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Ambient conditions to reproduce gamma-ray glow energy spectra assuming cosmic ray as source

Gabriel Sousa Diniz,[a,*] **Yuuki Wada,**[b] **Yutaka Ohira,**[c] **Kazuhiro Nakazawa,**[d] **Miwa Tsurumi**[a,e] **and Teruaki Enoto**[a,f]

[a] *Department of Physics, Graduate School of Science, Kyoto University, Kitashirakawa Oiwake-cho, Sakyo-ku, Kyoto-shi, Kyoto, 606-8502, Japan.*

[b] *Division of Electrical, Electronic and Infocommunications Engineering Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka, 565-0871 Japan*

[c] *Department of Earth and Planetary Environmental Science, The University of Tokyo, 7 Chome-3-1 Hongo, Bunkyo City, Tokyo 113-8654, Japan*

[d] *Kobayashi-Maskawa Institute for the Origin of Particles and the Universe, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8601, Japan*

[e] *Graduate School of Science and Engineering, Aoyama Gakuin University, 5-10-1 Fuchinobe, Sagamihara, Kanagawa 252-5258, Japan.*

[f] *Extreme Natural Phenomena RIKEN Hakubi Research Team, RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan*

E-mail: diniz.gabriel.58j@st.kyoto-u.ac.jp, ywada@eei.eng.osaka-u.ac.jp, y.ohira@eps.s.u-tokyo.ac.jp, nakazawa@u.phys.nagoya-u.ac.jp, tsurumi.miwa.36c@st.kyoto-u.ac.jp, enoto.teruaki.2w@kyoto-u.ac.jp

*Speaker

The electric field of thunderclouds modifies components and energy spectra of the cosmic-ray air shower resulting in an enhancement of gamma-ray fluxes on the ground, known as a gamma-ray glow. The Gamma-Ray Observation of Winter THunderclouds (GROWTH) collaboration has measured this phenomenon for several years in the Hokuriku area of Japan. The present work examines the ambient conditions required to produce spectral features of the previously detected gamma-ray glows. We use Monte Carlo simulations of particle interactions in the atmosphere with the cosmic-ray electron spectrum as input from the EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum (EXPACS). We focus on three parameters, the strength and length of the electric field and the size of a null-field attenuation region below the electrified region. The average spectrum of observed gamma-ray glows in winter thunderstorms of Japan requires an electric field intensity close to the Relativistic Runaway Electron Avalanche (RREA) threshold of 0.284 MV/m. The vertical size of the electric field region should be in the range of 0.5—1 km. The estimated attenuation region size is 300–500 m, necessary to reduce the low-energy photon flux of the average gamma-ray glows. The whole space of phase capable of generating the gamma-ray glow spectra uses only cosmic-ray electron shower as input. Thus, the interaction between cosmic-ray and the thundercloud is capable of producing the signal detected at the ground.

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1. Introduction

Cosmic rays produce Extensive Air Showers (EAS) related to High Energy Atmospheric Phenomena (HEAP). The EAS flux passes through the thundercloud that accelerates the electrons promoting gamma-ray emission augmentation through bremsstrahlung, the gamma-ray glow. The thunderstorm's electric field is responsible for an energy gain creating the so-called Relativistic Runaway Electron Avalanches (RREAs) when superior to ~ 0.286 MV/m [1].

We simulated how the EAS electrons produce ground-detected gamma-ray glows as they pass through the thundercloud. We compare it with the GROWTH measurement catalog [2] to find the ambient characteristics that produce the reported average spectrum.

We approximate the ambient characteristics in three coordinates: the uniform electric field strength E_S, the vertical length of the electric field region H_E, and the vertical distance between the electric field region base and the ground as the detector level H_a, see Figure 1.

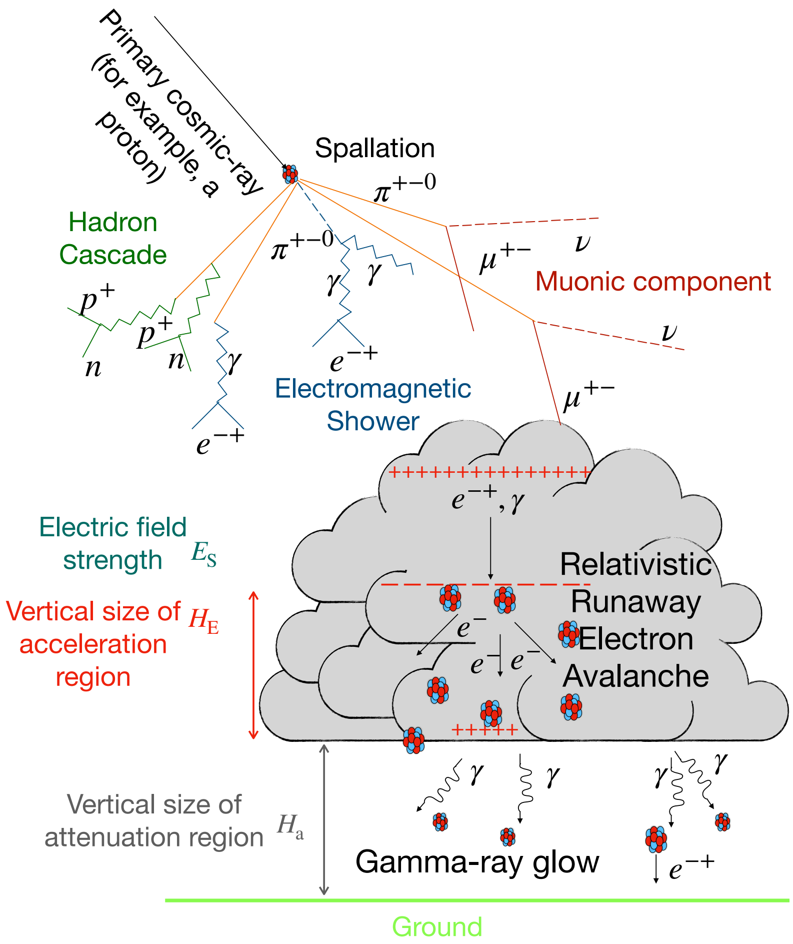

Figure 1: Schematic view of the interaction between thundercloud and cosmic-ray producing gamma-ray glow.

The RREAs produce a characteristic gamma-ray glow spectrum following Equation 1 [2] between 0.2 – 20 MeV,

$$F(\varepsilon) = F_0 \left(\frac{\varepsilon}{1\text{ MeV}}\right)^{-\Gamma} \exp\left(-\frac{\varepsilon}{\varepsilon_{\text{cut}}}\right). \tag{1}$$

where ε is the photon energy and $F(\varepsilon)$ is the photon flux in an unit of photons $\text{MeV}^{-1}\ \text{s}^{-1}\ \text{cm}^{-2}$. The reported normalization constant is $F_0 = 0.662 \pm 3.010$ for the energy range of 0.2–20 MeV range. The power-law photon index is $\Gamma = 0.5 \pm 0.28$ and the exponential cutoff energy is $\varepsilon_{\text{cut}} = 4.41 \pm 0.41$ MeV.

We focus on the gamma-ray glow spectral shape. Thus, we normalized the model from Equation 1 to Equation 3 in MeV^{-1} as follows,

$$F_{\text{i}} = \int_{0.2}^{20} F(\varepsilon) d\varepsilon, \tag{2}$$

$$f(\varepsilon) = \frac{F(\varepsilon)}{F_{\text{i}}} = f_0 \left(\frac{\varepsilon}{1\text{ MeV}}\right)^{-\Gamma} \exp\left(-\frac{\varepsilon}{\varepsilon_{\text{cut}}}\right). \tag{3}$$

2. Simulation methods

Our simulations were built with GEometry ANd Tracking 4 (GEANT4)[3]. The simulation geometry is a cylinder filled with Standard Temperature and Pressure (STP) homogeneous air with the density of sea level. The ranges of (E_{S},H_{E},H_{a}) are (0.10–0.32 MV/m, 0.1–1 km, 0.1–0.5 km) and an simulation with $E_{\text{S}} = 0$ defining the background. The primary electron spectrum follows the EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum (EXPACS) simulation [4] in the 1–300 MeV band at 1 km altitude for reference. The source altitude is defined by $H_{\text{E}} + H_{\text{a}}$. The initial electrons' momenta are anti-parallel to the electric field going downward.

We employed two independent simulations: (1) Output of electron and photon spectra at the electric field region bottom, i.e., they are detected H_{E} from the source altitude, thus $H_{\text{a}} = 0$. We calculate the spectral hardness η of simulation (1), assuming a different H_{E} and E_{S}. The hardness η definition is Equation 4. We use η to filter out the geometry pairs (E_{S}, H_{E}) that can not produce the observed gamma-ray glow spectrum after H_{E}.

The second simulation set (2) repeats the geometry of set (1) but only for the pairs (E_{S},H_{E}) that can produce the observed gamma-ray glow spectrum at the bottom of the attenuation region, thus $H_{\text{a}} \neq 0$.

$$\eta(\Gamma, \varepsilon_{\text{cut}}) = \frac{\int_{10\text{ MeV}}^{20\text{ MeV}} f(\varepsilon) d\varepsilon}{\int_{1\text{ MeV}}^{10\text{ MeV}} f(\varepsilon) d\varepsilon} = \frac{\int_{10\text{ MeV}}^{20\text{ MeV}} \varepsilon^{-\Gamma} e^{\frac{-\varepsilon}{\varepsilon_{\text{cut}}}} d\varepsilon}{\int_{1\text{ MeV}}^{10\text{ MeV}} \varepsilon^{-\Gamma} e^{\frac{-\varepsilon}{\varepsilon_{\text{cut}}}} d\varepsilon}. \tag{4}$$

3. Hardness filtering

The electrons attenuate rapidly in the absence of strong electric fields. Thus, the photon yield is less where $E_{\text{S}} = 0$ than within electrified regions. Thus, once the electrons and photons enter the $E_{\text{S}} = 0$ region, the lower energy end of the spectra will vanish faster than the high energy portion. This effect implies that H_{a} only increases η.

Figure 2 (A) shows the simulated spectral hardness, η, for different configurations of the simulation set (1), Section 2. The average, μ, and the associated standard deviation, σ of [2] observations define the blue patch. Configurations of $(E_{\rm S}, H_{\rm E})$ with $\eta > \mu + \sigma$ are unable to reproduce the measurements. Figure 2 (B) details the hardness of [2] spectra.

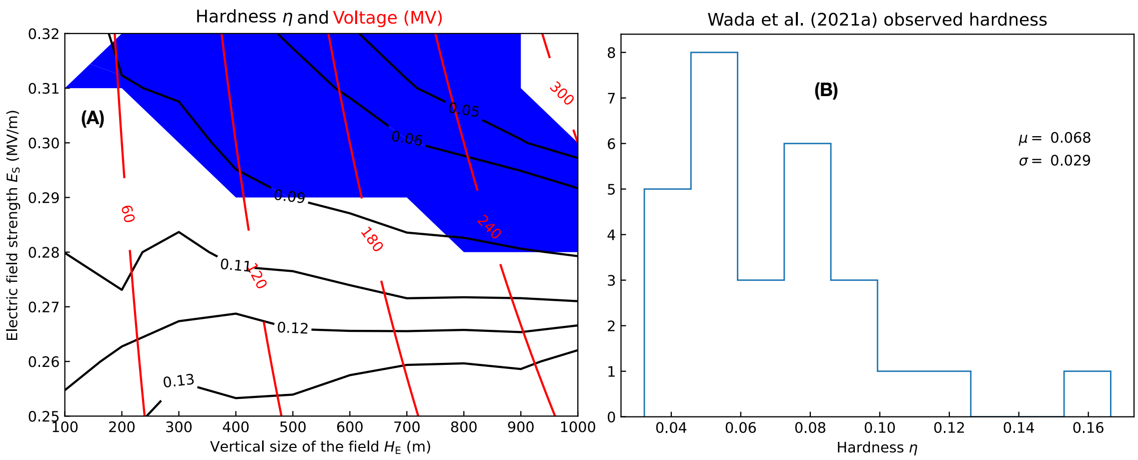

Figure 2: (A) Simulated spectral hardness η at the bottom of the acceleration region (black curves) as a function of $E_{\rm S}$ and $H_{\rm E}$. Voltage difference in the acceleration region as a product $E_{\rm S} \times H_{\rm E}$ is represented by the red lines. The blue region indicates the one σ region of observed hardness ($\mu \pm \sigma$, where μ is the mean of panel B and σ the standard deviation) reported in [2]. Panel (B) is the histogram of the hardness η of the 28 gamma-ray glows used by [2]. Figure adapted from [5].

4. Spectrum reproduction

Finally, Figure 3 shows the simulated spectra closest to [2] measurements shape. The triad configuration $(E_{\rm S}, H_{\rm E}, H_{\rm a})$ are (0.31 MV/m, 1000 m, 400 m) and (0.30 MV/m, 900 m, 300 m), indicated in the legend together with the fitting parameters.

Figure 3 spectra have ~ 4.65 (considering the configuration, 0.31 MV/m, 1000 m, 400 m) and 2.96 (considering the configuration, 0.30 MV/m, 900 m, 300 m) avalanche lengths to develop. Such vertical extensions are insufficient for the RREA steady state [1, 6]. Hence, the gamma-ray glow observation must be related to under-developed RREAs.

5. Conclusions

We have explored the ambient geometry and conditions through GEANT4 simulations testing the electric field strength, its vertical extension, and the vertical extension of an attenuation region $(E_{\rm S}, H_{\rm E}, H_{\rm a})$ to reproduce the spectral form of the gamma-ray glow observations performed by the GROWTH collaboration [2].

Our results indicate that the cosmic-ray interaction with the thundercloud environment is sufficient to generate the gamma-ray glow.

Several ambient combinations of $(E_{\rm S}, H_{\rm E}, H_{\rm a})$ can generate spectra similar to [2] observations in Japan. Nevertheless, our simulations show constraints in each variable. The electric field strength, $E_{\rm S}$, must be close to the RREA threshold $E_{\rm th}$; The vertical extension of the electrified region, $H_{\rm E}$, must be ~ 1 km to allow electron multiplication. A region with null (or weak) electric

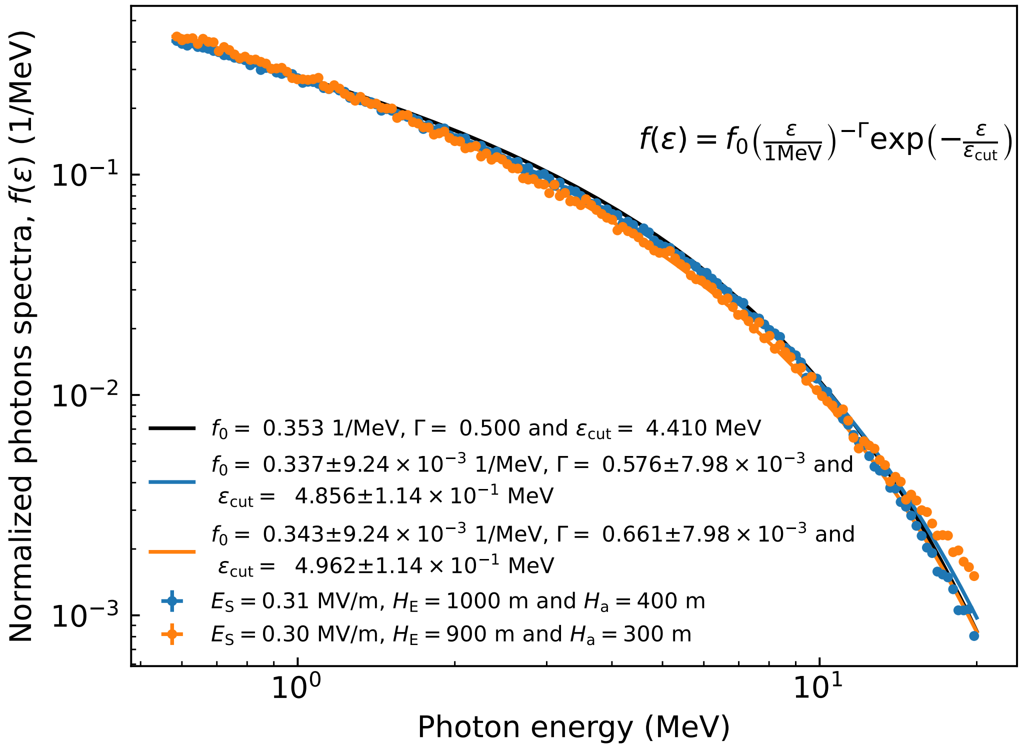

Figure 3: Background-subtracted simulated spectrum of gamma-ray glows (blue and orange points) closest to the average observed spectral shape (black curve). The simulated data are normalized by the integrated flux and fitted with the exponential cutoff power-law model (Equation 3). Adapted from [5].

field with vertical length H_a is necessary ($\sim$ 400 m) to attenuate the low particles and reproduce the observed power-law index, Γ. In particular, two triad sets of (E_S, H_E, H_a) replicates the observed gamma-ray glow within the one sigma, (0.30 MV/m, 900 m, 500 m) and (0.31 MV/m, 1000 m, 400 m).

Acknowledgments

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