Recent status of the GROWTH experiment
-Gamma-ray observations at the coastal area of Japan Sea-

(1) Background
(2) GROWTH experiment
(3) Observational results
  1. properties of thundercloud gamma rays
  2. relationship with lightning
  3. photonuclear reaction in lightning

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WRMISS in Tsuruga, Sep. 5, 2018
Background
- Radiation enhancement associated with thunderstorms -

Terrestrial Gamma-ray Flashes (TGFs)

- Gamma-ray glows
- Observed by airplane, balloons, high-altitude detectors and the ground-based ones.
- Duration: submilli-second to a few tens of minutes

Ref: Dwyer et al., SSR (2012)

Original figure J. Dwyer 2011
Background
- How runaway electrons are produced in air? -

Gurevich et al., PLA 165(1992), Dwyer GRL (2003)

Thus, the runaway electron avalanche occurs if
(1) Electric filed *is higher than* $E_c \text{ (MV/m)} = 0.28 P(\text{atm})$

(2) Seed electrons with high energies are present in the atmosphere

Possible sources
- Cosmic rays
- Radon-decay products

Observed $E :< 0.4 \text{ MV/m.}$

All electrons become runaway

$E_D \text{ (} \sim 30 \text{ MV/m)}$

Energy loss (MeV/m)

Kinetic energy (keV)

Ionization loss + bremsstrahlung
only Ionization loss

Runaway region

$T_c$

$E_c = \text{(N)}$

$E_c = 0.28 P_B(\text{UN})$

Two types of radiation bursts on the ground

Long bursts

Bremsstrahlung gamma rays

detector

Short bursts

Bremsstrahlung gamma rays

detector
Aim of observations

- How electrons are accelerated to relativistic energies in a dense terrestrial atmosphere?
- How those bursts are associated with lightning/thunderclouds?
- How positrons and neutrons are produced in lightning and thunderclouds?
- How lightning is triggered?
GROWTH experiment (-fy2014)

Gamma Ray Observation of Winter Thunderclouds

Observations at Kashiwazaki-Kariwa power plant (PRL 2007, 2013; JGR 2011)

- Start in 2006
- NaI, CsI, BGO scintillation detectors and Monitoring posts
- Low altitude of cloud base: < 1 km

Observations at high mountains (PRL 2009; PRD 2012)

- Mt. Norikura (2770 m)
- Tibet (4330 m)

Photo from Tibet AS gamma group
GROWTH experiment (fy2015-)

Gamma Ray Observation of Winter Thunderclouds

- NaI, CsI, BGO scintillation detectors + Raspberry Pi for downsizing system

Winter sites
Komatsu High School
Science Hills Komatsu
Izumigaoka High School
Kanazawa Univ. High School
Kanazawa University

Summer sites
Kanazawa
Komatsu
Suzu
Kashiwazaki

Mt. Norikura (2770 m)
Mt. Fuji (3775 m)
Observational results

(1) General properties of long bursts
Counts histories of long bursts
Kashiwazaki+Mt. Noikrura

Duration: a few tens of sec to a few minutes

Counts / 12sec

10 min or less of mature stage of winter thunderclouds.
(Kitagawa & Michimoto, 1994)
Energy spectrum
Long bursts vs TGFs

Maximum energy
TGF \sim 100 \text{ MeV}
GROWTH \sim 20 \text{ MeV}

# of >1 \text{ MeV electrons}
TGF \sim 10^{16} - 10^{17}
GROWTH \sim 10^9 - 10^{11}

Not corrected for detector response

RHESSI: 289 events (Dwyer & Smith, GRL 2005)
AGILE: 130 events (Tavani et al., PRL 2011)
GROWTH: 5 events Revised Tsuchiya et al., JGR 2011
Discussions

- Long bursts have been observed by airborne detectors, high-mountain ones as well as ground-based ones. They have never been observed by detectors onboard satellites (because primarily of moving of satellites)

- It has been thought that long bursts are related to electrification of thunderclouds. We may observe them from the electrification region when it being “ON”.

![Diagram showing the process of electrification and production of high-energy electrons](Diagram of the process)

1. Electrification starts
2. High-energy electrons are produced via cosmic rays or radons
3. Acceleration and multiplication of electrons
4. Bremss. gamma rays
5. Electrification ceases

 detector

 detector

 detector
In order to observe the whole cycle of a long burst, we need to prepare mapping observations such as the GROWTH one. Also air-shower experiments using many detectors would be suitable for those observations. Actually, several air-shower experiments have reported thunderstorms-related enhancements [Tibet ASg group (Amenomori+, Proc.of ICRC2013), TA group (Abbasi+ PLA, 2017)]

Some groups have reported increases or decreases of muon flux during thunderstorms (Alexeenko+2002, Dorman+2003, Muraki+2004). So far, those muon variations have been observed only at high mountains.
Observational results

(2) Relationship between long bursts and lightning
Relation between a long burst and lightning

Termination of long bursts just prior to lightning

Y. Wada, G. S. Bowers, T. Enoto et al, GRL 45 5700 (2018)

• Simultaneous observations of gamma rays (GROWTH and GODAT), electric field (Kamogawa team) and LF (Morimoto team) were done.
Relation between a long burst and lightning

Termination of long bursts just prior to lightning

 LF network detected leader development of an IC*

![Graph showing IC starts around 15 km away from the detector and IC leader destroyed the gamma-ray emitting region.]

IC : Intra/Inter cloud discharge
Relation between a long burst and lightning

Termination of long bursts just prior to lightning

Schematic view of this event

Y. Wada, G. S. Bowers, T. Enoto et al, GRL 45 5700 (2018)
Observational results (3) Photonuclear reactions in lightning

Lightning and neutron production

1970’s-1990’s : nuclear fusion  \( D + D \rightarrow (2.45 \text{ MeV}) + ^{3}\text{He} \)

- Possibility of neutron production in lightning Libby & Lukens JGR (1973)

However,

- DD Fusion : Not feasible in normal lightning environment
  
  Extremely intense electric field would be required for detectable neutron flux \( (10^{10}-10^{15} \text{ n}) \)

2000’s : Photonuclear reaction: \( \gamma (>10.5 \text{ MeV}) + ^{14}\text{N} \rightarrow \text{n} + ^{13}\text{N} \)

- Clear detections of >10 MeV gamma rays from lightning

- Much more feasible than fusion : Babich+ JGR (2007), Carlson+ JGR (2010)
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 radiation detectors and monitoring stations around the Sea of Japan]

- Detectors
- Monitoring stations

Relative enhancement
- $10^3$
- $10^2$
- $10^1$

- Detection at Kashiwazaki station on February 6, 2017, 17:34:06
- Lightning discharges occurred at 08:34:06
- Observations from radiation detectors A to D

Counts (10 ms)$^{-1}$

- Detector C (>1.2 MeV)
  - Gamma-ray afterglow
  - Time (ms): 100 ms

- Detector A (0.35-0.60 MeV)
  - Annihilation gamma rays
  - Time (sec): 60 s

- Monitoring stations 0.5–1.7 kilometres away from the lightning
- Time (ms): 0-400
- Time (sec): 0-100

- Center of prolonged line emission corresponds to 10 megaelectronvolts
- Operating radiation detectors since 2006
- Photonuclear reactions triggered by lightning
light curves and energy spectra

- Exponential decay constant of the sub-second afterglow is ~56 ms of the neutron thermalization time.
- Spectrum with a sharp cutoff at 10 MeV
Photonuclear reactions triggered by lightning

downward TGF (initial spike)

atmospheric nitrogen \( ^{14}\text{N} \)

radioactive isotope \( ^{13}\text{N} \)

carbon isotope \( ^{13}\text{C} \)

\( \gamma + ^{14}\text{N} \rightarrow ^{13}\text{N} + n \)

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

positron
Gamma rays from neutrons and positrons

Moderation

Fast neutron

Atmospheric nitrogen $^{14}\text{N}$

Neutron capture

Nitrogen isotope $^{15}\text{N}$

Prompt gamma rays

Gamma-ray afterglow

Annihilation gamma rays at 0.511 MeV

Delayed emission

Positron

Electron-positron annihilation

Electron

Annihilation
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 thermalization time.
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

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)
Discussions

We have confirmed that photonuclear reactions occur in a lightning discharge. It is noted that Bowers et al., (GRL, 2017) also detected photonuclear neutron signals at the same coastal area of Japan sea.

Time structure of this event is consistent with that proposed by Rutjes et al. (GRL, 2017).
Discussions

This observation showed that radioactive isotopes such as $^{13}$N and $^{15}$O were produced.

$^{14}$C would be also produced via $^{14}$N(n, p)$^{14}$C. This means that lighting may be an additional source of $^{14}$C in the atmosphere as reported by Libby & Lukens (JGR, 1973) and Babich (GRL, 2017).
Discussions

- **Fast neutron**
- **Atmospheric nitrogen** $^{14}\text{N}$
- **Neutron capture**
- **Carbon isotope** $^{14}\text{C}$ (semi-stable, half-life 5730 years)
- **Nitrogen isotope** $^{15}\text{N}$
- **Prompt gamma rays**
- **Gamma-ray afterglow**
- **Delayed emission**
- **Electron-positron annihilation**
- **Electron**
- **Annihilation gamma rays at 0.511 MeV**
- **(n,p) reaction**

**Radiocarbon dating**

**Moderation**
Summary

The GROWTH experiment has so far observed two types of bursts;

- **Long burst** & **Short burst**

- **Long burst**: Bremsstrahlung gamma rays emitted from electrons accelerated in thunderclouds (occasionally) annihilation gamma rays, muons

- **Short burst**: Bremsstrahlung gamma rays emitted from electrons accelerated in lightning (occasionally) prompt gamma rays emitted from a de-excitation nucleus

- Photonuclear reactions are triggered by lightning neutrons, positrons and radioactive isotopes ($^{13}\text{N}$, $^{15}\text{O}$, $^{14}\text{C}$)