Relativistic runaway electron avalanche acceleration in complex thunderstorm electric structures

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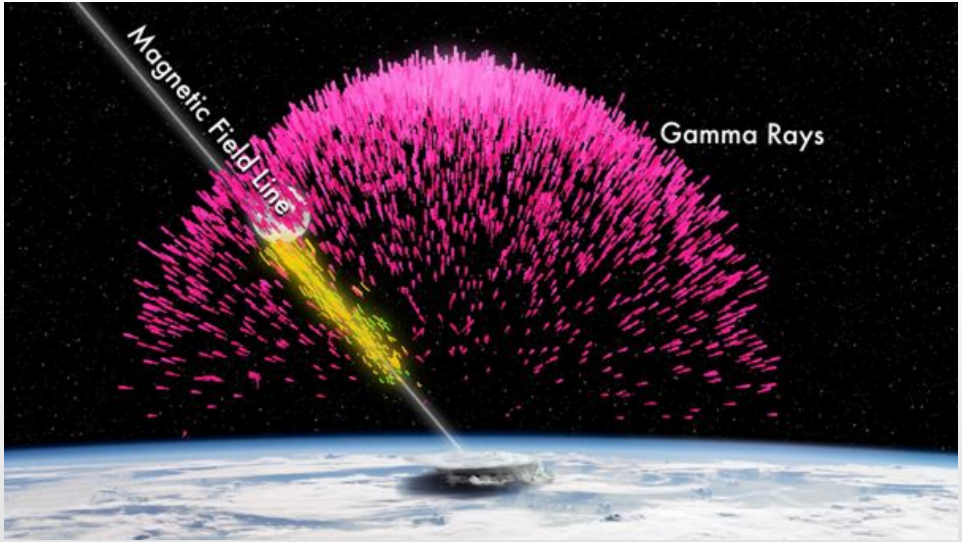
Terrestrial Gamma-ray Flashes

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.



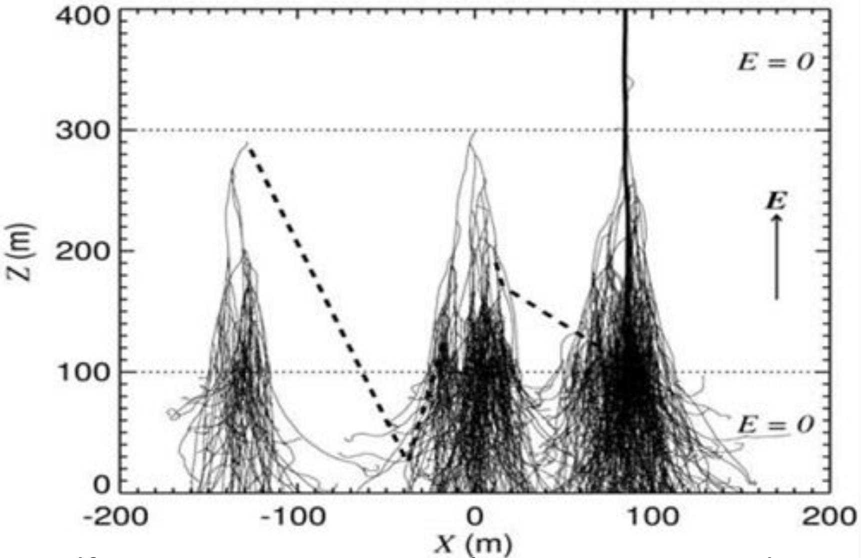
TGFs according to NASA.

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.

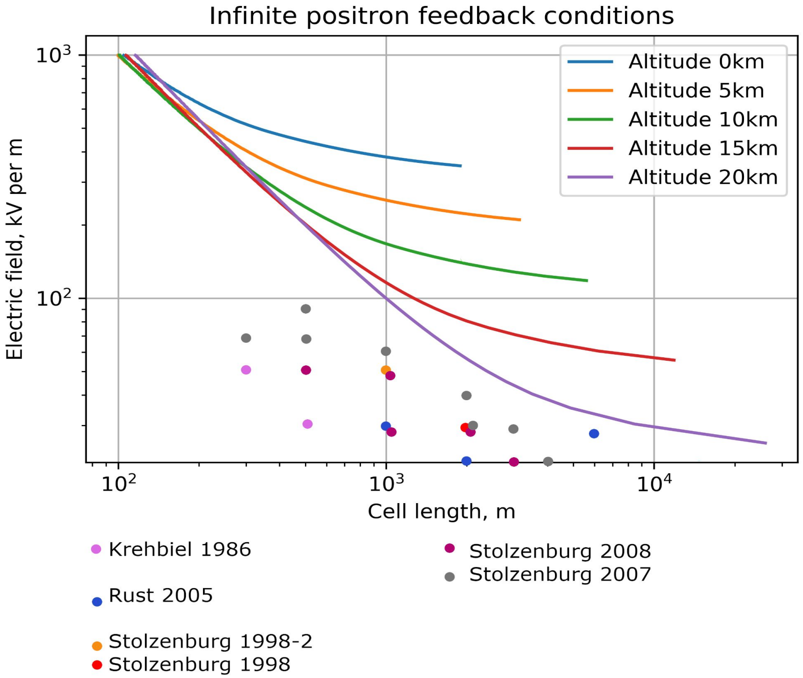
Feedback leads to a large number of particles, which might result in TGF.



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

TGF necessary conditions in RFDM



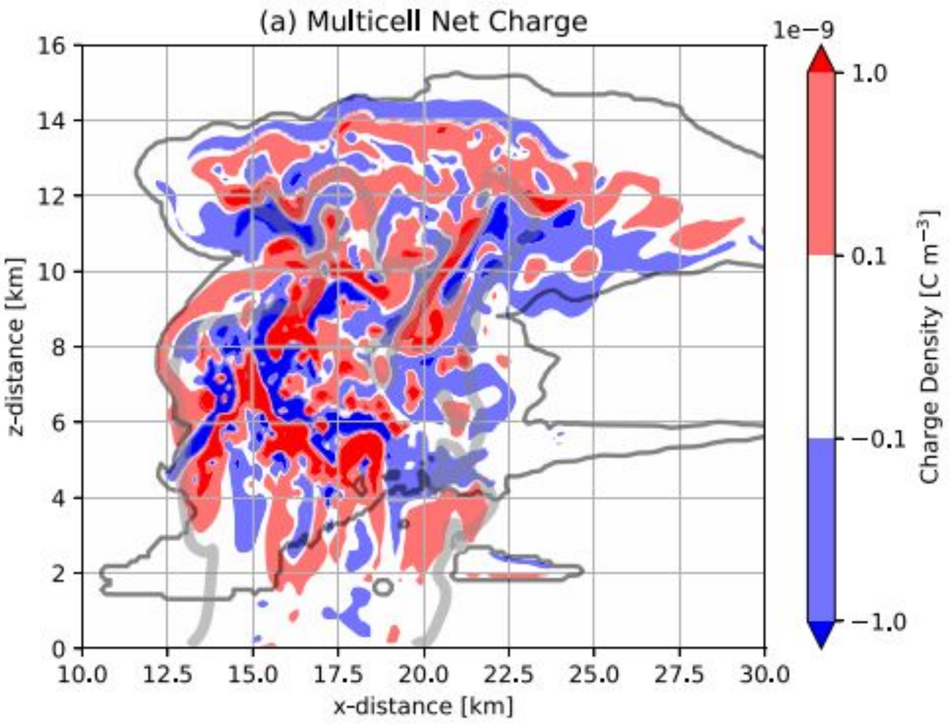
Necessary conditions for TGF production by RREA: $\Gamma = 1$

Such conditions are not observed in the direct experiment.

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

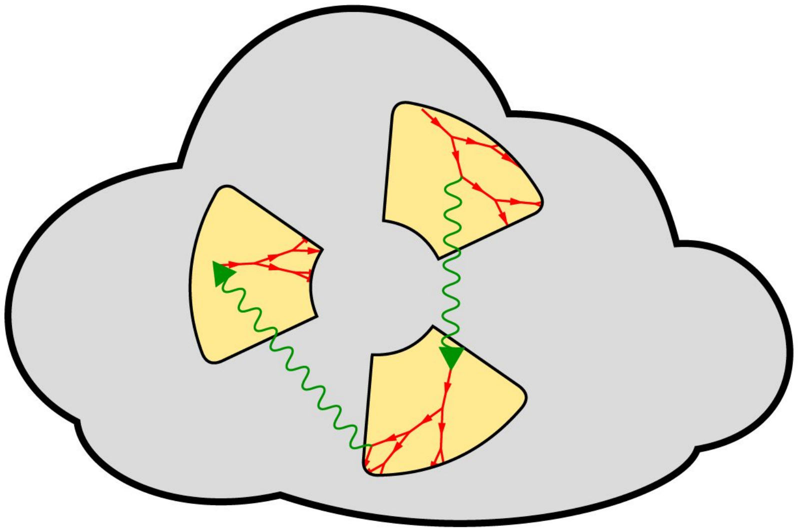


Reactor model

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.

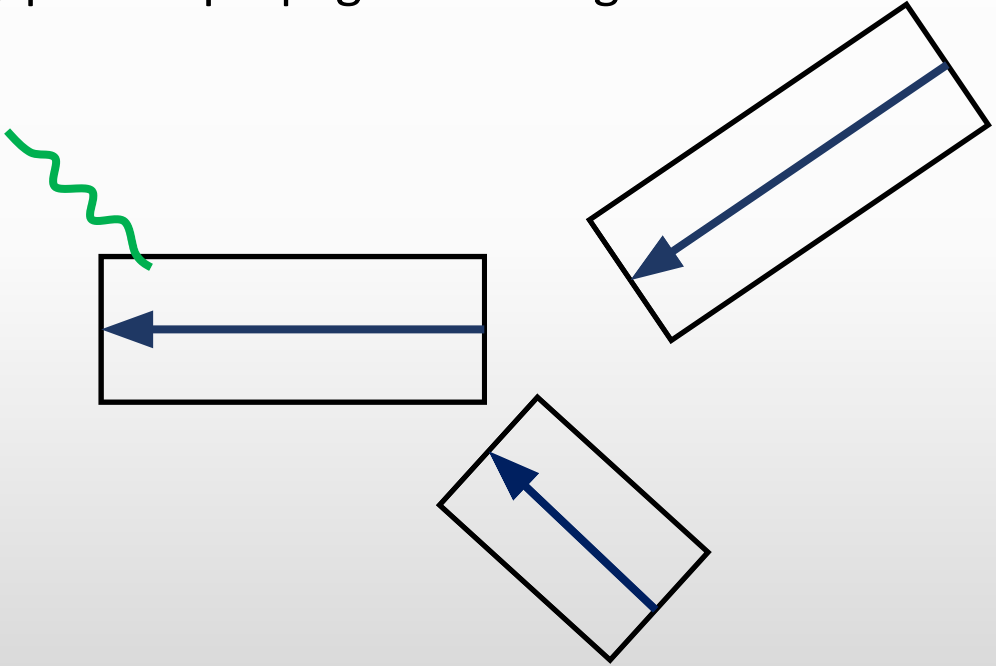


An illustration of the reactor feedback.

https://doi.org/10.1029/2021JD035278

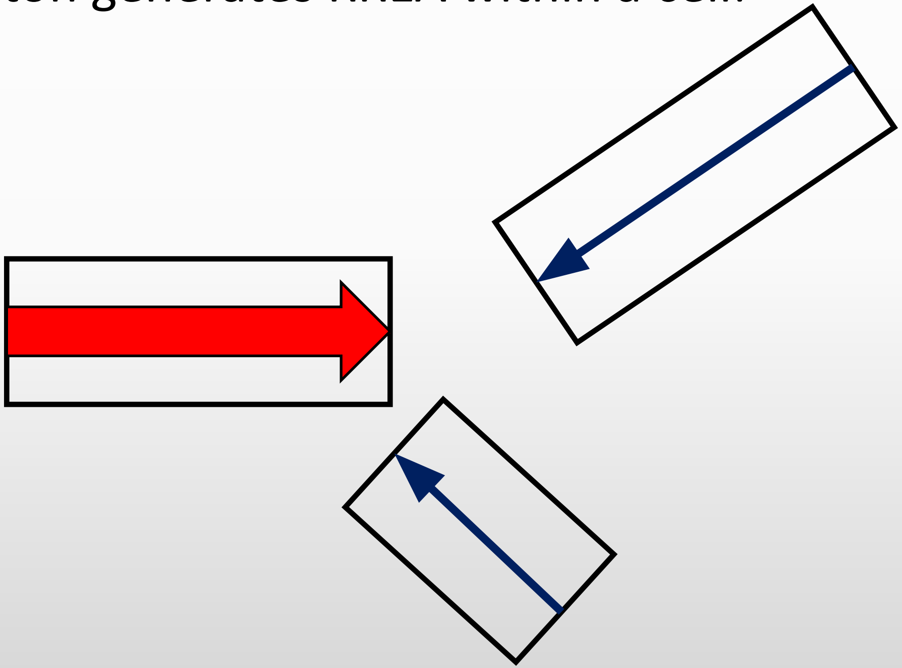
Reactor feedback

A gamma-ray photon propagates through the thundercloud:



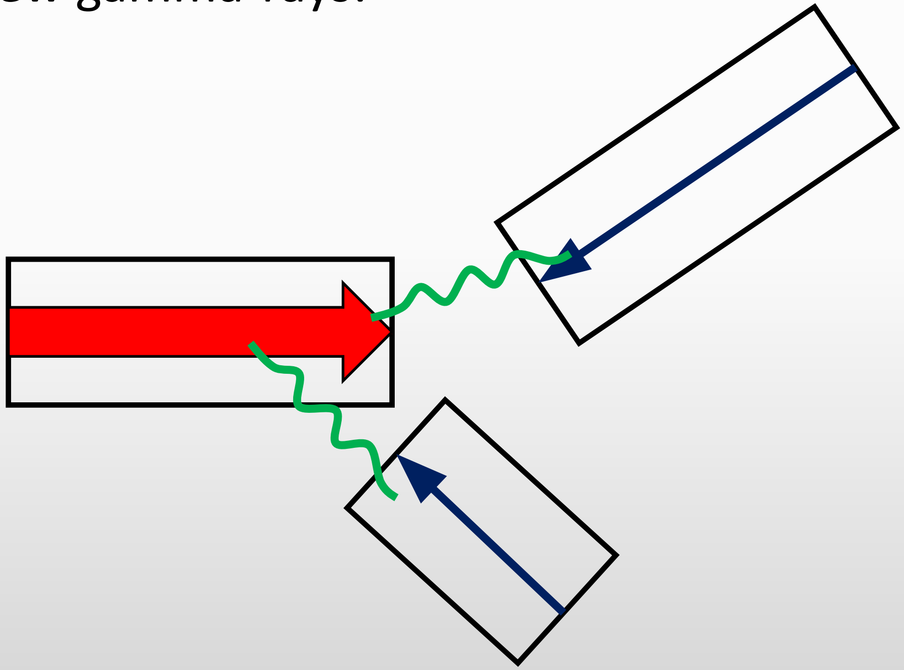
Reactor feedback

Gamma-ray photon generates RREA within a cell:



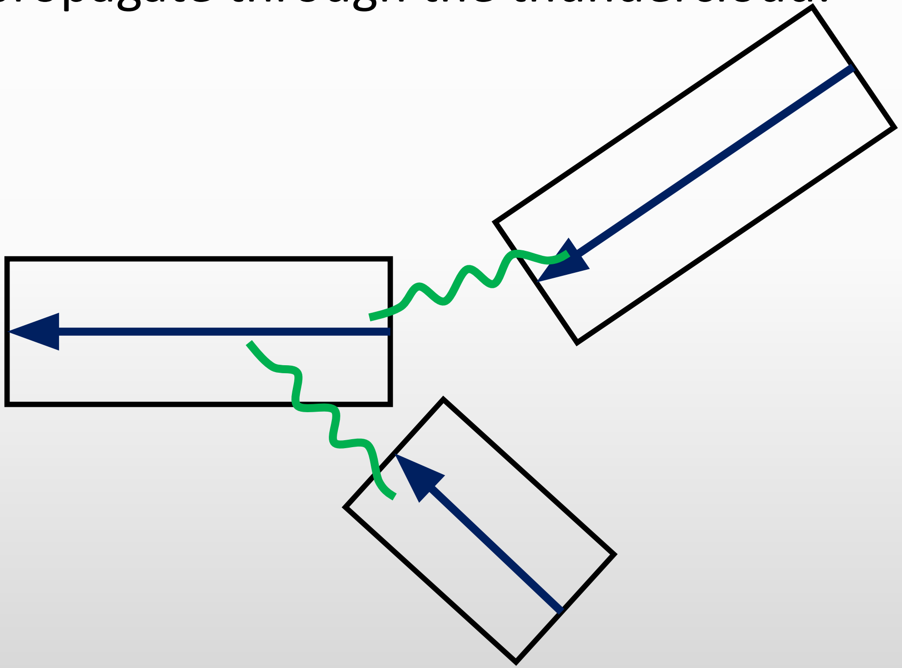
Reactor feedback

RREA radiates new gamma-rays:



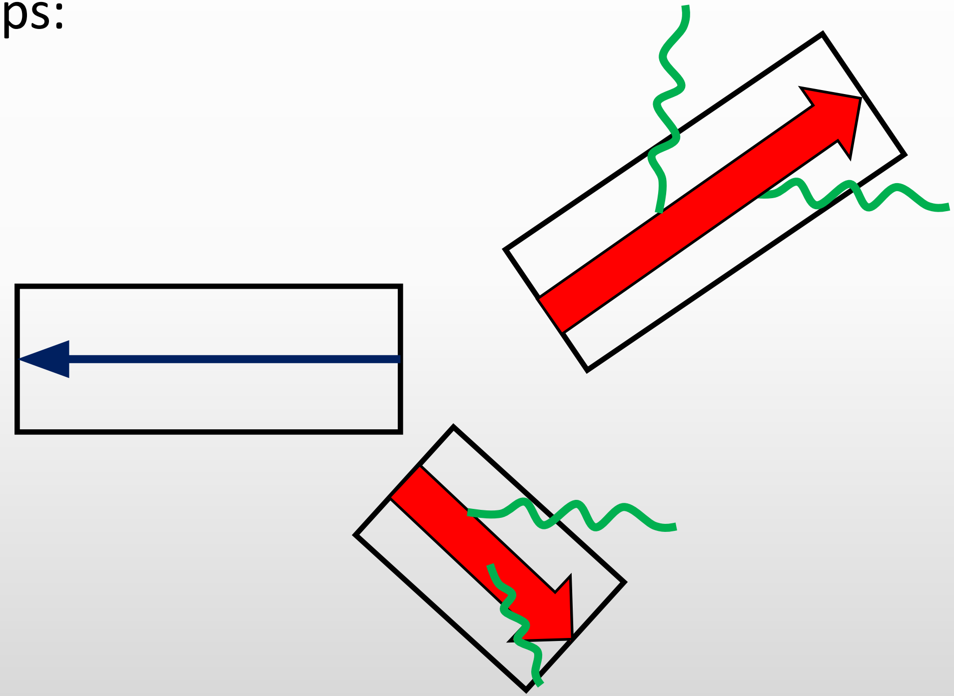
Reactor feedback

These gammas propagate through the thundercloud:



Reactor feedback

The process loops:



Multicell reactor

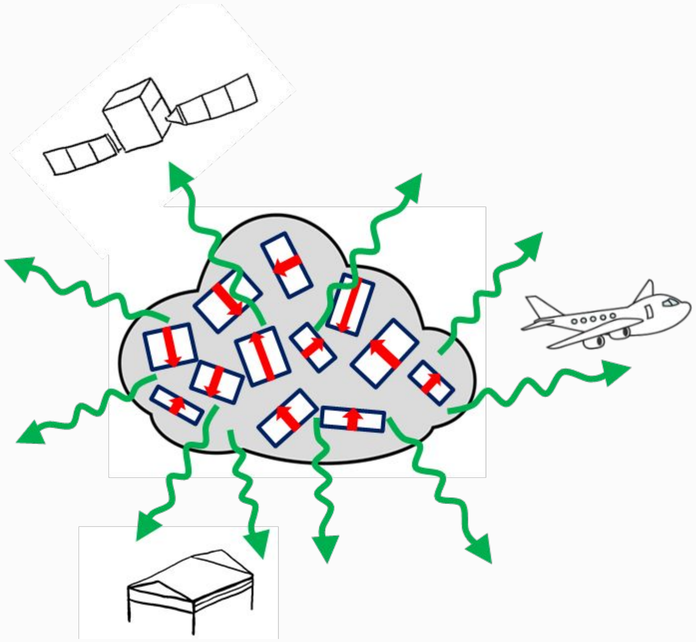
A system of a large number of interacting differently oriented cells can be described with the following equation:

$$D\Delta n - c\Sigma n + \nu c\Sigma n = \frac{\partial n}{\partial t}$$

$$n|_{z=0,h} = 0$$

$$n|_{r=a} = 0$$

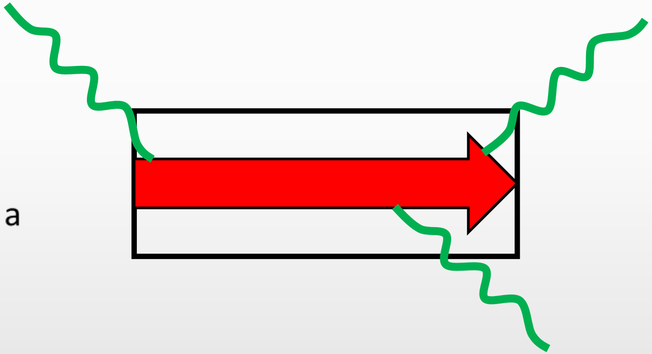
n - gamma-ray concentration, D - gamma-ray diffusion coefficient, Σ - gamma-ray macroscopic cross-section.



Local multiplication factor

Local multiplication factor is mean number of gammas generated by one gamma in a cell:

$$\nu = \text{RREA FORMATION PROBABILITY} \cdot \frac{\lambda_{RREA}}{\lambda_{e\rightarrow\gamma}} \cdot \left(\exp\left(\frac{L}{\lambda_{RREA}}\right) - 1\right)$$



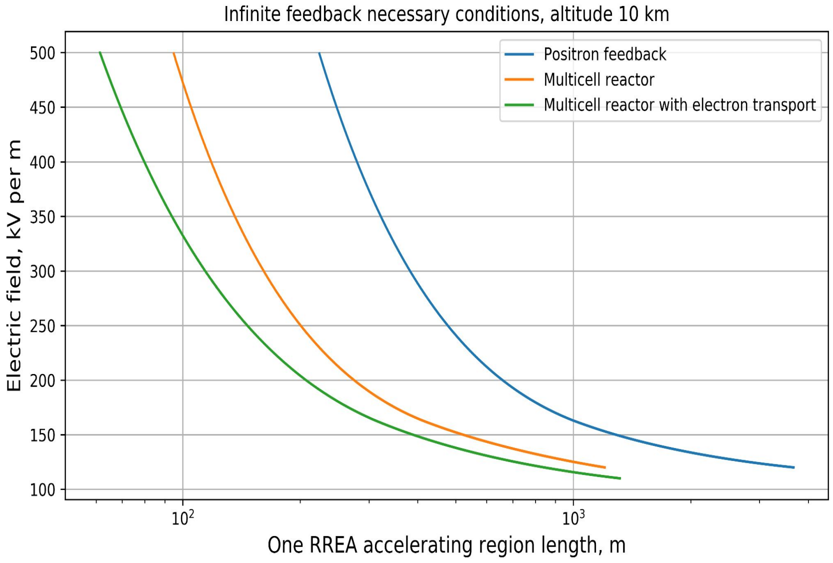
L – cell length.

RREA FORMATION PROBABILITY – average probability of RREA creation in a critical cell by gamma, also considering electric field geometry.

$\lambda_{RREA} = \frac{22mc^2}{eE}$ - Gurevich characteristic length of avalanche exponential growth (m, e – electron mass and charge, E – mean critical electric field).

$\lambda_{e\rightarrow\gamma}$ - gamma production by runaway electrons length.

Runaway electron transport



Local multiplication factor can consider the impact of runaway electron transport between cells on gamma-ray multiplication in the following way:

$$\nu = \frac{P}{L}\frac{\lambda_{RREA}}{\lambda_{e^- \to \gamma}}\left(\lambda_{RREA} e^{\frac{l}{\lambda_{RREA}}} - \lambda_{RREA} - L\right) + \\ + \frac{\lambda_{RREA}}{\lambda_{e^- \to \gamma}}\left(e^{\frac{L}{\lambda_{RREA}}} - 1\right) \cdot \frac{0.5\delta P \frac{\lambda_{RREA}}{L}\left(e^{\frac{L}{\lambda_{RREA}}} - 1\right)}{1 - 0.5\delta e^{\frac{L}{\lambda_{RREA}}}}$$

The additional term softens self-sustainable reactor feedback conditions.

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):

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

https://arxiv.org/abs/2201.13220

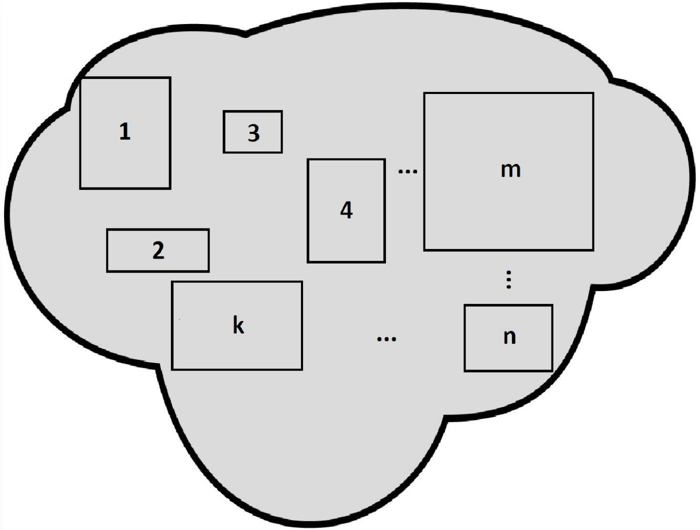
General feedback operator

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

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

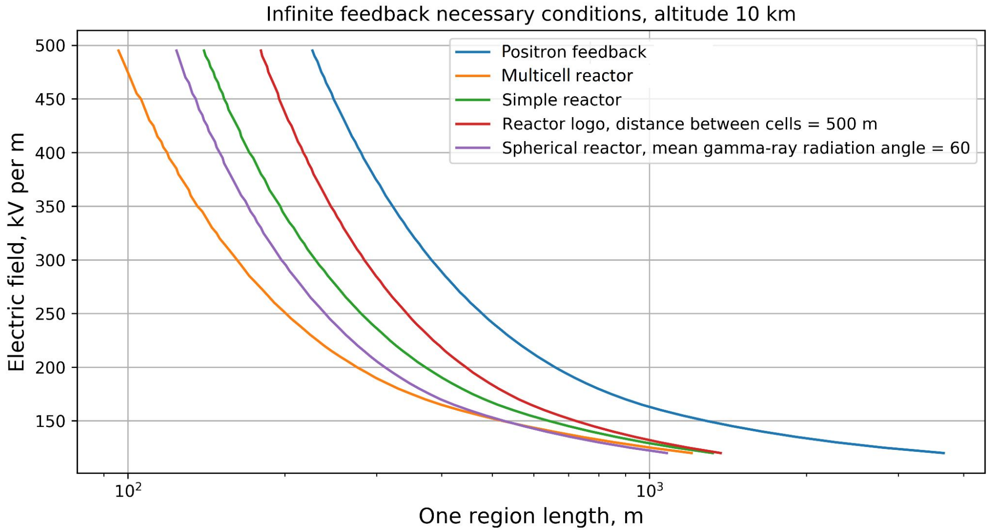
Thus, the RREA distribution vector in the cloud changes from generation to generation by the action of the feedback matrix:

$$\vec{A}^{i+1}(z) = \hat{F}\vec{A}^{i}(z)$$

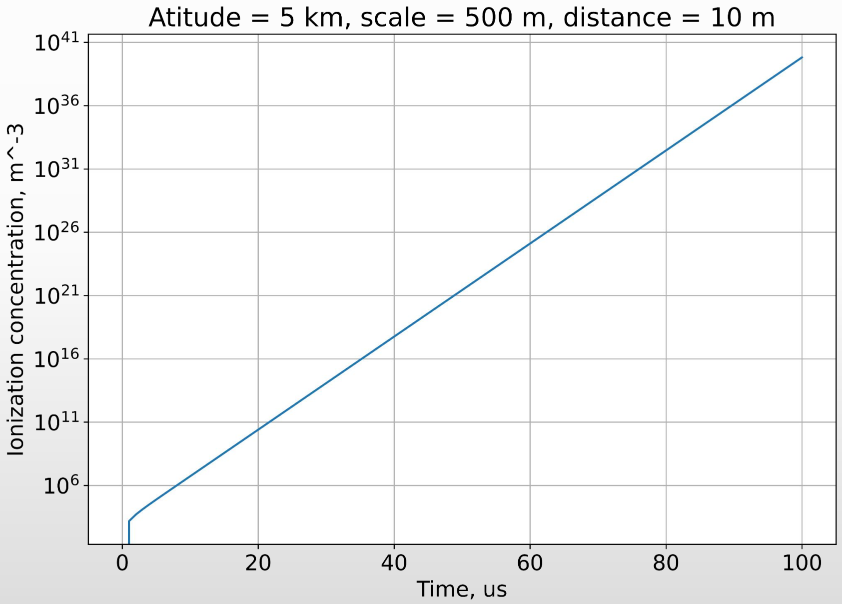


Infinite feedback conditions

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



Lightning initiation by infinite feedback



Infinite feedback leads to exponential growth of ionizing particles in thunderstorms.

This can cause extreme ionization rate, which can result in lightning leader formation.

In multicell reactor infinite feedback leads to fast and bulk ionization, which allows to connect charges distributed throughout the volume of a cloud.

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 reactor feedback can be described as a chain reaction in a system of a large number of cells.
- The dynamics of RREA with positive feedback in thunderclouds can be described with the feedback operator.
- Reactor feedback can initiate lightning.

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Thank you for your attention!

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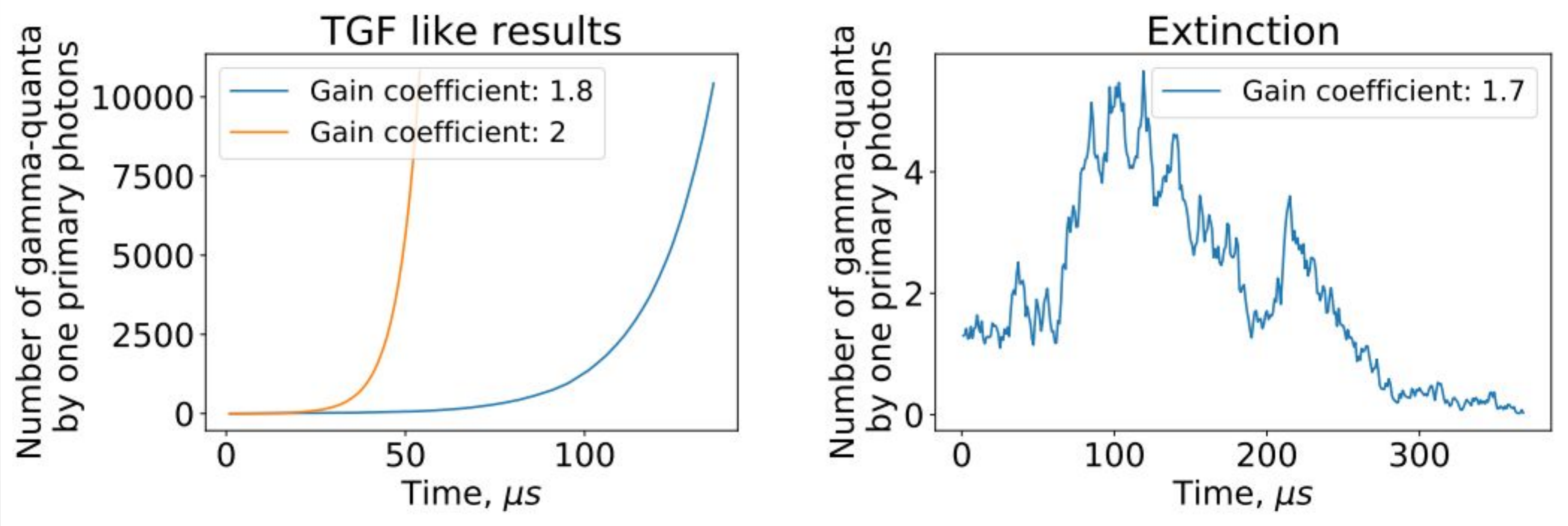
Multicell reactor simulation results



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

https://doi.org/10.1029/2021JD035278

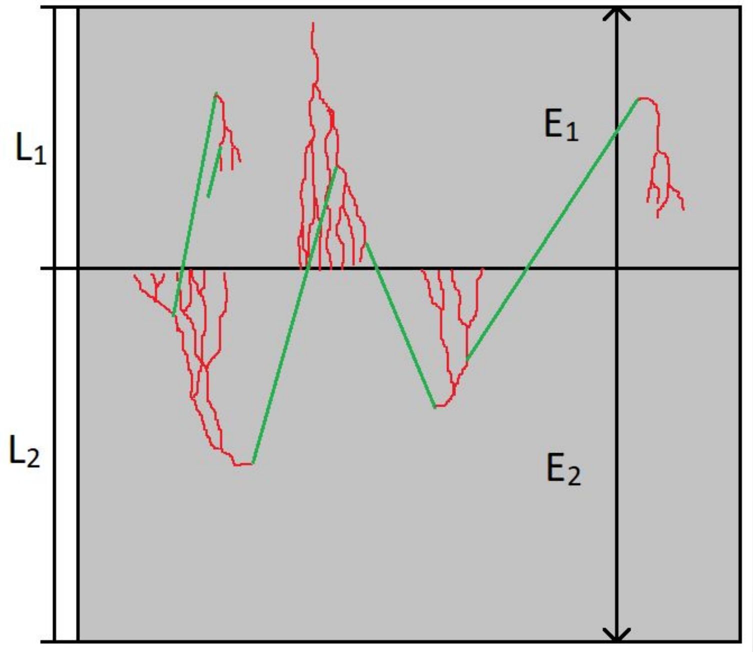
Simple reactor

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:

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

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



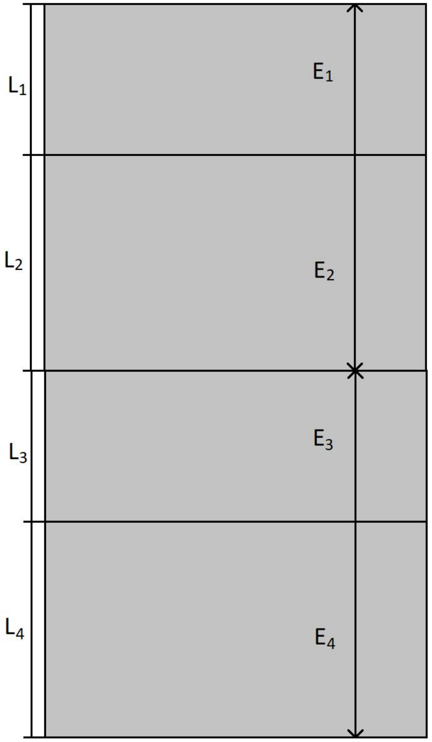
Multilayer thundercloud

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:

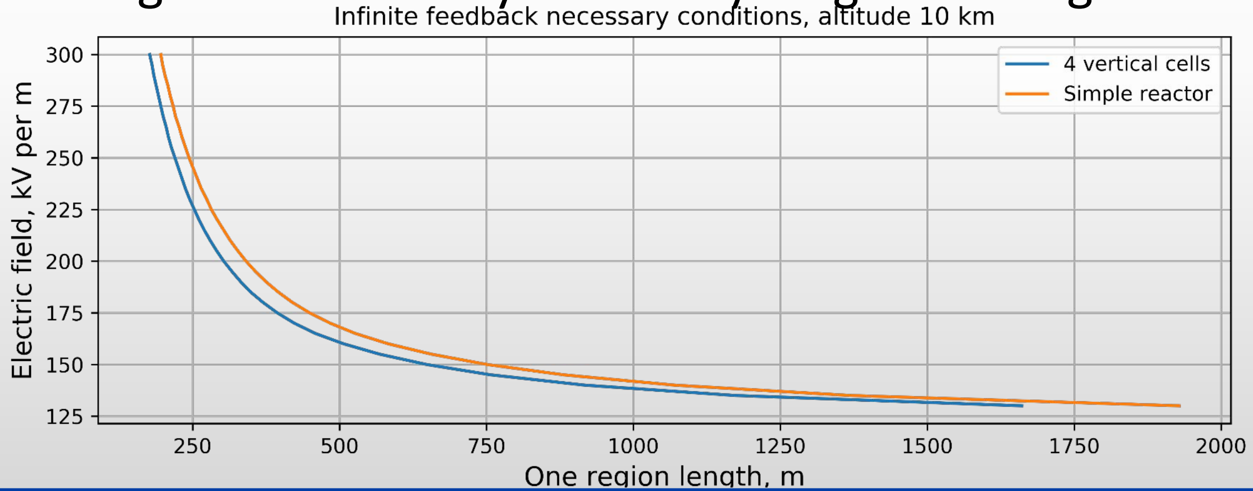
$$\lambda = \frac{\Gamma_{14} + \sqrt{\Gamma_{14}^2 + 4\Gamma_{12}^2 + 4\Gamma_{12}\Gamma_{31}}}{2}$$



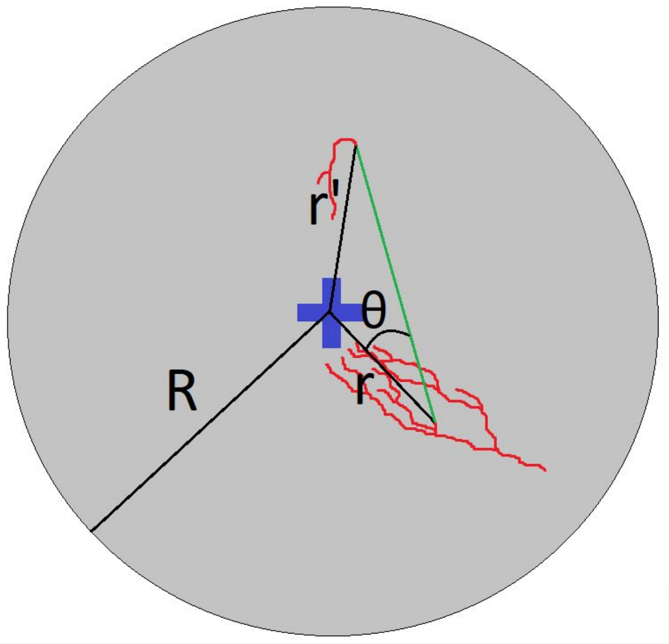
Effect of the number of charge layers

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.



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.