Modelling the runaway relativistic electron avalanche and the feedback mechanism with GEANT4

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We investigate the Runaway Relativistic Electron Avalanche (RREA) and the feedback process as well as the production of Bremsstrahlung photons from Runaway Electrons (REs). These processes are important to understand the production of Terrestrial Gamma-Ray Flashes (TGFs). Results are obtained from Monte Carlo (MC) simulations using the GEometry ANd Tracking 4 (GEANT4) programming toolkit, version 9.6. Our results indicate that the multiplication of electrons during the development of RREAs and under the influence of feedback, are consistent with previous estimates.

1. Introduction

Terrestrial gamma-ray flashes(TGFs) were first discovered in the early 1990'ies by the Burst And Transient Source Experiment(BATSE) on board NASA's Compton Gamma-Ray Observatory [1]. Since then, the observation of these sub-millisecond bursts of up to several tens of MeV photons has been confirmed in multiple studies [2,3,4].

Although the exact production mechanism is not yet fully understood, the strong electric fields generated inside thunderclouds are capable of accelerating electrons to the intensities and energies required [5]. Two leading theories have been presented to explain the multiplication of energetic electrons and subsequent production of Bremsstrahlung photons. 1) The thermal acceleration of electrons in the tips of streamers and the subsequent acceleration during the stepping of lightning leaders [6]. 2) The initiation of Runaway Relativistic Electron Avalanches (RREAs) by cosmic-ray seed particles and the feedback mechanism during the charging of the ambient electric field [8,9,10]. We will discuss the latter theory. This thoery is constrained by the available potential in the cloud as well as the strength, size and location of the electric field.

2. Results

2.1. The RREA and the feedback mechanism

The electron energy spectrum of RREAs is expected to reach a steady state after a few e-folding (avalanche lengths) and follow the exponential cut-off $\propto \exp(-\varepsilon/7300\ \text{keV})$ [9]. The electron energy spectrum we obtained corresponds well with previous studies and follows the cut-off $\exp(-\varepsilon/7700\ \text{keV})$. This can be seen in figure 1.

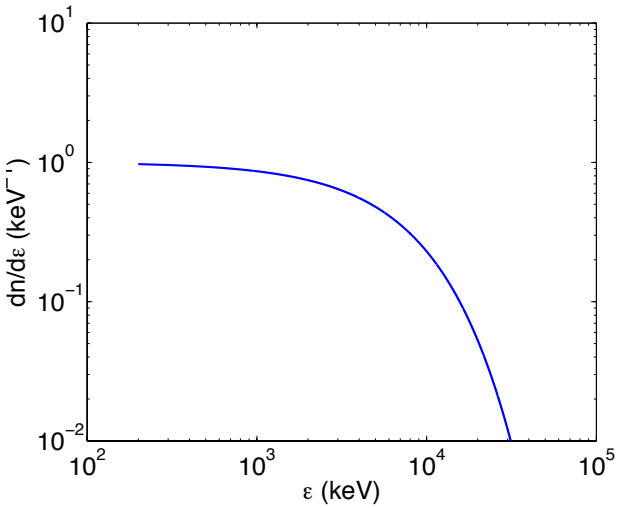

Figure 1: The average electron energy distribution of RREAs propagating in electric fields, 310 kV/m < E < 2500 kV/m.

We also present the first study of the feedback mechanism using GEANT4. Our results confirm previous estimates of the potential required for the feedback mechanism to become unstable, $\gamma>1.0$, where γ is the feedback factor. The feedback factor describes the relation between the amount of electrons produced in a RREA, N_0, and the number of secondary avalanches initiated, N_{RREA} by backscattering photons and positrons inside the electric field. These results are shown in Figure 2 as the red line. The blue line indicates previous results by Dwyer [8], including the maximum electric field possible before feedback become untable, E_{max}=2550 kV/m. We also indicate the maximum potential and electric field available in thunderclouds (dashed lines). These parameters are the important constraints necessary to validate feedback as an important mechanism for electron multiplication.

We have not taken into account the location of the electric field. Due to the density of the atmosphere, the electric field scale with altitude. As a result weaker electric fields is required at higher altitudes. However, as the required potential does not scale, the vertical extention of the electric field become correspondingly larger. At 15km altitude the sea-level threshold at 2500kV/m is ~19m, which corresponds to a scaled field of $E=E_0 \exp(-h/H)$ =320kV/m, where h is the altitude and H is the scale height ~7.3km. The scaled vertical extention the become ~148m. Such large field over relatively large distances may be an unlikely scenario.

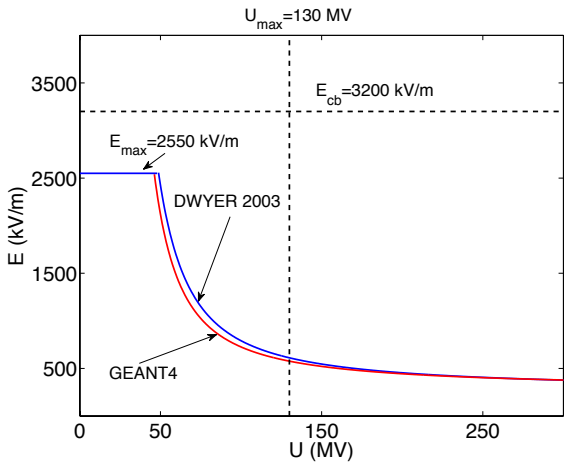

Figure 2. The graphs show the conditions required to for the feedback factor, γ, to be 1.0. The figure also shows the constraints in which feedback is unstable (γ>1.0). These constraints are the maximum potential available in thunderclouds (130 MV was found from measurements by [11]), and the conventional breakdown electric field, E_{cb}=3200 kV/m.

3. Summary

1) We have validated GEANT4 as a toolkit to study the RREA and the feedback mechanism.
2) We present the first study of the feedback mechanism using GEANT4. Our simulations confirm previous estimates for the potential required for feedback to become unstable.

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