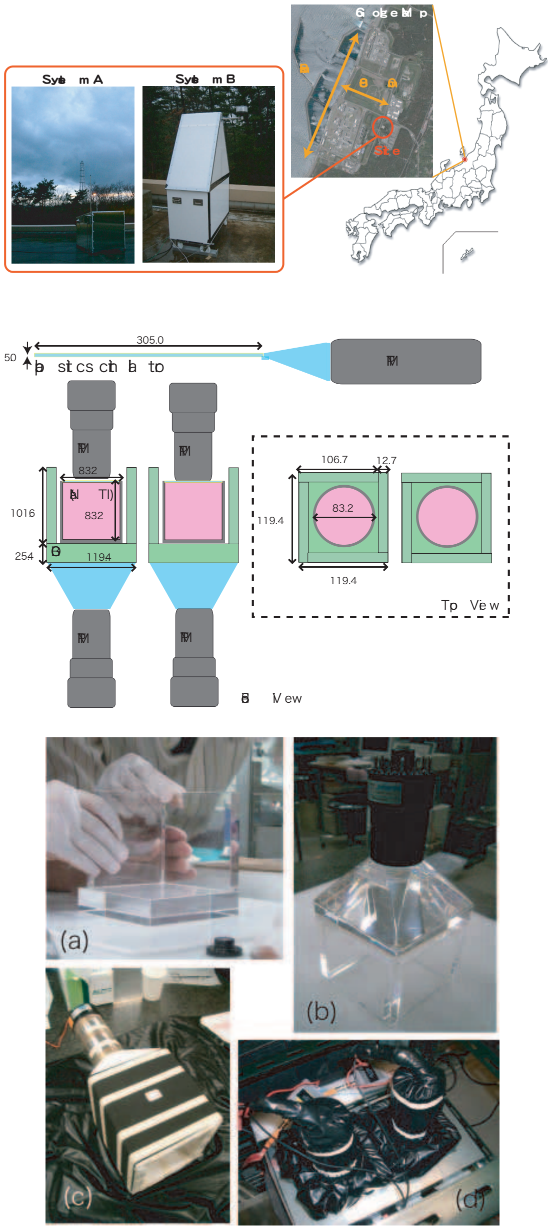

Figure 1: (Top) The location of Kashiwasaki-kariwa in Japan, and the appearance of two radiation detectors. (Middle) Cross-sectional view and top view of the radiation detector System-A. (Bottom) Manufacturing of well-type BGO active shields of System-A.

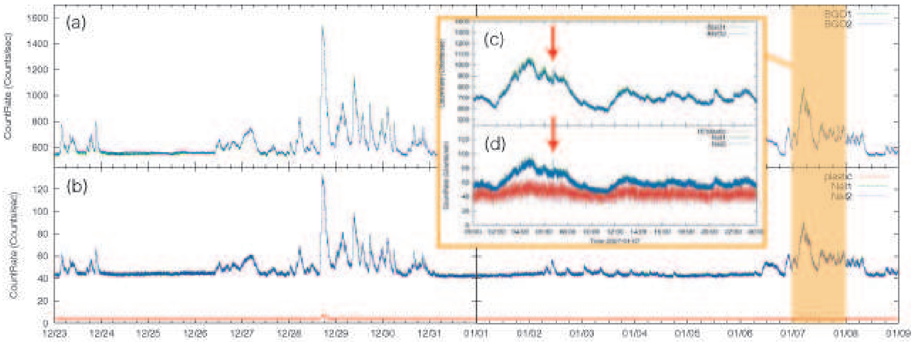

Figure 2: (a) Long-term (16 days) count-rate (per 1 sec) histories of the BGO active shield of System-A. (b) Those of the System-A NaI (blue) and the plastic scintillator (red). (c)(d) Extended details of panels (a) and (b), forcusing on 2007 January 7 (JST). Count rates of the scintillator are multiplied by a facor 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 increse the environmenal 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 occurance of this event, January 6 21:43 on 2007 (UT) is indicated in figure 2 as a red allow. On this day, above the Japan Sea two low-pressure systems merged together, producing a 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 increses with $\sim$1 minute duration. In addition, at $\sim$70 seconds after this enhancement, the optical and electric field sensors recorded 5 lightning discahrges.

The count rate increase is statistically significant, bacause the hypothesis that the count rate is constant was rejected by a chi-square test with reduced-chisquare $\sim$3 for NaI,and $\sim$8 for BGO. Next, the possibilitiy of electrical noise is also rejected, because a reference detector, a photomultiplier 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 NaI and BGO counts during the increse period is higher than those of for environmental signals, meaning that the photons came from the sky rather than from the groud.

Figure 4 shows 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 theier 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) [4]. The gamma-rays which observed are likely to be bremsstrahlung gamma-rays from these high energy electrons. Because the bremsstrahlung photons are beamed toward the electron motion, a beam-like radiation cone is expected to sweep the ground. The duration of enhancement corresponds to the motion of this cone above our detectors, with a typical speed of the thundercloud [3]. The subsequent lightning discharges may be produced by this strong electric field.

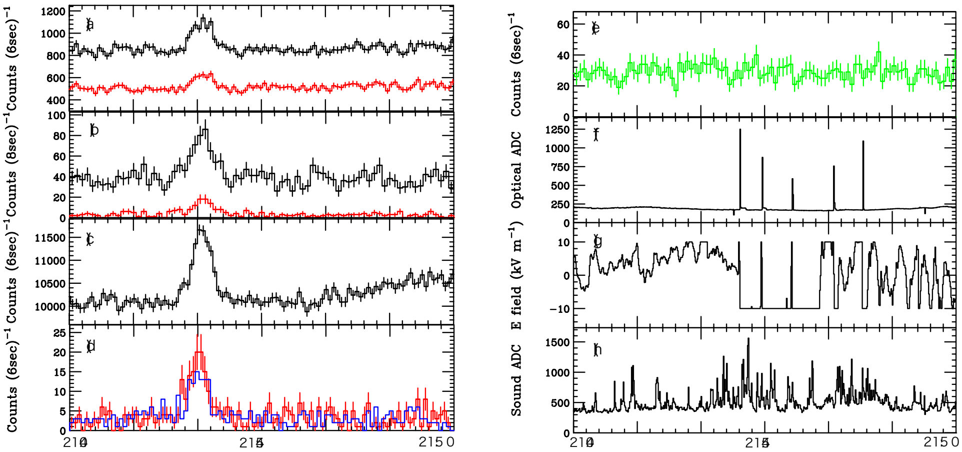

Figure 3: (a) The NaI count rate (>40 keV) of system-A with (black) and without (red) anti-coincidence. (b) The NaI count rate (>3 MeV) of system-A with (black) and without (red) anti-coincidence. (c) The BGO count rate (>40 keV) of system-A. (d) The NaI (red) and CsI (blue) count rates in 3-10 MeV of 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.

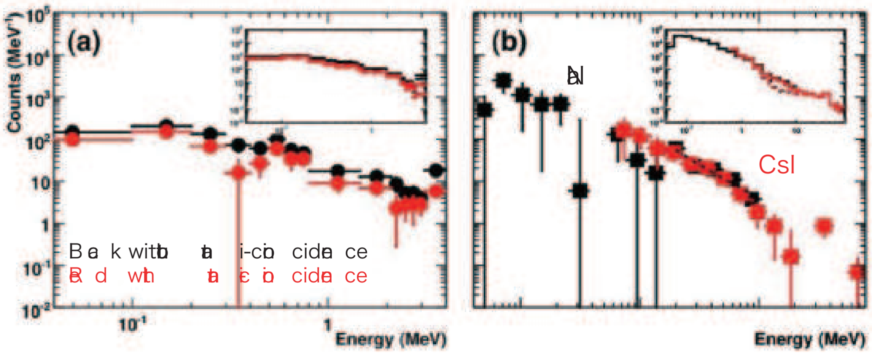

Figure 4: The background-subtracted energy spectrums of (a) System-A and (b) System-B, both accumlated over a 36 sec interval around the burst peak. The insets show the source (black) and background (red).

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