Production of terrestrial gamma-ray flashes by an electromagnetic pulse from a lightning return stroke

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[1] Recent observations of terrestrial gamma-ray flashes (TGFs) (Smith et al., 2005) suggest the need for a new mechanism of TGF production. Consideration of 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_p > 450–700 kA with velocities v_{rs}/c = 0.99–0.995.

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1. Introduction

[2] TGFs have been a subject of keen interest [*Inan*, 2005] since their discovery [*Fishman et al.*, 1994]. Recent observations on the RHESSI spacecraft [*Smith et al.*, 2005] of 10–20 TGFs per month indicate a high rate of occurrence of ~50 events per day globally, and motivates the new physical mechanism involving partially synchronized RRE acceleration by return stroke EMPs.

[3] TGFs have been attributed to bremsstrahlung radiation from a RRE beam, accelerated upward by quasi-electrostatic (QES) fields following large positive cloud-to-ground (+CG) lightning discharges (see review by *Gurevich and Zybin* [2001]). This mechanism requires a very large amount of charge removal to exceed the threshold of runaway acceleration, from extreme altitudes of ~20 km (as discussed by *Lehtinen et al.* [2001]). Furthermore, TGFs [*Fishman et al.*, 1994; *Smith et al.*, 2005] are observed mostly near the Earth's equator, where the vertical electron motion is impeded by the (nearly) horizontal geomagnetic field $\mathbf{B}_E$. RRE avalanche cannot proceed for $\mathbf{B} \perp \mathbf{E}$ and $B \gtrsim 2E/c$ [*Lehtinen et al.*, 1999], and thus vertical avalanche could not occur at ≳35–40 km altitude, as required for TGFs to be observed on a satellite [*Smith et al.*, 2005]. A variant of the QES model [*Gurevich et al.*, 2004] involving TGF production inside a thundercloud at <20 km altitude, avoids the $\mathbf{B}_E$ difficulty, but is hindered by atmospheric attenuation.

[4] Other suggested mechanisms of RRE/TGF production include acceleration by EMP from fractal intracloud lightning [*Milikh and Valdivia*, 1999] and RRE-carried whistlers [*Milikh et al.*, 2005]. The model of *Milikh and Valdivia* [1999] also involves TGFs driven by EMPs from lightning, but we exclusively consider −CG or +CG lightning with enhanced fields due to rapid return stroke motion, while *Milikh and Valdivia* [1999] only considered intracloud lightning.

2. Experimental Evidence for TGF Production by a Lightning EMP

[5] Large number of TGFs observed on RHESSI allow a statistical study of causative lightning discharges. An analysis (U. S. Inan et al., Terrestrial gamma ray flashes and radio atmospherics, submitted to *Geophysical Research Letters*, 2005) of radio atmospherics observed at Palmer Station, Antarctica, arriving from the direction of RHESSI and within ±1 ms of the expected time (with all propagation times accounted for as described by *Inan et al.* [1996]) shows that ≳50% of 66 TGF-correlated sferics have peak VLF intensities that are in the upper 20% of all sferics from the same thunderstorm, with ~30% having intensities in the upper 10% range. This result supports our EMP-driven model of avalanche RRE and TGF production, since the peak VLF power of a radio atmospheric is directly proportional to the intensity of lightning EMP [*Reising et al.*, 1996]. At least some TGFs are associated [*Cummer et al.*, 2005] with lightning discharges with small charge moment change, inconsistent with the existing QES-driven theories of TGF production.

3. Number of RREs and TGF Intensities Produced by Lightning EMP

3.1. Fluid Model of RRE Avalanche

[6] We use a fluid model, neglecting the RRE velocity dispersion, to estimate TGF production by lightning EMP. The necessary condition for avalanche production of RRE is for EMP electric field to exceed the runaway threshold E_t with the reduced value $E_t/N_m \approx 8$ Td, where N_m is the air molecule number density and 1 Td = 1 townsend = 10^{-21} V m^2. Without magnetic field, the RRE avalanche growth rate can be approximated by a polynomial based on the Monte Carlo calculations of *Lehtinen et al.* [1999]:

$$\nu_i = 2\pi N_m Z_m r_0^2 c\left[(\delta - 1) + 0.04(\delta - 1)^2\right], \quad \delta = E/E_t \qquad (1)$$

where $Z_m \approx 14.5$ is the average molecular nuclear charge, $r_0 \approx 2.82 \times 10^{-15}$ m is the classical electron radius and c is the speed of light.

[7] The RRE number density N satisfies the equation

$$\frac{\partial N}{\partial t} + \nabla(\mathbf{v}N) = \nu_i N + S$$

where S is the external source.

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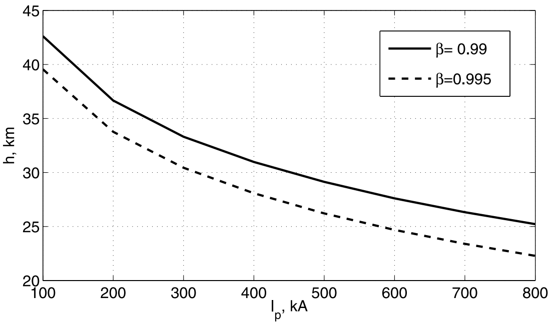

Figure 1. The altitudes at which the EMP field, given by (4), exceeds E_t. The field (4) is maximized at the zenith angle $\theta = \tan^{-1}\sqrt{1-\beta^2}$.

[8] A constant uniform source of seed MeV electrons was used in earlier works [*Lehtinen et al.*, 1999]. However, *Gurevich and Zybin* [2001] recognized that RRE avalanche may be seeded not necessarily by the continuous flux of bulk cosmic rays, but also by individual particles of energy $\mathcal{E}_{CR} \sim 10^8$–$10^{10}$ MeV. The flux of particles $\gtrsim 10^{10}$ MeV is $\sim$0.1 km^{-2} s^{-1} [*Eidelman et al.*, 2004, chapter 24]. For a thundercloud area of $\sim$100 km^2 [*Lehtinen et al.*, 1997], an extensive air shower may occur every $\sim$100 ms, and may coincide with a high QES and EMP electric field.

[9] The initial seed for an RRE avalanche is the maximum number of electrons in a cosmic ray shower [*Hillas*, 1982]:

$$N_0 = \frac{0.31}{\sqrt{\log(\mathcal{E}_{CR}/\mathcal{E}_c)}}\frac{\mathcal{E}_{CR}}{\mathcal{E}_c} \quad (2)$$

where $\mathcal{E}_c \approx 80$ MeV is the critical energy in air, which gives $N_0 \sim 10^5$–10^7 for $\mathcal{E}_{CR} \sim 10^8$–$10^{10}$ MeV.

[10] If the source S consists only of the N_0 electrons initially created by the cosmic ray air shower at position $\mathbf{r}_0$, then the total number of RRE is

$$N_{tot}(t) = N_0 e^{\int_0^t \nu_i(\mathbf{r}(t'),t')\,dt'}$$

where the position of avalanche $\mathbf{r}(t)$ is found by integrating $\dot{\mathbf{r}}(t) = \mathbf{v}(\mathbf{E})$ with $\mathbf{r}(0) = \mathbf{r}_0$ and $\mathbf{v}(\mathbf{E})$ being the RRE drift velocity of $\approx(0.5$–$0.9)c$. The electron motion at >30 km altitude is constrained along $\mathbf{B}_E$, so that the effective E in (1) is the projection of $\mathbf{E}$ onto $\mathbf{B}_E$ [*Gurevich et al.*, 1996].

[11] The number of γ-photons emitted by the RRE beam per unit time is

$$\frac{dN_{ph}}{dt} = \chi v N_{tot}(t) N_m(\mathbf{r}(t))$$

where $v = |\mathbf{v}|$, and $\chi \approx 10^{-28}$ m^2 is the bremsstrahlung cross section [*Heitler*, 1954, p. 245] integrated over the RHESSI photon detection range of 0.003–17 MeV [*Lin et al.*, 2002], assuming $\sim$35 MeV electrons [*Smith et al.*, 2005].

[12] The total number of photons in an average RHESSI TGF is $\gtrsim 3 \times 10^{15}$, assuming isotropicity [*Smith et al.*, 2005]. However, bremsstrahlung emission is likely to be anisotropic due to collimated motion of electrons and since the bremsstrahlung cross section is forward-directed within $\sim\gamma^{-1} \approx 1/70$ radians, where γ is the relativistic factor of $\sim$35 MeV electrons. Thus, the requirement on total number of photons is reduced to $\sim 3 \times 10^{15}(1/70)^2 \approx 10^{12}$, leading to

$$\frac{N_{ph}}{N_0} = \int_0^\infty \chi v N_m(\mathbf{r}(t)) e^{\int_0^t \nu_i(\mathbf{r}(t'),t')\,dt'}\,dt \gtrsim 10^5 - 10^7 \quad (3)$$

for initial electron number $N_0 = 10^5$–10^7.

[13] Higher altitudes are favored in our model due to a slow $1/R$ decrease of E for an EMP. Since photons are produced at altitudes >35 km, propagation through the atmosphere does not significantly reduce their observed flux.

3.2. Production of TGF by an EMP From a Rapidly Moving Return Stroke

[14] The electric field of the EMP radiated by a lightning return stroke propagating upward with velocity v_{rs} is [*Krider*, 1992]:

$$E(t) = \frac{\mu_0 I(t - R/c)}{2\pi R}\frac{c\beta\sin\theta}{1-\beta^2\cos^2\theta} \quad (4)$$

where R is the distance from source, θ is the zenith angle and $\beta = v_{rs}/c$, assuming that the EMP is emitted close to the surface of the Earth. The current $I(t)$ is assumed to have a non-zero constant value I_p during a time interval of $\sim$50 μs. This corresponds to the propagation time to the altitude h = 15 km [*Rakov and Tuni*, 2003] for $\beta \approx 1$, which approximately corresponds to the upper cloud boundary (which can be as high as 20 km). We note that the typical lightning channel length is usually shorter, $\sim$7.5 km.

[15] The electric field given by (4) is higher in comparison to a nonrelativistic case by a factor $(1 - \beta^2\cos^2\theta)^{-1} > 1$, relaxing the peak current requirements to exceed RRE threshold E_t, at the altitudes indicated in Figure 1. The validity of equation (4) is discussed in detail in Section 4.1.

[16] The ground-observed average values of β are $\sim$0.55 for −CG and $\sim$0.3 for +CG [*Rakov and Uman*, 2003, p. 232]. VHF emissions from return strokes [*Shao et al.*, 2003] suggest an average value of $\beta = 0.75$, as determined from the beam pattern observed by the FORTE satellite. Under certain conditions, values as high as 0.99 have been considered [*Rakov and Tuni*, 2003]. We note, however, that the high measured values of $\beta \approx 1$ might result from the initial bidirectional development of the return-stroke channel [*Rakov and Uman*, 2003, p. 414]. The EMP electric field for I_p = 200 kA and $\beta = 0.99$ in Figure 2 demonstrates that the RRE avalanche threshold E_t is exceeded at a wide range of altitudes. Discharge currents of 200 kA are fairly common for +CG discharges [*Rakov and Uman*, 2003, p. 215]. There currently exist no direct current measurements >300–350 kA. Currents up to 500 kA were reported by the National Lightning Detection Network (NLDN), with an expected maximum of $\sim$800 kA (K. Cummins, personal communication, 2005). However, these estimates can involve an up to an order of magnitude uncertainty, depending on v_{rs}. Furthermore, the NLDN field-to-current conversion equation is calibrated only for smaller negative subsequent strokes, as opposed to first negative or positive strokes, the latter type being considered herein.

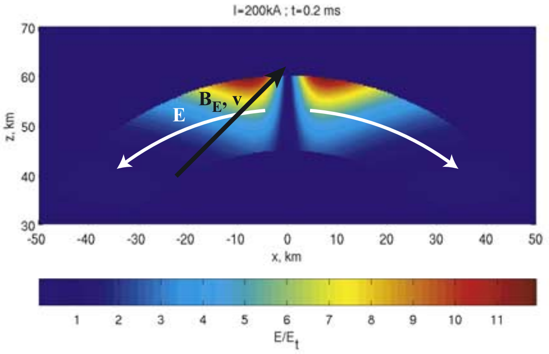

Figure 2. Dimensionless electric field $\delta = E/E_t$, where E_t is the RRE avalanche threshold, for I_p = 200 kA and β = 0.99, shown in the vertical plane containing the source and $\mathbf{B}_E$. The duration of the pulse 50 μs is chosen to correspond to the travel time to h = 15 km. The electric field is shown with white arrows. $\mathbf{B}_E$ at 45° dip angle and a RRE trajectory which is aligned with it are shown with a black arrow. The directions of arrows correspond to a −CG discharge.

[17] Figure 3 shows the calculated number of γ-photons, maximized over all possible RRE avalanche starting points $\mathbf{r}_0$. The optimal $\mathbf{B}_E$ dip angle (at which RRE motion along $\mathbf{B}_E$ partially synchronizes the electrons with the wave) is 45° for −CG and 0° for +CG. The case of −CG is illustrated in Figure 2, showing that electrons accelerated by the E field also acquire a velocity component along the direction of the EMP. For +CG, the direction of electron motion is reversed, resulting in a different optimal $\mathbf{B}_E$ dip angle. There is a dramatic increase in TGF production for β = 0.995. Electrons moving along $\mathbf{B}_E$ at 45° do not escape the atmosphere since, as schematically shown in Figure 2 for a −CG, their upward motion is interrupted at the axis of the discharge. This important feature of our mechanism is consistent with the fact that previously predicted upward escaping energetic electron beams or "curtains" [*Lehtinen et al.*, 2000] are not observed on satellites such as SAMPEX.

4. Discussion

4.1. Model Uncertainties

[18] The proposed TGF generation mechanism requires extreme values for the return-stroke current and speed. Although some measurements show possibilities for such extreme values, the methods of their derivation might involve significant errors, as discussed below equation (4). Moreover, our model is encumbered by uncertainties in the distribution of return stroke currents and the resulting duration of EMP, an essential input in equation (3), which is not well known. Our calculations in Figure 2 assume the EMP source to be effectively at the Earth surface, as is inherent in many EMP models, e.g., the modified transmission line [*Rakov and Uman*, 2003, chapter 12] with sufficiently fast current decay with height. However, if the current does not decay with height, EMP source region moves up with velocity v_{rs} and EMP duration decreases by $(1 - \beta \cos \theta)$, tending to reduce RRE (and thus TGF) production. The shortening of the pulse at large β and small θ, which reduces the validity of equation (4) for certain models, was pointed out by *Rakov and Tuni* [2003]. Another uncertainty of our model is the effective altitude of the source region. Equation (4) was considered by *Krider* [1992] for a source located at the Earth surface. On the other hand, if the EMP source region is elevated significantly above the Earth surface, as evidenced by satellite observations [*Shao et al.*, 2003], TGF production may increase, lowering the threshold, e.g. to I_p = 500 kA for β = 0.99 (and I_p = 370 kA for β = 0.995) for a source at 10 km altitude.

4.2. The Role of E × B Drift

[19] The lightning EMP **E** field is perpendicular to the direction of propagation. However, the **E** × **B** drift of the electrons in the propagation direction may extend the time over which the electrons stay synchronized with the wave, thus enhancing number of RREs and (therefore) γ-photons. Monte Carlo calculations [*Lehtinen et al.*, 1999] show that RRE avalanche can occur in $\mathbf{E} \perp \mathbf{B}_{tot}$ only when $B_{tot} = |\mathbf{B}_E + \mathbf{B}| < 2E/c$ (where $B = E/c$ is the EMP magnetic field), with the drift velocity **v** having components both along **E** × **B** and −**E** directions. The RRE avalanche rate was shown by *Lehtinen et al.* [1999] to reduce insignificantly due to a velocity component along the **E** field. For the optimal case, when **B** and $\mathbf{B}_E$ are anti-parallel, initial estimates show a slight decrease of threshold current to ∼400 kA (for β = 0.995). Moreover, TGF production then takes place at lower altitudes, ∼30–40 km, compared to ≳50 km without the **E** × **B** drift, resulting in faster growth of N_{ph} with I_p. Even the more stringent requirement for TGF detection for isotropic emission ($N_{ph} = 3 \times 10^{15}$) can then be satisfied at lower currents of I_p = 600 kA for β = 0.99 and I_p = 500 kA for β = 0.995. More accurate estimates of effects of partial synchronization due to **E** × **B** drift require 3D modeling.

4.3. Occurrence Rate of High-Current Discharges

[20] In the context of our model, TGF occurrence rate is proportional to the rate of flashes with very high return stroke peak currents, the threshold values ranging from 400–500 kA at $v_{rs} = 0.995c$ to 600–700 kA at $v_{rs} = 0.99c$ (see Figure 3). The cumulative distributions of measured currents [*Berger et al.*, 1975] imply that these values are rare for −CG lightning. For +CG discharges, extrapolation of the data of *Berger et al.* [1975], indicates that ∼0.5% of all +CG discharges may have currents >700 kA. With ∼45 s^{-1} discharges globally [*Christian et al.*, 2003], ∼15–30%

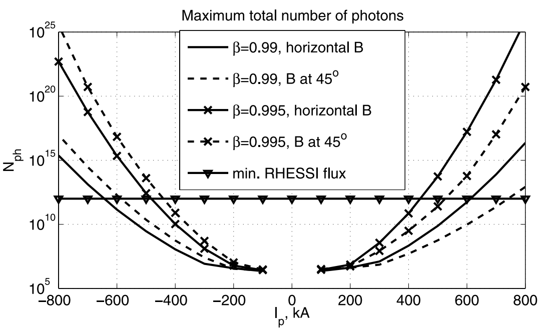

Figure 3. The maximum number of gamma photons in RHESSI range, produced for $N_0 = 10^7$. The discharge polarity is indicated by the sign of I_p.

being CG [*Rakov and Uman*, 2003, p. 44] and ~10% of all CGs being +CGs, the global rate of high peak current discharges may be ~6–12 per day, a significant fraction of the deduced TGF rate of ~50 per day [*Smith et al.*, 2005]. Considering that −CG discharges can also produce TGFs in our model, at least some of the observed TGFs may be produced by EMPs from rapidly moving return strokes. Note that many of the newly observed TGFs [*Smith et al.*, 2005] are over the oceans, and in other areas (e.g., Central America and Africa) in which ground-based lightning measurements are relatively sparse.

4.4. Cosmic Rays as the Seed of RRE Avalanche

[21] Above, we considered cosmic rays with energies in the interval $\mathcal{E}_{CR} \sim 10^8$–$10^{10}$ MeV as the source of RRE avalanche for TGF production. The smaller-energy cosmic rays, although more abundant, are less effective in producing TGFs because they produce a smaller N_0. On the other end of energy spectrum, the ultra-high energy cosmic rays of up to 3×10^{14} MeV have been observed [*Bird et al.*, 1994]. Since TGFs are rather rare (even with the RHESSI observations), they may be seeded by ultra-high energy cosmic rays [*Gurevich et al.*, 2004], with N_0 in (2) orders of magnitude higher than assumed in Figure 3, allowing the production of TGFs by return strokes with much lower peak currents and velocities. Note, however, that observed occurrence rate of ultra-high energy cosmic rays is rather low, ~1 km^{-2} yr^{-1} at energies >10^{13} MeV.

4.5. Observable Signatures of EMP-Driven Mechanism

[22] For RRE formation at higher altitudes, in the plane of $\mathbf{B}_E$, as in Figure 2, the motion of electrons and thus the TGF emission is along $\mathbf{B}_E$. While this aspect of our model is the same as that for QES model [*Lehtinen et al.*, 1999], the EMP-driven process occurs even at low latitudes. For the case described in Section 4.2, TGF emission takes place in the plane $\perp\mathbf{B}_E$, with partial cancellation of $\mathbf{B}_E$ by B of the EMP. The EMP $\mathbf{B}$ field is along a circle centered above the discharge in the counter-clockwise direction for −CG (clockwise for +CG). At the geomagnetic equator, the partial cancellation of $\mathbf{B}_E$ and $\mathbf{B}$ of the EMP and thus the TGF location is biased to the west (east) from the causative −CG (+CG), by ~20–40 km (depending on altitude). This predicted signature may be sought for in geo-location of TGFs and causative lightning as it amounts to a difference in time delays for TGFs arriving to the observing satellite from the east or the west directions. We also note that in this case the EMP-driven process occurs at lower altitudes, which may render TGFs to be isotropic due to Compton scattering of photons as they propagate to the satellite.

4.6. Application to Intracloud Lightning

[23] The formula (4) is also applicable to intracloud lightning considered by *Milikh and Valdivia* [1999], when $\theta = \pi/2$ and without the image current. However, (4) is different by a factor of $4\pi^2$ from the formula of *Milikh and Valdivia* [1999, p. 527], stating $E = \frac{\pi}{\varepsilon_0 c^2}\frac{Iv}{R}$, where the velocity of the discharge $v = L_{eff}/T = LG(D)/T$, and the distance $R = z - z_{lit}$. Thus, for intracloud lightning (4) would in fact result in a required value of peak current $I_p \approx 2$ MA, much higher than $I_p = 50$ kA quoted by *Milikh and Valdivia* [1999].

5. Summary

[24] TGFs can be produced by an EMP from lightning return strokes with high peak currents $I_p \gtrsim 450$–700 kA and velocities $v_{rs} > 0.99c$, the threshold also depending on the $\mathbf{B}_E$ dip angle. The intensity of the RRE beam, and thus the resultant TGF is highly dependent on the model of lightning current in the return stroke channel, the important factor being the effective altitude of the source of the EMP, determined by the distribution of the current in the return-stroke channel.

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