Terrestrial Gamma-ray Flashes produced by complex thunderstorm electric structures

Egor Stadnichuk

MIPT, HSE University
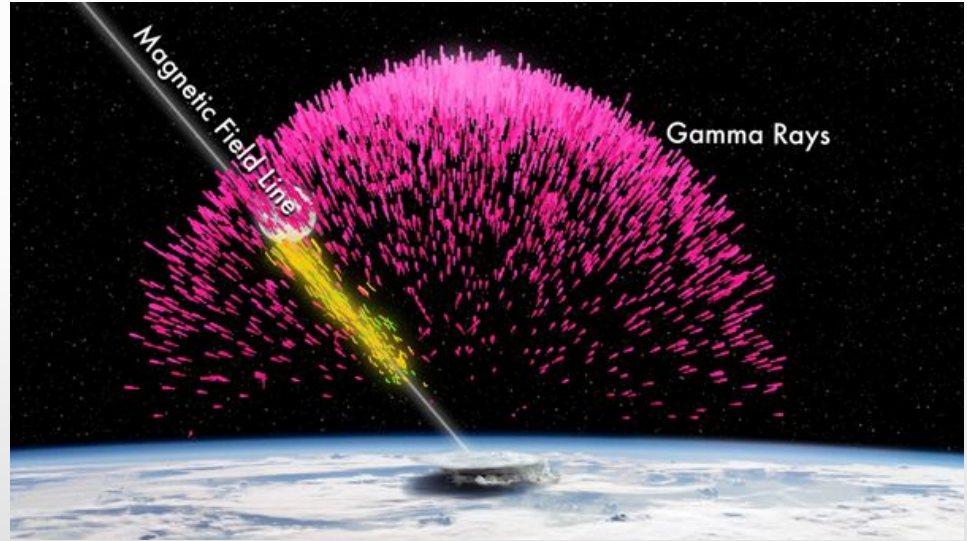
Terrestrial Gamma-ray Flashes

Space gamma telescopes observe intensive gamma-ray flashes from the Earth.

TGF – intensive and short bursts of gamma-rays radiating from the Earth into space.

The source of TGFs are thunderstorms, mostly on equatorial latitudes.
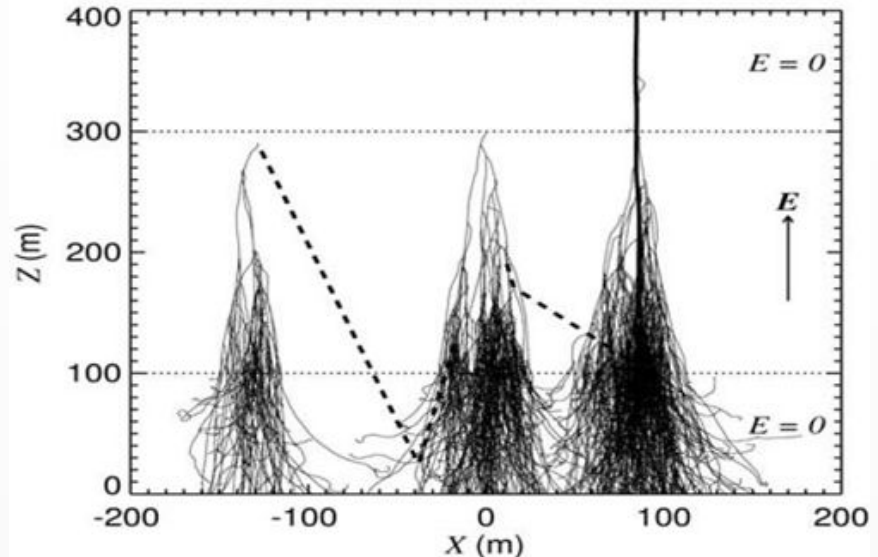

TGFs according to NASA.

Relativistic Feedback Discharge Model

TGF can be produced by a lightning leader or by relativistic runaway electron avalanches (RREA).

RREA can reproduce themselves by positron and gamma feedback mechanisms.

Feedback leads to a large number of particles, which might result in TGF.

Self-sustaining RREA within RFDM simulation. Continuous lines - electrons, dashed lines - gamma-rays, thick lines - positrons.
https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2003GL017781

Feedback operator in RFDM

A one-dimensional consideration of the dynamics of runaway electron avalanches with positron feedback yields the following operator:

$$\frac{df_{i+1}(z)}{dz} = \int_0^L d\zeta K(z,\zeta) \frac{\partial f_i(\zeta)}{\partial \zeta}$$

Operator core:

$$K(z,\zeta) = \frac{P\lambda_{RREA}}{\lambda_2\lambda_+\lambda_\gamma} \frac{\lambda_{RREA}\lambda_x}{\lambda_x-\lambda_{RREA}} \cdot e^{-\frac{\zeta}{\lambda_{RREA}}} e^{\frac{z}{\lambda_x}} \left(e^{\frac{L(\lambda_x-\lambda_{RREA})}{\lambda_x\lambda_{RREA}}} - e^{\frac{z(\lambda_x-\lambda_{RREA})}{\lambda_x\lambda_{RREA}}} \right)$$
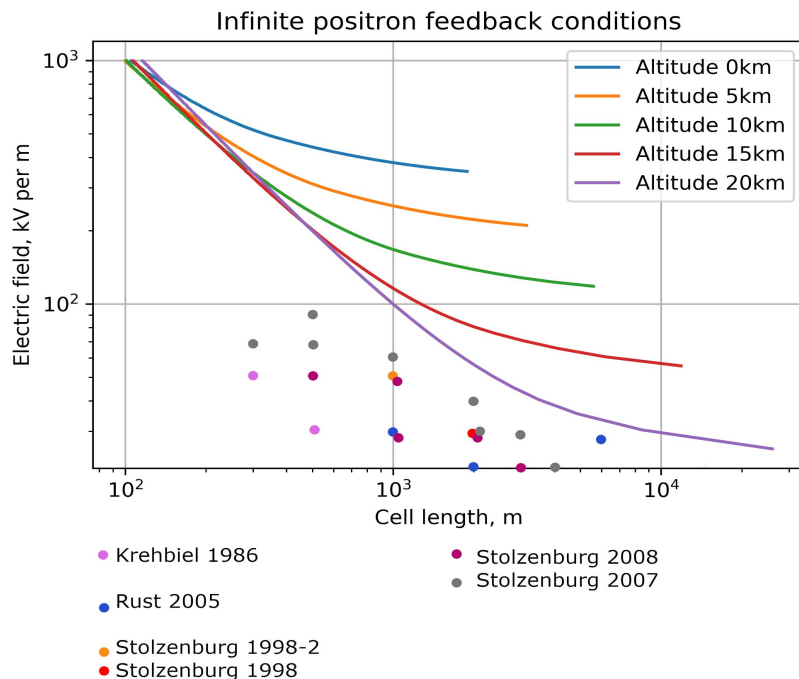
Eigenvalue (feedback factor):

$$\Gamma = \frac{P\lambda_{RREA}}{\lambda_2\lambda_\gamma\lambda_{\gamma\rightarrow e^-e^+}\cos\alpha} \left(\frac{\lambda_{RREA}\lambda_x}{\lambda_x-\lambda_{RREA}} \right)^2 \left(e^{\frac{L(\lambda_x-\lambda_{RREA})}{\lambda_x\lambda_{RREA}}} - 1 - \frac{L(\lambda_x-\lambda_{RREA})}{\lambda_x\lambda_{RREA}} \right)$$

TGF necessary conditions in RFDM

Infinite positron feedback conditions

Necessary conditions for TGF production by RREA: $\Gamma = 1$

Such conditions are not observed in the direct experiment.
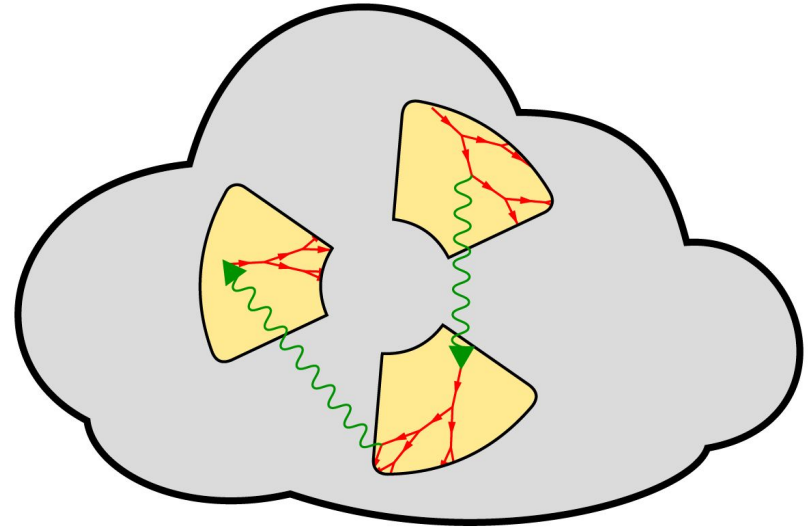
Reactor model

RFDM assumes the dynamics of RREA within a single region with a uniform electric field.

RREA can self-sustainably multiply in a system with a large number of separate RREA-producing regions - cells.

The multiplication of RREAs due to the geometry of the electric field is called the reactor feedback.

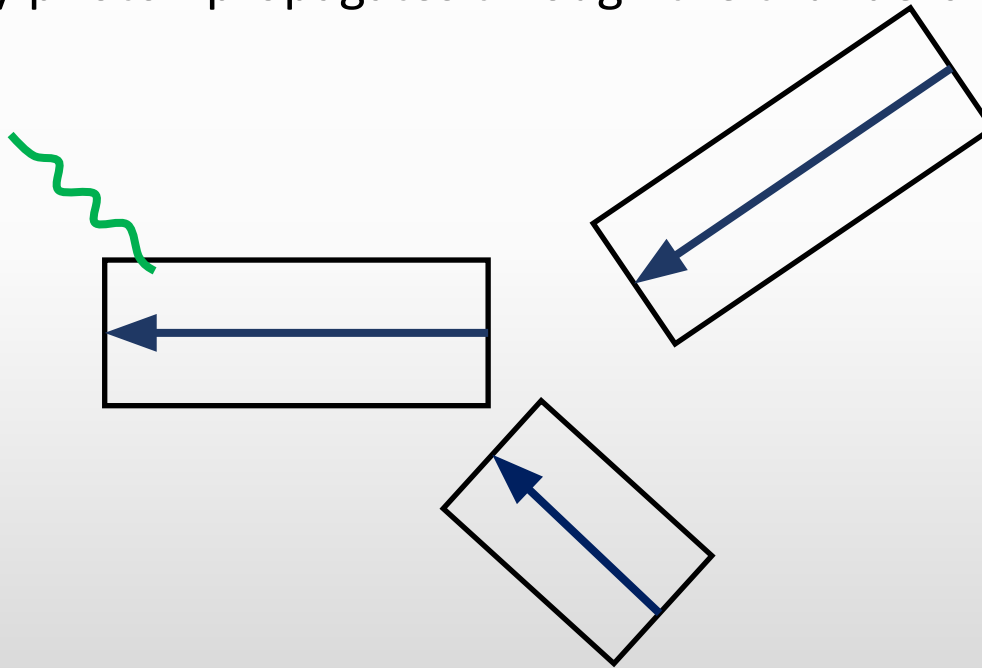

An illustration of the reactor feedback.
https://doi.org/10.1029/2021JD035278
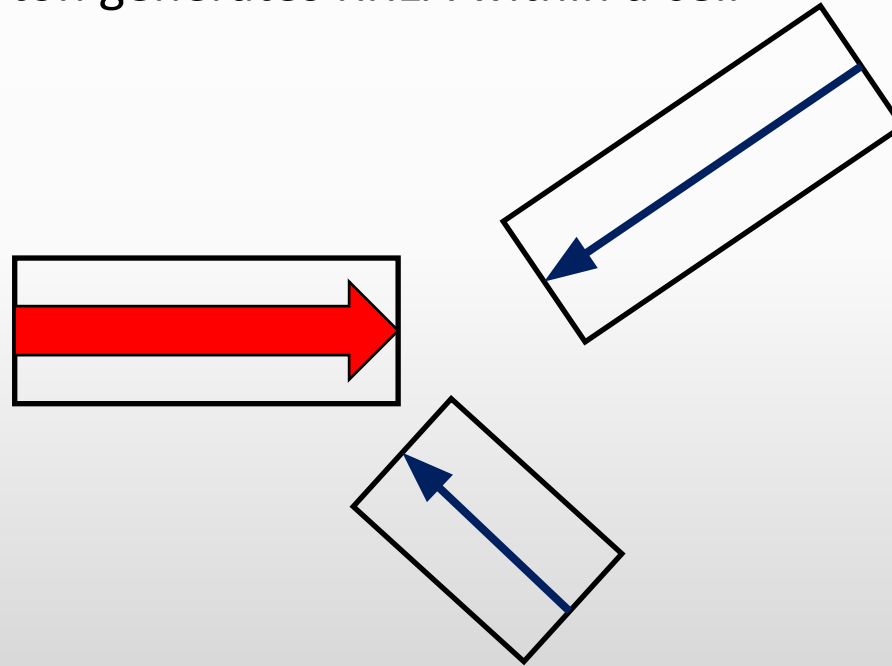
Reactor feedback

A gamma-ray photon propagates through the thundercloud:

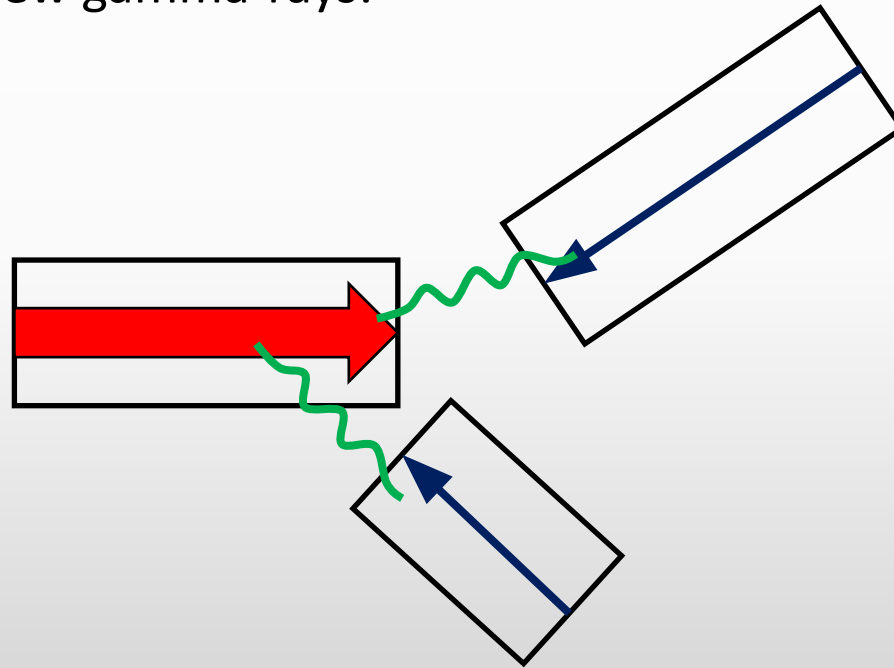# Reactor feedback

Gamma-ray photon generates RREA within a cell:
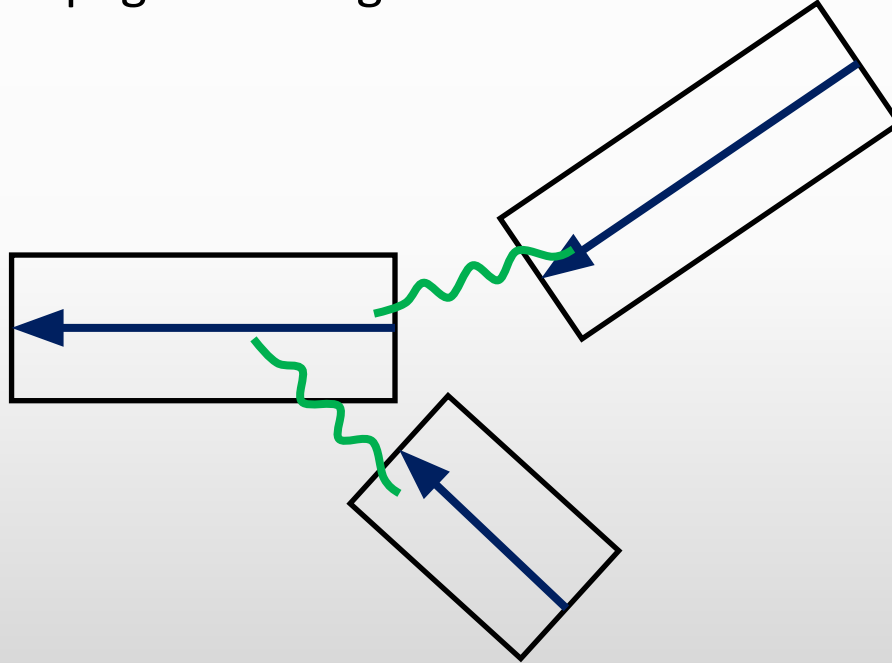
Reactor feedback

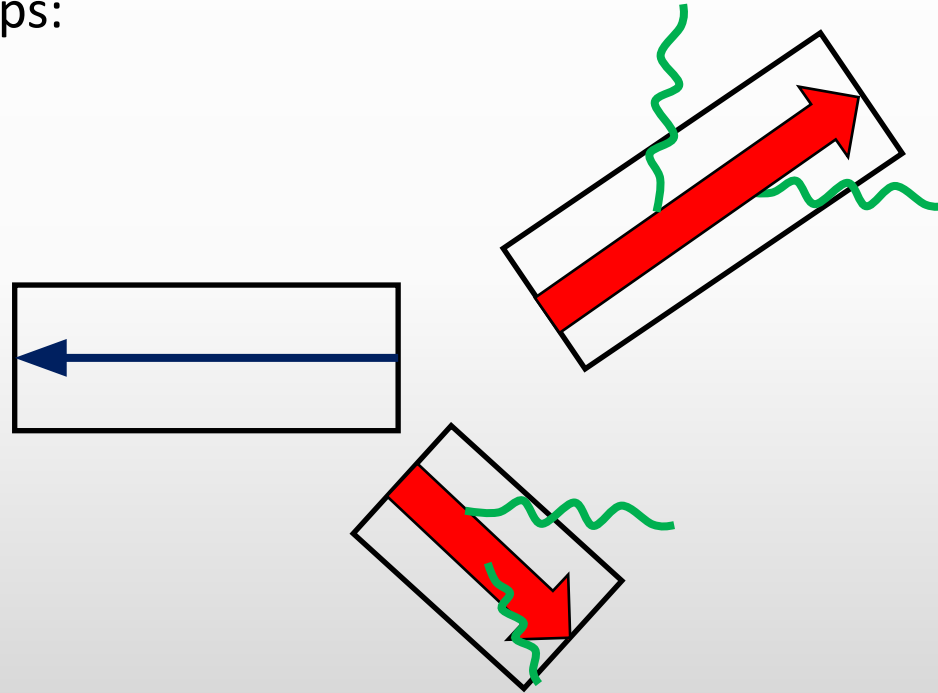RREA radiates new gamma-rays:

These gammas propagate through the thundercloud:
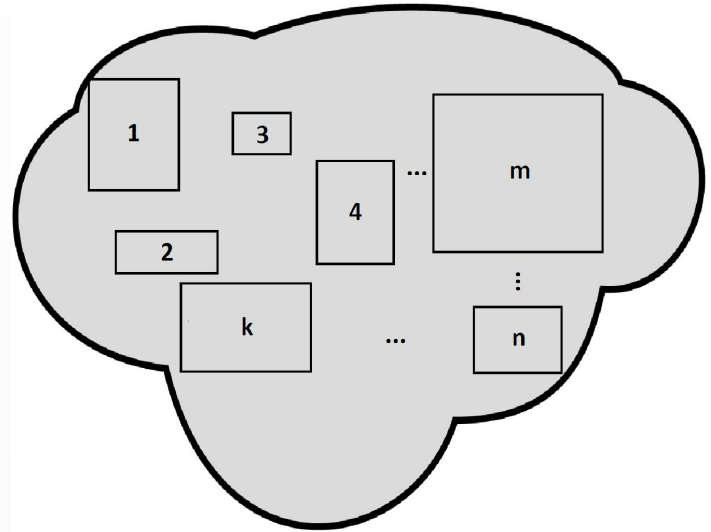
The process loops:

General feedback operator

The total contribution of the radiation of all cells of the thundercloud to RREA, generated inside the m-th cell:

$$A_m^{i+1}(z) = \sum_{k=1}^{n} \hat{F}_{mk} A_k^i(z)$$

Thus, the RREA distribution vector in the cloud changes from generation to generation by the action of the feedback matrix:
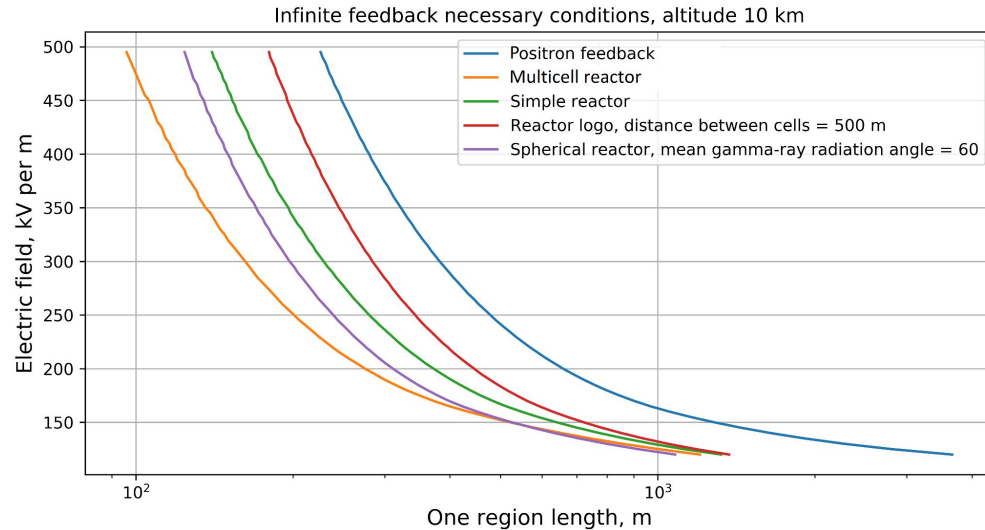
$$\vec{A}^{i+1}(z) = \hat{F} \vec{A}^i(z)$$

Results

The reactor feedback softens the conditions required for self-sustainable RREAs at the expense of the geometry of the thunderstorm electric field.

Infinite feedback necessary conditions, altitude 10 km

E. Stadnichuk. Terrestrial Gamma-ray Flashes produced by complex thunderstorm electric structures

Conclusions

- Non-uniform thunderstorm electric-field geometry leads to positive feedback in RREA physics.
- Reactor feedback arises due to high-energy particles exchange between separate thunderstorm regions.
- The dynamics of RREA with positive feedback in thunderclouds can be described with the feedback operator.
- The problem of finding a criterion for the occurrence of TGF in the system under study is reduced to finding the eigenvalues of the operator.
- The more complex the structure of the thunderstorm electric field, the smaller the electric field is required for TGF to occur.
- The contribution of positron feedback in complex thunderstorm systems is negligible compared to reactor feedback for considered electric fields geometries.

Thank you for your attention!

egrstadnichuk@yandex.ru
vk.com/egrstadnichuk
@EgorStadnichuk

Acknowledgements

Bibliography

- Stadnichuk, E., Svechnikova, E., Nozik, A., Zemlianskaya, D., Khamitov, T., Zelenyy, M., & Dolgonosov, M. (2021). Relativistic runaway electron avalanches within complex thunderstorm electric field structures. Journal of Geophysical Research: Atmospheres, 126, e2021JD035278. https://doi.org/10.1029/2021JD035278
- E. Stadnichuk, E. Svechnikova, The criterion for infinite positron feedback in dynamics of relativistic runaway electron avalanches, arXiv:2201.13220 [physics.plasm-ph]
- Dwyer J. R. Journal of Geophysical Research: Atmospheres1132008. https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2007JD009248
- Gurevich A.V., Milikh G.M., Roussel-Dupre R. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm // Physics Letters A. — 1992. — Vol. 165, no. 5. — Pp. 463 – 468. — URL: http://www.sciencedirect.com/science/article/pii/037596019290348P.
- R. Dwyer J. A fundamental limit on electric fields in air // Geophysical Research Letters. — Vol. 30, no. 20. — URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2003GL017781.
- Geant4—a simulation toolkit / S. Agostinelli, J. Allison, K. Amako et al. // Nuclear Instruments and Methods in Physics Research Section A: Accelerators
- Л.П. Бабич, Лавины релятивистских убегающих электронов, 2020, Успехи Физических Наук
- R.U. Abbasi, M. Abe, T. Abu-Zayyad, et al, The bursts of high energy events observed by the telescope array surface detector, Physics Letters A, Volume 381, Issue 32, 2017, Pages 2565-2572, ISSN 0375-9601, https://doi.org/10.1016/j.physleta.2017.06.022.
- Brothers, M. D., Bruning, E. C., & Mansell, E. R. (2018). Investigating the Relative Contributions of Charge Deposition and Turbulence in Organizing Charge within a Thunderstorm, Journal of the Atmospheric Sciences, 75(9), 3265-3284. Retrieved May 24, 2022, from https://journals.ametsoc.org/view/journals/atsc/75/9/jas-d-18-0007.1.xml
- Østgaard, N., Neubert, T., Reglero, V., Ullaland, K., Yang, S., Genov, G., et al. (2019). First 10 months of TGF observations by ASIM. Journal of Geophysical Research: Atmospheres, 2019; 124: 14024– 14036. https://doi.org/10.1029/2019JD031214
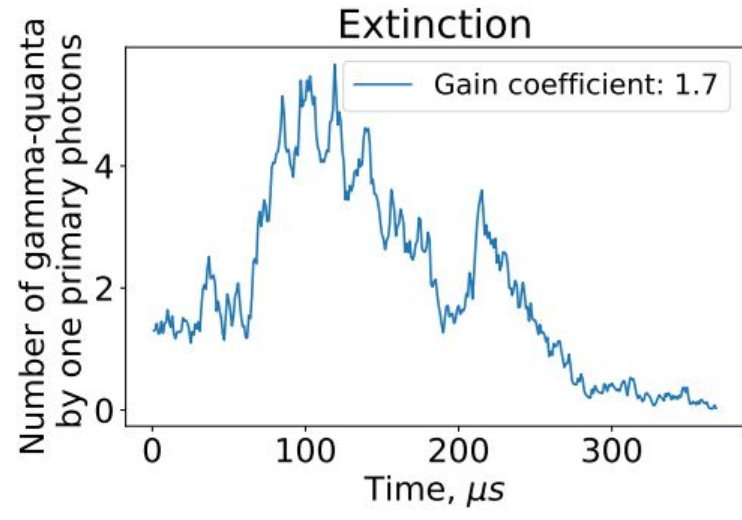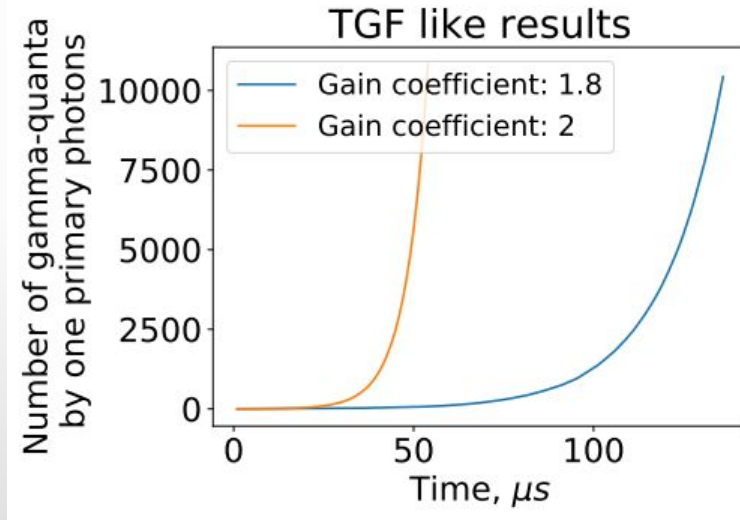
Thunderstorm electric structure

The charge structure of a thundercloud can be much more complex than the multilayer structure with a uniform electric field assumed in RFDM.

https://journals.ametsoc.org/view/journals/atsc/75/9/jas-d-18-0007.1.xml

(a) Multicell Net Charge
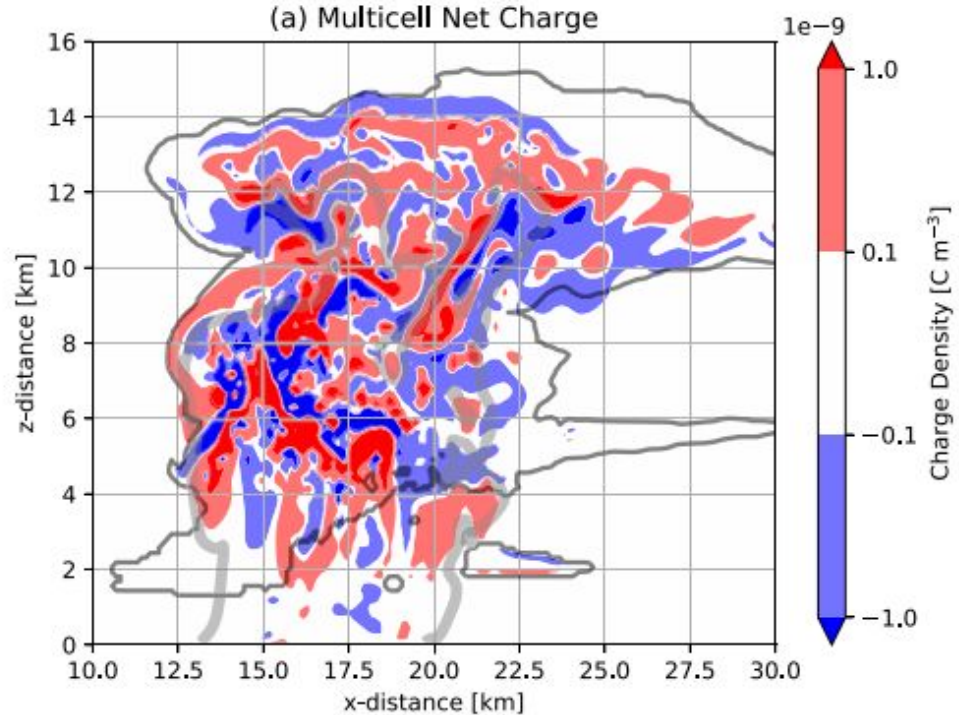
Multicell reactor simulation results

Reactor model can potentially describe TGFs and gamma-ray glows.

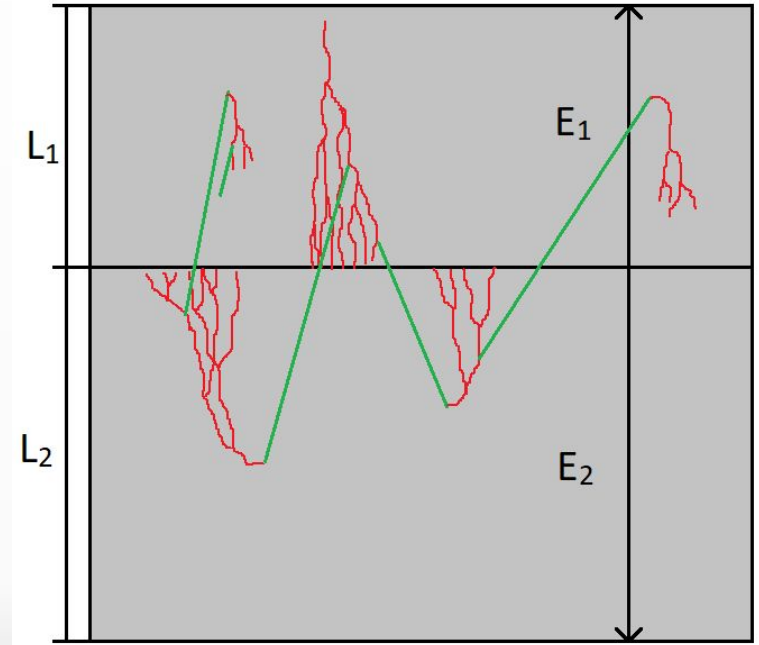E. Stadnichuk. Terrestrial Gamma-ray Flashes produced by complex thunderstorm electric structures

Simple reactor

For a thundercloud with the simplest inhomogeneous field structure, the reradiation matrix Γ has the form of a 2x2 matrix.

The infinite feedback conditions are determined by the maximum eigenvalue of the matrix:

$$\lambda_{\mathrm{max}} = \frac{\Gamma_{11} + \Gamma_{22} + \sqrt{(\Gamma_{11} - \Gamma_{22})^2 + 4\Gamma_{12}\Gamma_{21}}}{2} \geq 1$$

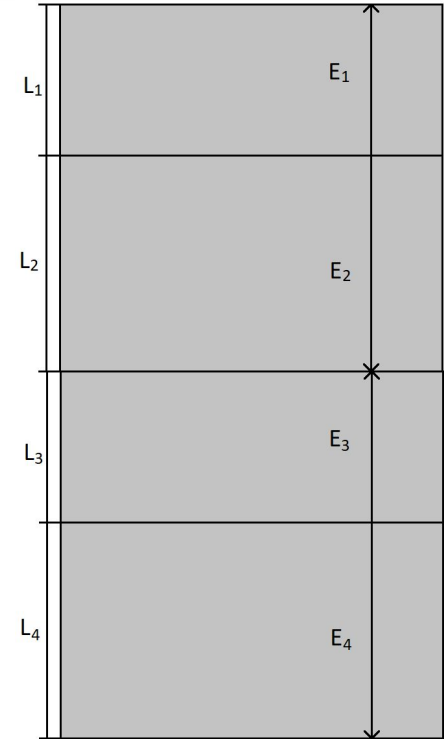https://meetingorganizer.copernicus.org/EGU21/EGU21-13395.html

Multilayer thundercloud

If we neglect the relativistic feedback, the feedback matrix has the form:

$$\Gamma = \begin{pmatrix} 0 & \Gamma_{12} & 0 & \Gamma_{14} \\ \Gamma_{21} & 0 & 0 & \Gamma_{24} \\ \Gamma_{31} & 0 & 0 & \Gamma_{34} \\ \Gamma_{41} & 0 & \Gamma_{43} & 0 \end{pmatrix}$$

The system consists of two simple reactors that reinforce each other. Feedback coefficient:

$$\lambda = \frac{\Gamma_{14} + \sqrt{\Gamma_{14}^2 + 4\Gamma_{12}^2 + 4\Gamma_{12}\Gamma_{31}}}{2}$$
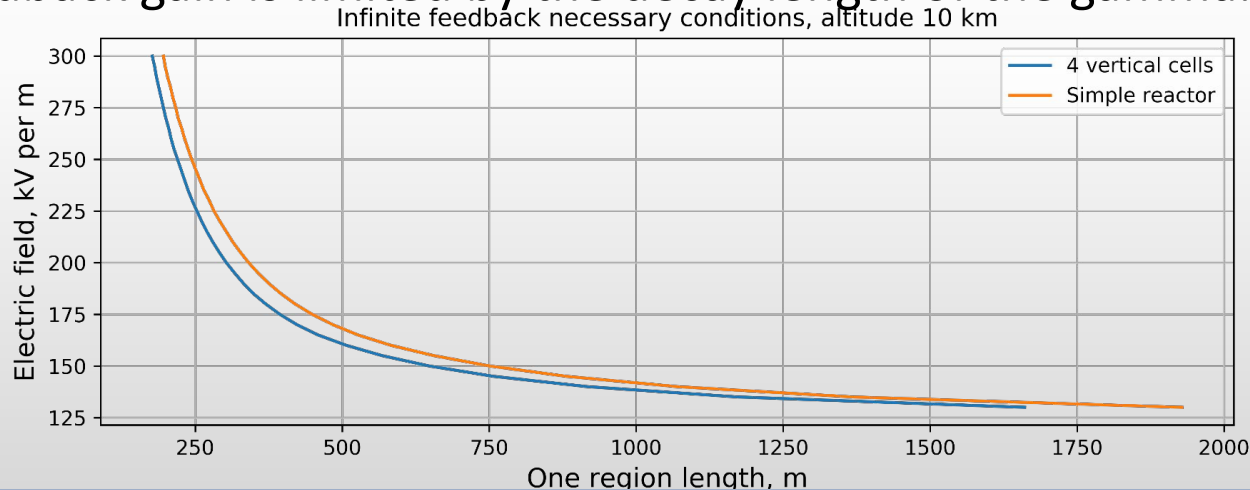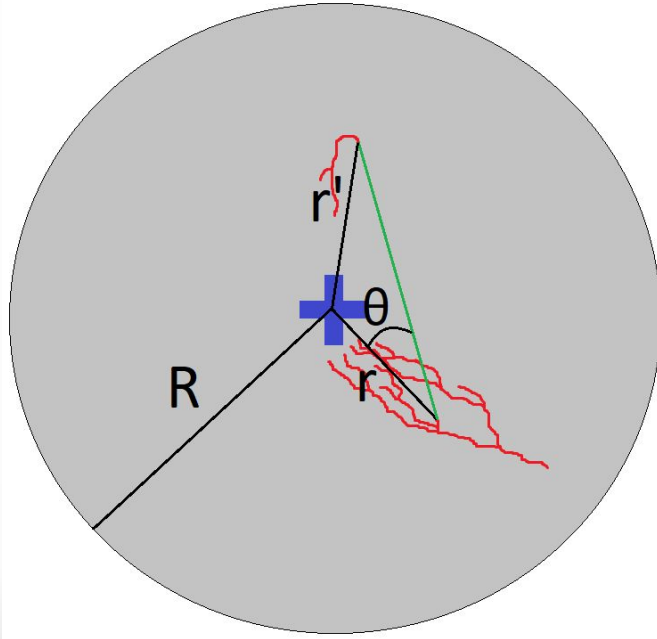
Effect of the number of charge layers

A large number of charge layers softens the conditions for the occurrence of TGF. Also, the more layers, the higher the intensity of gamma radiation.

The feedback gain is limited by the decay length of the gamma.

Infinite feedback necessary conditions, altitude 10 km

Spherical reactor

Toy model.

Feedback occurs geometrically.

All cells accelerate avalanches of runaway electrons towards each other.

This leads to an intensive exchange of bremsstrahlung gamma radiation between the cells.

Gamma rays form new avalanches by knocking out relativistic electrons inside the reactor.