Photonuclear reactions triggered by lightning discharges in a Japanese winter thunderstorm

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Enoto et al., Nature 551, 481 (2017)
Winter thunderstorm and lightning in Japan

- Low altitude (<1 km), powerful lightning, frequent positive discharge
- Ideal for observing the high-energy atmospheric phenomena

**GROWTH (Gamma-Ray Observation of Winter Thundercloud) project**

- Started in 2006, and expanded to multi-point measurements since 2015 for gamma-ray glow.

![Map of Siberian airmass and Japan island](image)

2017/2/6 15:00 JST

Himawari-8 / NICT

http://himawari8.nict.go.jp

**Graph showing count rate (cnt/s) [>3 MeV]**

- “Long”-duration event (Tsuchiya+07)
- Bremsstrahlung gamma-rays from accelerated electrons in thunderstorms

**Notes:**

- 10 minute cosmic-ray induced background

- 6.15: \( \frac{0.8}{0.8} \) MeV

- \( \frac{3}{3} \) MeV

- 0.8 MeV

- Count rate (cnt/s) [>3 MeV]

- Time (JST)
Radiation detectors for mapping observations

A new stand-alone, low cost, and high-performance data acquisition (DAQ) system was developed; e.g., FPGA board of 4 channel 50 MHz, 12 bit ADC

- Gamma-rays detected with BGO scintillators
- Recorded with energy and GPS time tag
- Environmental sensors (temperature, pressure, etc)
- Mobile data transfer & remote control
- Deployed at local high schools, universities
- Supported by academic crowdfunding, and aiming at distributing to citizen scientists

Wada, Master thesis of the University of Tokyo, “Construction of the multi-point observation network for thundercloud gamma-rays” (ref) FPGA/ADC board specification http://ytkyk.info/blog/2016/09/04/growth-fpga-adc-board/ (C) T. Yuasa
Radiation detectors for mapping observations

Cost >$20 k

Cost ~$4 k

2006 December

2016 October

Front-end Board
ADC board
Raspberry Pi
DAQ

BGO scintillator (25x8x2.5 cm³)
web camera
PMT
water proof box

DAQ electronics

(Detector FY2016)

Wada, Master thesis of the University of Tokyo, “Construction of the multi-point observation network for thundercloud gamma-rays” (ref) FPGA/ADC board specification http://ytkyk.info/blog/2016/09/04/growth-fpga-adc-board/ (C) T. Yuasa

(C) T. Yuasa
Short-duration burst associated with lightning on February 6, 2017, 17:34:06, at Kashiwazaki station had three components:

1. Intensive initial spike (<~a few milliseconds, exceeds 10 MeV)
2. Gamma-ray afterglow (<~100 ms, <10 MeV)
3. Delayed annihilation gamma rays (~minute, at 0.511 MeV)

[Diagram showing the location of detectors and monitoring stations, with graphs illustrating the time courses of different components of the radiation.]

- **2. Gamma-ray afterglow**
  - Detector C (>1.2 MeV)
  - Count (10 ms)
  - Time (ms)

- **3. Annihilation gamma rays**
  - Detector A (0.35-0.60 MeV)
  - Count (10 ms)
  - Time (ms)

[Arrow showing the wind speed and direction.]
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Photonuclear reactions triggered by lightning

\[ \gamma + ^{14}\text{N} \rightarrow ^{13}\text{N} + n \]

\[ ^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu \quad (p \rightarrow n + e^+ + \nu) \]
fast neutron

positron
Gamma rays from neutron and positrons

- **(n,p) reaction**
- **(n,p) reaction**
- **carbon isotope** $^{14}\text{C}$
- **nitrogen isotope** $^{15}\text{N}$
- **atmospheric nitrogen** $^{14}\text{N}$
- **neutron capture**
- **prompt gamma rays**
- **electron-positron annihilation** at 0.511 MeV
- **annihilation gamma rays**
- **gamma-ray afterglow**
- **delayed emission**
- **positron**
- **electron**
- **semi-stable (half-life 5730 year) radiocarbon dating**
Short-duration burst associated with lightning on February 6, 2017, 17:34:06, at Kashiwazaki station had three components:

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3. **Delayed annihilation gamma rays** (~minute, at 0.511 MeV)
Neutrons make the gamma-ray afterglow

**Diagram:**
- Detector A: decay constant $56 \pm 3$ (ms)
- Detector B: decay constant $55 \pm 12$ (ms)
- Detector C: decay constant $36 \pm 4$ (ms)

- Exponential decay constant of the sub-second afterglow is consistent with the theoretical prediction $\sim 56$ ms of the neutron thermalisation.
Neutrons make the gamma-ray afterglow

- Exponential decay constant of the sub-second afterglow is consistent with the theoretical prediction ~56 ms of the neutron thermalisation.
Neutrons make the gamma-ray afterglow

- Exponential decay constant of the sub-second afterglow is consistent with the theoretical prediction ~56 ms of the neutron thermalisation.
- Spectrum with a sharp cutoff at 10 MeV is well explained by prompt gamma rays from atmospheric nitrogens and surrounding materials.
Short-duration burst associated with lightning on February 6, 2017, 17:34:06, at Kashiwazaki station had three components:

1. **Intensive initial spike** (<~a few milliseconds, exceeds 10 MeV)
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**Graphical representation:**

- **1. Intensive initial spike**
  - Red circle: Detector A (0.35-0.60 MeV)
  - Graph: Count s⁻¹ vs. Time (sec) with a peak at 60 s

- **2. Gamma-ray afterglow**
  - Blue circle: Detector C (>1.2 MeV)
  - Graph: Count (10 ms) vs. Time (ms) with a peak at 100 ms

- **3. Annihilation gamma rays**
  - Green circle: Detector A (0.35-0.60 MeV)
  - Graph: Deadtime-corrected Count (10 ms) vs. Time (ms) with a peak at 100 ms

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**Diagram notes:**

- Relative enhancement values: $10^3$, $10^2$, $10^1$
- Monitoring stations marked: 1 to 9

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**References:**

Positron annihilation signal at 0.511 MeV

- The ~35 sec delay is consistent with the cloud moving from the lightning.
- The duration ~13 sec (1σ) x wind speed ~17 m/s → emission size ~200 m

- Relative intensity of the 0.511 MeV emission line and continuum below it gives a distance to the base of the positron-emitting cloud: ~80 m
- A lightning-triggered photonuclear event produces $4 \times 10^{12}$ neutrons.

The observed annihilation spectrum and simulated models.
The background-subtracted spectrum in the delayed phase for detector A, accumulated over $t = 11.1–62.8$ s, is plotted, with black crosses indicating ±1σ errors. The simulated model curves are overlaid, for assumed distances to the base of the positron-emitting cloud of 0 m (that is, the detector is within the cloud; red), 40 m (green), 80 m (blue) and 160 m (magenta). The models are normalized by the total counts in the 0.4–0.6-MeV band.
Discussion

- Atmospheric oxygen also contributes to the lightning photonuclear reactions.
- Can explain past reports of 0.511 MeV (Umemoto+2016) and neutrons (Bowers+2017).
- Lightning produces atmospheric $^{13}\text{N}$, $^{15}\text{N}$, $^{13}\text{C}$, and $^{14}\text{C}$ isotopes.

Estimated number of neutron $4 \times 10^{12}$ produced by photonuclear reaction is within predicted range of $10^{11-15}$ (Babich+10, Carlson+14).
Summary

• GROWTH project has been observing high-energy atmospheric phenomena in the Japanese winter thunderstorm and lighting since 2006. We are also aiming at expanding to citizen science.

• We provided unequivocal evidence for the lightning-triggered photonuclear reactions of atmospheric nitrogen $^{14}\text{N} + \gamma \rightarrow ^{13}\text{N} + n$; (1) downward terrestrial gamma-ray flash, (2) gamma-ray afterglow of thermalised neutrons, and (3) annihilation gamma-ray signal at 0.511 MeV from the beta-plus decay of $^{13}\text{N}$.

• Lightning provides channels to generate carbon isotopes.


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