"Seed" electrons from muon decay for runaway mechanism in the terrestrial gamma ray flash production

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[1] We describe a mechanism of enhanced terrestrial gamma ray flash production seeding via muon decay in the presence of high electric fields associated with lightning. Our model predicts 10^7 relativistic seed electrons per millisecond at about 15 km altitude with mean energy of 35 MeV and an avalanche multiplication factor of about 10^{10}, in good agreement with Monte Carlo simulations.

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1. Introduction

[2] Terrestrial gamma ray flashes (TGFs) are very short blasts of gamma rays lasting about one millisecond emitted into space from Earth′s upper atmosphere. They seem to be connected with powerful thunderstorm activity [*Cummer et al.*, 2005]. TGFs were first observed in the early 1990s [*Fishman et al.*, 1994] and more recently on the RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) spacecraft [*Dwyer and Smith*, 2005]. The measurements of TGFs obtained by the RHESSI show a photon spectrum extending of 0.003 up to typically 10 to 20 MeV (sometimes exceeding 20 MeV).

[3] Acceleration of electrons to high energies in electric fields above thunderstorms was predicted in 1924 by *Wilson* [1924] and this runaway process was recently shown [*Gurevich et al.*, 1992] to be capable of avalanche multiplication, making its variants good candidates for the TGFs parent process [*Roussel-Dupré et al.*, 1998]. However, the proper mechanism that accelerates electron beams to produce gamma rays is still uncertain. Suggested physical mechanisms include the following:

[4] 1. In model of relativistic runaway breakdown from quasi-static electric field (QES) [*Roussel-Dupré et al.*, 1998], electrons originated by the cosmic rays are accelerated upward by the transient electric field at high altitudes (>30 km) produced by the lightning will form TGFs by a process of bremsstrahlung of electrons with atoms;

[5] 2. In low-altitude (<20 km) QES-driven runaway electrons [*Gurevich et al.*, 2004], a new type discharge generated in thunderclouds by joint action of runaway breakdown and extensive atmospheric shower will produce TGFs;

[6] 3. In heating by the electromagnetic pulse (EMP) associated with the rapidly moving return strokes of cloud-to-ground (CG) lightning [*Inan and Lehtinen*, 2005] the relativistic runaway electron (RRE) avalanche driven by electromagnetic impulses (EMP) radiated by rapidly moving lightning return strokes indicates that TGFs can be produced by discharges with peak return stroke currents $I_{\mathrm{p}} > 450-700$ kA with velocities $v_{\mathrm{rs}}/c = 0.99-0.995$.

[7] 4. In EMP acceleration from a fractal intracloud flash [*Milikh and Valdivia*, 1999] the model relies upon a horizontal fractal lightning discharge, which generates the electromagnetic pulses that produce the stochastic electron runaway discharge in the stratosphere that will form TGFs;

[8] 5. In whistler generation of runaway electrons [*Kaw et al.*, 2001] the runaway discharge produces a plasma in which the whistler waves are excited by the energetic electrons. Whistlers are produced abundantly during thunderstorms and the coupling to the relativistic electrons of the runaway discharge can excite a self-focusing instability which leads to the formation of ducts in which the energetic electrons propagate to higher altitudes and producing TGFs.

[9] A new physical concept of an avalanche type increase of a number of energetic electrons in air under action of the thundercloud electric field was proposed by *Gurevich et al.* [1992]. The avalanche can grow in the thundercloud at the heights 3–10 km in the electric fields $E > Ec \approx 1-2$ kV/cm, which is almost an order of magnitude less than the threshold electric field of conventional air breakdown $E_{th} \approx 10-20$ KV/cm. The condition $E > E_c$ alone is insufficient for "runaway breakdown" (RB). The presence of fast seed electrons, having energy of 0.1–1MeV, is also necessary. Because of collisions with air they can generate new fast electrons having energies $\varepsilon > \varepsilon_c$. This process of acceleration and collisions leads directly to the avalanche type growth of the number of runaway electrons.

[10] In this paper we consider the production of "seed" electrons based on the assumption that they come out from the decay of a rest muon after an intracloud lightning discharge. Considering a source with an area of 1 km^2, we estimate that 10^7 relativistic electrons per millisecond with mean energy of 35 MeV are produced in this process.

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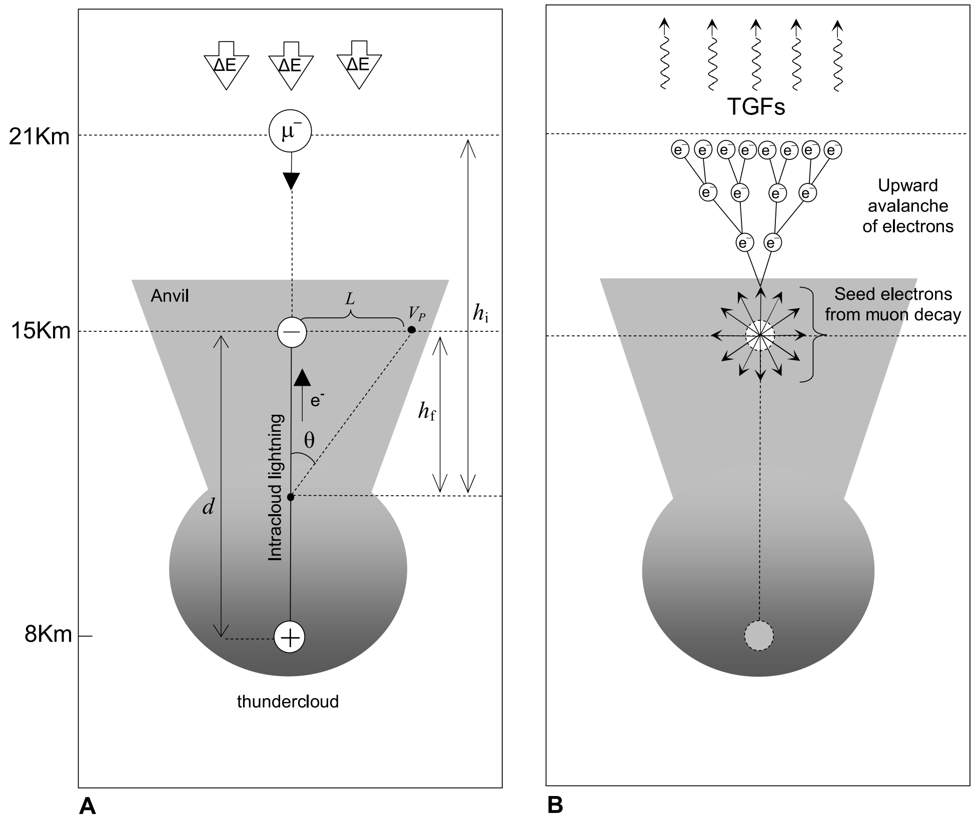

Figure 1. (a) Muon stopped by the ΔE transient electrostatic field produced by an energetic intracloud lightning. (b) Isotropic muon decay producing seed electrons, electron avalanche, and TGFs.

Section 2 describes the TGFs muon model. Calculations and discussions are presented in section 3.

2. TGF Muon Model

[11] In this work we suggest that relativistic upward electrons produced by the muon decay

$$\mu^- \rightarrow e^- + \nu_e + \overline{\nu}_\mu$$

originates the TGF energy spectrum observed above electrical storms. Muons are particles originated by several nuclear processes, including decay of pions produced in hadronic interactions of cosmic rays [*Yao et al.*, 2006]. Experimental measurements show that muon decay produces electrons with mean kinetic energy 35 MeV [*Barlow et al.*, 1964]. Surprisingly, Monte Carlo calculations of *Smith et al.* [2005] indicate that seed electrons producing TGFs have this same mean energy. Then, our model is consistent with such findings.

[12] As illustrated in Figure 1, these muons decelerate because of repulsion with the transient electrical field (ΔE) created by lightning discharges (ΔQ). From the isotropic muon decay, the relativistic upward electrons will produce gamma rays in an avalanche-type process of runaway electrons.

3. Results

[13] Lightning is responsible for rapid electrostatic field changes of thunderstorms [*Uman*, 1984]. When positive charge of the cloud is destroyed because of an intracloud discharge, a transient electric field produces runaway electrons on the top of the thunderstorm, as illustrated in Figure 1b. The potential change measured on the conductive plane due to an intracloud discharge destroying a portion of vertically oriented positive electrical dipole can be calculated according to equation (1) [*Uman*, 1984]:

$$\Delta V = \frac{1}{4\pi\varepsilon_0}\frac{Qd\cos\theta\sin^2\theta}{L^2} \tag{1}$$

where Q is the total charge transferred by the lightning, d is the dipole length (lightning length), ε_0 is the vacuum dielectric permissivity, and L is the distance to the center of the horizontal conductive plane, and θ is the angle relative to the dipole axis. Using equation (1), we verify that ΔV is approximately constant along of a horizontal plane above the positive charge ($+Q$) for $0 \leq L \leq 1$ km, a representative thundercloud radius [*Uman*, 1984]. Thus, the maximum kinetic energy of muons that the cloud can stop is given by:

$$K_{\max} = q(V_f - V_i) = q\left(\frac{Q\,d}{2\pi\varepsilon_0}\left(\frac{1}{h_f^2} - \frac{1}{h_i^2}\right)\right) \tag{2}$$

where q is the muon charge, and h_i and h_f are the initial and final positions of muon relative to the center of the dipole (see Figure 1). *Dwyer and Smith* [2005] and *Williams et al.*

[2006], proceeding from the results of simplified simulations, placed the TGFs source origin in the range of 15–21 km. Thus, we will consider those stopped muons between 15 and 20 km, corresponding to the estimated source altitudes given by *Dwyer and Smith* [2005]. TGFs are strongly concentrated around Earth's equator when compared to lightning [*Williams et al.*, 2006] and thundercloud tops are higher near to this region. In general case, the main negative charge in the lower part of a thundercloud [*Krehbiel et al.*, 1979] occurs at a height where the atmosphere temperature is between $-10°$C and $-20°$C. This temperature range is typically between 6 and 8 km. The positive charge at the top of the storm does not have so clear a relationship with temperature as the negative charge but can typically occur between $-25°$C and $-60°$C depending on the size of the storm. This temperature range usually lies between 8 and 16 km in altitude [*Singh et al.*, 2004; *Uman*, 1984]. For the other side, *Stanley et al.* [2006] recorded a link between TGFs and intracloud lightning discharges. In this case, TGFs were produced by positive polarity intracloud (+IC) discharges that transferred electrons upward. A typical intracloud discharge travels over a total path length of 5 to 10 km and neutralizes 10 to 30 C [*Uman*, 1984]. TGFs are relatively atypical and rare phenomena. The more recent RHESSI satellite has a greatly improved detection rate [*Smith et al.*, 2005] with >620 probable TGFs events detected in over 3 years of operations.

[14] The peak currents of TGF-associated lightning discharges are often among the most intense [*Inan et al.*, 2006], in the range of 450–700 kA [*Inan and Lehtinen*, 2005]. Here, we will consider positive polarity energetic intracloud lightning (+EIC) as responsible for the TGFs production. EIC is an isolated lightning event that occurs in thunderstorms and produce very powerful HF/VHF radiation and distinctive narrow bipolar electric field change pulses, occurring between 7 and 15 km altitude ground level [*Smith et al.*, 2004]. The association of a TGF with strong VHF pulses from IC flashes was recorded by *Rison et al.* [1999] and *Jacobson* [2003].

[15] Thus, let us consider an intracloud charge transfer of Q = 450 C over a time scale $\sim$ 1 ms (corresponding to the peak current of 450 kA) between 8 and 15 km altitude, h_i = 9.5 km, and h_f = 3.5 km (see Figure 1a), the calculated (equation (2)) maximum kinetic energy of muons that the thunderclouds can stop is about $K_{\max}$ = 4 GeV. However, muons lose energy at a fairly constant rate of about 2 MeV $g^{-1}cm^2$ [*Earnshaw et al.*, 1973]. According to the barometric height formula given by:

$$A = 1033 - (0.03648H) + \left(4.26 \times 10^{-7}H^2\right) \qquad (3)$$

where A is in g/cm^2 and H is the altitude in feet [*Ziegler*, 1996], the mean amount of air between 21 km and 15 km is about 90 g/cm^2. Thus, muons will lose $K_{\rm i}$ = 0.2 GeV to ionization before reaching the top of the cloud. Consequently, the total kinetic energy loosed by the muons is $K_{\max} + K_i$ = 4.2 GeV.

[16] Roughly 80% of the secondary cosmic ray flux consists of positive and negative muons [*Motoki et al.*, 2003], where about half of this flux is formed by negative muons [*Yao et al.*, 2006]. Let us consider that the cosmic ray rate of muon is $\sim 10^4$ m^{-2}s^{-1} at sea level, for all energies, and all angles [*Djemil et al.*, 2007]. Particle flux of cosmic ray increased very rapidly with altitude, with a 10 times increase at 15 km altitude [*Pfotzer*, 1936; *Ziegler*, 1996]. This means an ambient atmospheric muon flux of $\phi_0 = 1.5 \times 10^5$ m^{-2}s^{-1} at about 15 Km altitude. Considering a cloud area of A = 1 km^2, the total muon flux is:

$$\phi_t = \phi_0 A \cong 1.5 \times 10^{11} s^{-1} \qquad (4)$$

From the muon momentum spectrum of *Bugaev et al.* [1998] we estimate that about 15% of the total flux has energy between 1GeV and 4.2 GeV. Without an electric field, we estimate that less than 0.001% of total atmospheric muon flux (with energy less than 0.2 GeV) is stopped through ionization process. This fraction is insufficient to produce TGFs. Then, it seems that a strong electrical field is needed to produce detectable TGFs in higher altitudes. Considering that the duration of a TGF is 1 ms [*Smith et al.*, 2004] the muon flux over the cloud can be taken as 2×10^7. Considering that about half of this flux is formed by negative muons, this amount of decelerated muons will decay to produce about 10^7 energetic seeding electrons per millisecond. Monte Carlo simulations of *Dwyer and Smith* [2005] predict that about 10^{16} runaway electrons are created by the runaway breakdown avalanche for a source at 21 km altitude, and 2×10^{17} runaway electrons are created if avalanche was located at 15 km altitude. *Dwyer and Smith* [2005] have considered an ambient atmospheric cosmic ray flux of 1000 m^{-2}s^{-1} and a source with an area of 1 km^2, resulting in 10^6 seed electrons per millisecond (at 15 km altitude). In this work, we consider ambient cosmic ray flux (of muons) as being 1.5×10^5 m^{-2}s^{-1} and a source (thundercloud) with an area of 1 km^2, resulting in 10^7 seed electrons per millisecond (at 15 km altitude). It corresponds to the avalanche multiplication factor of about 10 times lower ($\sim 2 \times 10^{10}$ at 15 km altitude) as compared with that calculated by *Dwyer and Smith* [2005] ($\sim 2 \times 10^{11}$ at 15 km altitude).

[17] The proposed model raises many interesting questions, including the origin of electrons that produces gamma rays seen on the ground. *Dwyer et al.* [2004] detected gamma rays on the ground in association with rocket-triggered lightning with energies extending up to more than 10 MeV. According to our model, the possibility of muons stopped below 15 km is important for its possible connections to ground based gamma ray bursts (Figure 2). Thus, we believe that the ground based observations of gamma rays may be different in nature from those observed on satellites. In other words, seed electrons for ground-based X-ray observations, and satellite based X-ray observations, may be dominated by different altitudes, where different physical mechanisms (involving decaying of positive or negative muons) are dominant. For example, below altitude

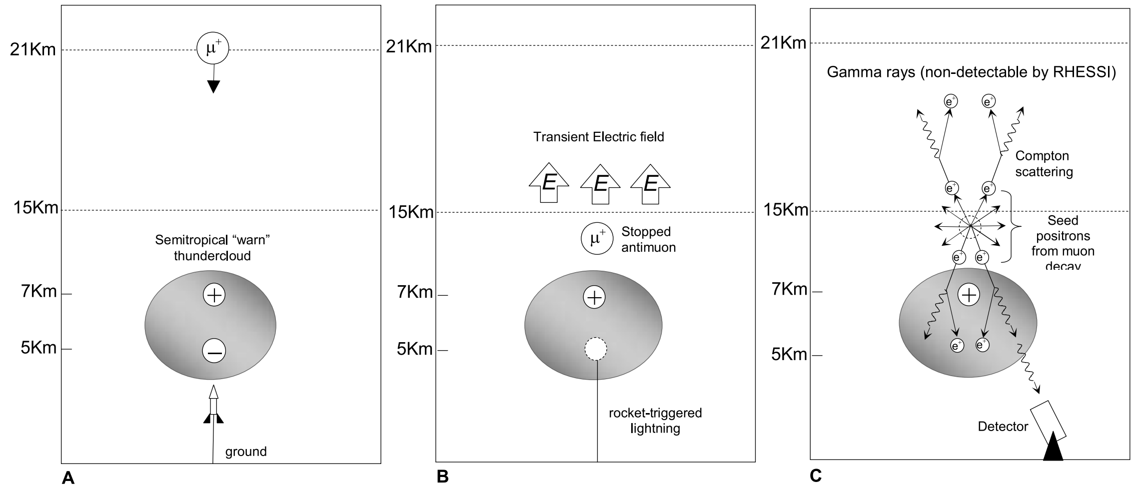

Figure 2. Mechanism for production of TGFs seen on the ground. (a) Small thunderclouds can stop positive muons by (b) rocket-triggered lightning. (c) It will produce gamma rays on the ground.

of 15 km (considering a negative cloud-to-ground lightning), positive muon decay is dominant, producing an avalanche of positrons. Efforts in exploring such questions are in progress.

4. Conclusion

[18] In this paper we consider an aspect of TGFs production that has been comparatively ignored by theoreticians, which is the availability of so-called upward "seed" electrons to feed into (upward) avalanche process. Considering a source area of 1 km^2, the present model for TGFs formation based on stationary muon decay predicts 10^7 relativistic seed electrons per millisecond with mean energy of 35 MeV and an avalanche multiplication factor of about 10^{10}, in good agreement with *Dwyer and Smith* [2005]. According to muon decay model, seed electrons for ground-based X-ray observations [*Dwyer et al.*, 2004], and satellite based X-ray observations, may be dominated by different altitudes, where different physical mechanisms (involving positive or negative muon decay) are crucial.

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