論文の内容の要旨

Observational Studies of Photonuclear Reactions Triggered by Lightning Discharges

(雷放電による光核反応の観測的研究)

和田 有希

Lightning and thunderstorms are closely associated with high-energy phenomena in the atmosphere. Terrestrial gamma-ray flashes (TGFs) are powerful and instant emissions coincident with lightning discharges. They were serendipitously discovered by an in-orbit satellite in 1991, and are now routinely detected by successive gamma-ray satellites. TGFs are thought to originate from bremsstrahlung emissions of energetic electrons accelerated and multiplied by strong electric fields in lightning.

In addition to space-borne observations of TGFs, on-ground experiments have also detected high-energy phenomena in thunderstorms. We have performed the Gamma-Ray Observation of Winter thunderclouds experiment during winter thunderstorms in Japan since 2006. During more than 10 years of its operation, minute-lasting gamma-ray glows and sub-second-lasting short bursts have been detected. Gamma-ray glows were also found to be bremsstrahlung emissions of energetic electrons accelerated by quasi-stable electric fields inside thunderclouds. However, the origin of short bursts was unresolved due to insufficient observations with a single detector, while they are clearly distinguished from TGFs by their longer duration.

At the same time, a possibility of atmospheric photonuclear reactions in lightning and thunderstorms such as $^{14}N + \gamma \rightarrow {}^{13}N + n$ has been discussed because TGFs and gamma-ray glows contain photons of >10 MeV, high enough to trigger this reaction. The reaction emits a fast neutron and a proton-rich radioactive nucleus ^{13}N. Since ^{13}N decays with a half-life of 10 minutes and emits a positron, the annihilation line at 0.511 MeV should be detected. In fact, detections of neutrons and positrons have been reported separately, and they have thought to originate from photonuclear reactions in the atmosphere. However, such separated detections of neutrons and positrons cannot rule out possibilities of neutron productions by nuclear fusions or positron productions by pair creations. Therefore, a simultaneous detection of neutrons and positrons is the definitive way to demonstrate photonuclear reactions in lightning.

For further understanding of gamma-ray glows and short bursts, we developed brand-new compact gamma-ray detectors. We deployed them at multiple observation sites in Kashiwazaki and Kanazawa, coastal areas of the Sea of Japan, and started a new mapping observation campaign in 2016. The Kashiwazaki site, operated since 2006, was improved with four gamma-ray detectors.

On February 6th, 2017, the four detectors in Kashiwazaki successfully recorded a short burst simultaneously, lasting for ~200 ms. In the beginning of the short burst, the detectors were heavily saturated by a strong gamma-ray flash. Furthermore, two of them recorded an afterglow lasting for tens of seconds immediately after the short burst. The energy spectra of the afterglow are shown in Figure 1. There is a clear spectral line at 0.511 keV, suggesting positron

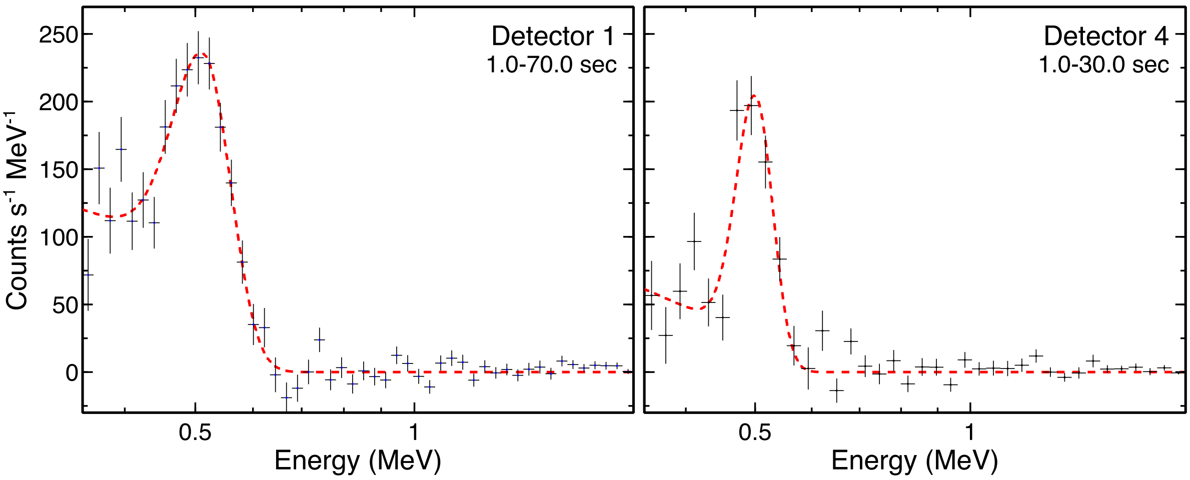

Figure 1: Background-subtracted spectra of a sub-minute emission after the short burst on February 6th, 2017. Source spectra are extracted from 1 sec< t <70 sec and 1 sec< t <30 sec for Detectors 1 and 4 respectively, where *t* is an elapsed time from the beginning of the short burst. Best-fit models of a gaussian plus a quadratic function are overlaid with red-dotted lines.

annihilation around the detectors. These observational features are interpreted to originate from atmospheric photonuclear reactions in lightning as follows:

- A lightning discharge produced an enormous number of gamma rays. This phenomenon is similar to TGFs observed from space, but going downward, called "downward TGF". Gamma-ray photons of the downward TGF reaching the ground saturated the detectors.
- Gamma-ray photons of >10 MeV triggered photonuclear reactions with ^{14}N and ^{16}O in the atmosphere, and produced fast neutrons and β^+-decay nuclei such as ^{13}N and ^{15}O.
- Fast neutrons were thermalized by multiple elastic scatterings with atmospheric nuclei, and disappeared by neutron captures or charge-exchange reactions with ^{14}N.
- ^{15}N in an excited state by neutron captures emitted de-excitation gamma rays. These gamma rays were detected as the short burst.
- Proton-rich nuclei ^{13}N and ^{15}O emitted positrons via β^+-decay with a half-life of 10 and 2 minutes, respectively. Gamma-ray detectors recorded annihilation gamma rays when these nuclei were passed over with ambient wind.

In addition to the short burst on February 6th, 2017, two short bursts in Kashiwazaki and two in Kanazawa were detected. All the detected short bursts were confirmed to originate from atmospheric photonuclear reactions. This is the first time to demonstrate the occurrence of photonuclear reactions in lightning by both neutron and positron signatures.

For quantitative evaluation of photonuclear reactions and downward TGFs, we performed Monte-Carlo simulations. First, we considered all the major photonuclear channels including photoneutron productions without β^+-decay nuclide production. Starting from energetic electrons produced in lightning, spatial distributions of photoneutrons and β^+-decay nuclei were obtained, as shown in Figure 2. Based on the distributions, atmospheric propagation of neutrons and positrons from the β^+-decay nuclei were calculated, and spectral models were constructed. In addition, models of on-ground doses by downward TGFs were also made.

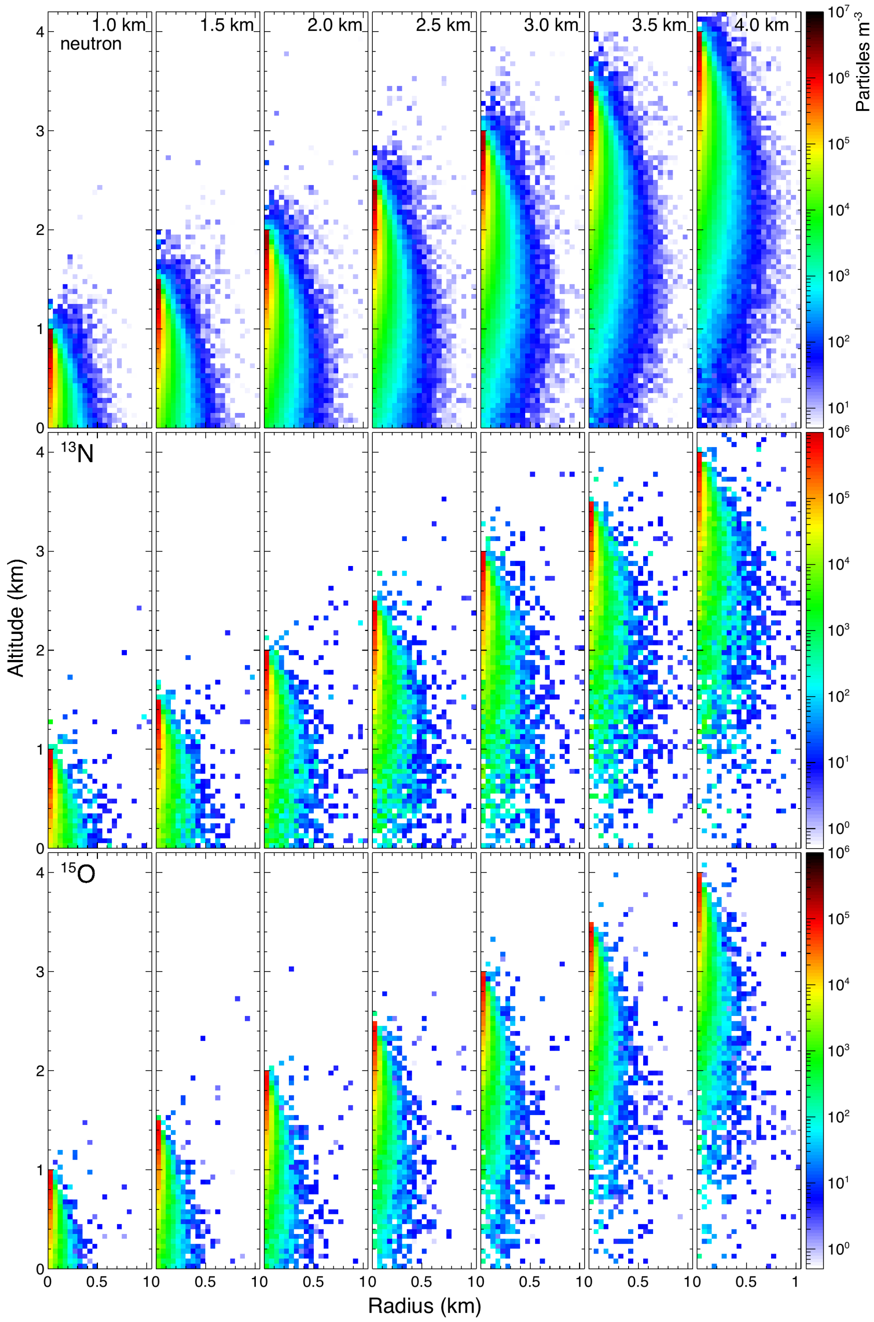

Figure 2: Spatial distributions of neutron and β^{+}-decay nuclide productions by photonuclear reactions in a function of altitude and radius. The initial electrons are injected at altitudes ranging from 1 to 4 km with a 0.5-km interval. Production densities of the distributions are normalized to the initial electron number of 10^{18} (1-50 MeV).

These models were compared with the observations of three short bursts detected at the Kashiwazaki-Kariwa site. The gamma-ray spectra of the short bursts and annihilation emissions were successfully reproduced by the models. The dose models of downward TGFs were also compared with doses measured by monitoring posts at the Kashiwazaki site. Combining the analyses of TGF doses and spectra of de-excitation and annihilation gamma rays, the source altitudes of downward TGFs were estimated to be 1.4-2.7 km, and the source positions were also determined with a systematic uncertainty of less than 0.5 km. Furthermore, 10^{18}-10^{19} energetic electrons of >1 MeV were estimated to be generated, and 10^{13}-10^{14} photoneutrons by photonuclear reactions in a single downward TGF. This is also the first time to quantitatively compare the three components originating from TGF photons, photoneutrons, and positrons.

Figure 3 compares the present results with those of TGFs detected by satellites (upward TGFs). The present cases took place at lower altitudes than upward TGFs. This is caused by observation biases due to atmospheric attenuation between the TGF source and detectors, and the meteorological differences between summer and winter thunderclouds. Despite the difference in source altitudes, the numbers of avalanche electrons for downward TGFs is the same order of magnitude as those for upward TGFs. Therefore, the downward TGFs in the present study are suggested to be intrinsically the same phenomena as upward TGFs observed from space.

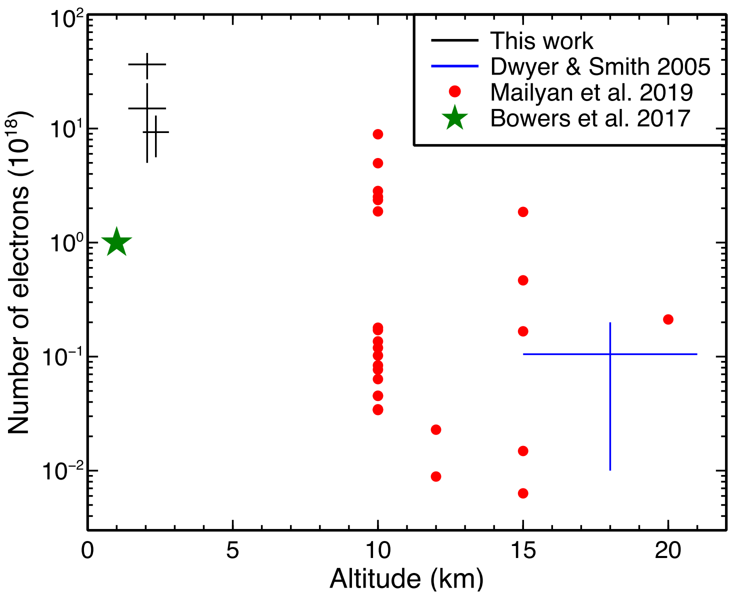

Figure 3: Comparison of upward and downward TGFs in the phase space of source altitude and electron number. Points from Dwyer and Smith [2005] and Mailyan et al. [2019] are results for upward TGFs, and from Bowers et al. [2017] and the present work for downward TGFs in winter thunderstorms. Mailyan et al. [2019] derived the source altitudes with four calculation points of 10, 12, 15, and 20~km.