Modeling the Runaway Electron Acceleration in Thunderstorms

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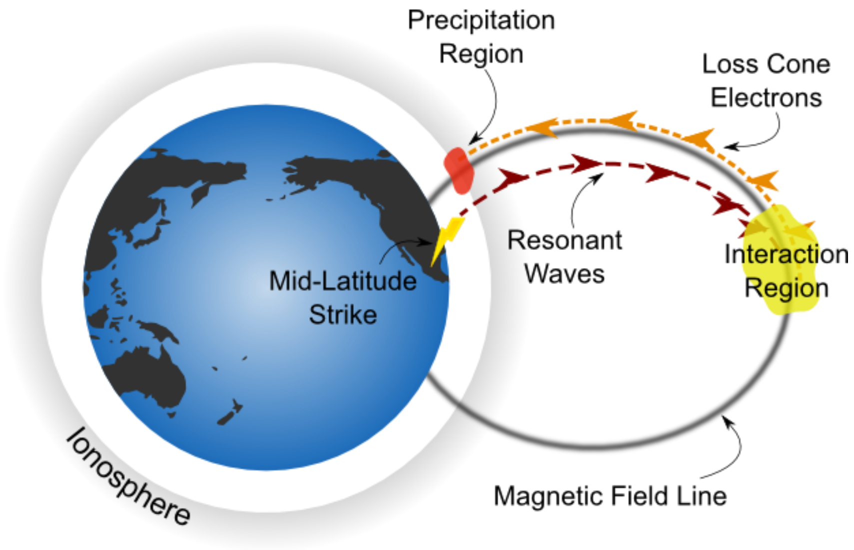
Commission H: Waves in Plasmas
Commission J: Radio Astronom
Commission K: Electromagnetics in Biology and Medicine

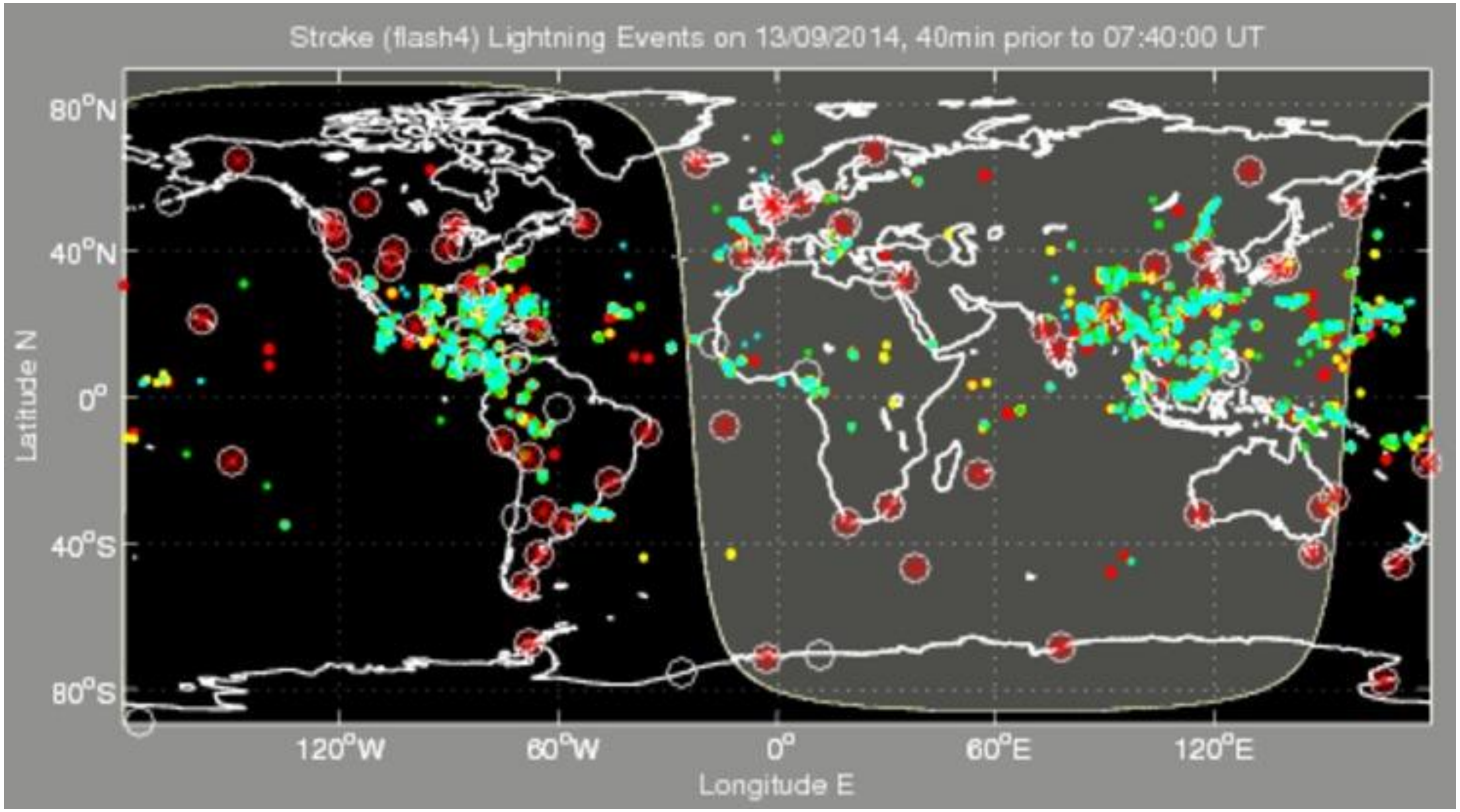
EFFECTS OF LIGHTNING DISCHARGES ON THE IONOSPHERE AND THE RADIATION BELTS

by Inan et al.

Lightning discharges release tremendous amount of energy (up to 109 Joules) and occur much more frequently than is commonly realized (2000 thunderstorms active at any time with 40-100 flashes per second globally). While the significance of the physical effects of these discharges on the ionosphere and the radiation belt has long been debated, phenomena such a Lightning-induced Electron Precipitation (LEP), Transient Luminous Events (TLEs) and Terrestrial Gamma Ray Flashes (TGFs) continue to attract attention.



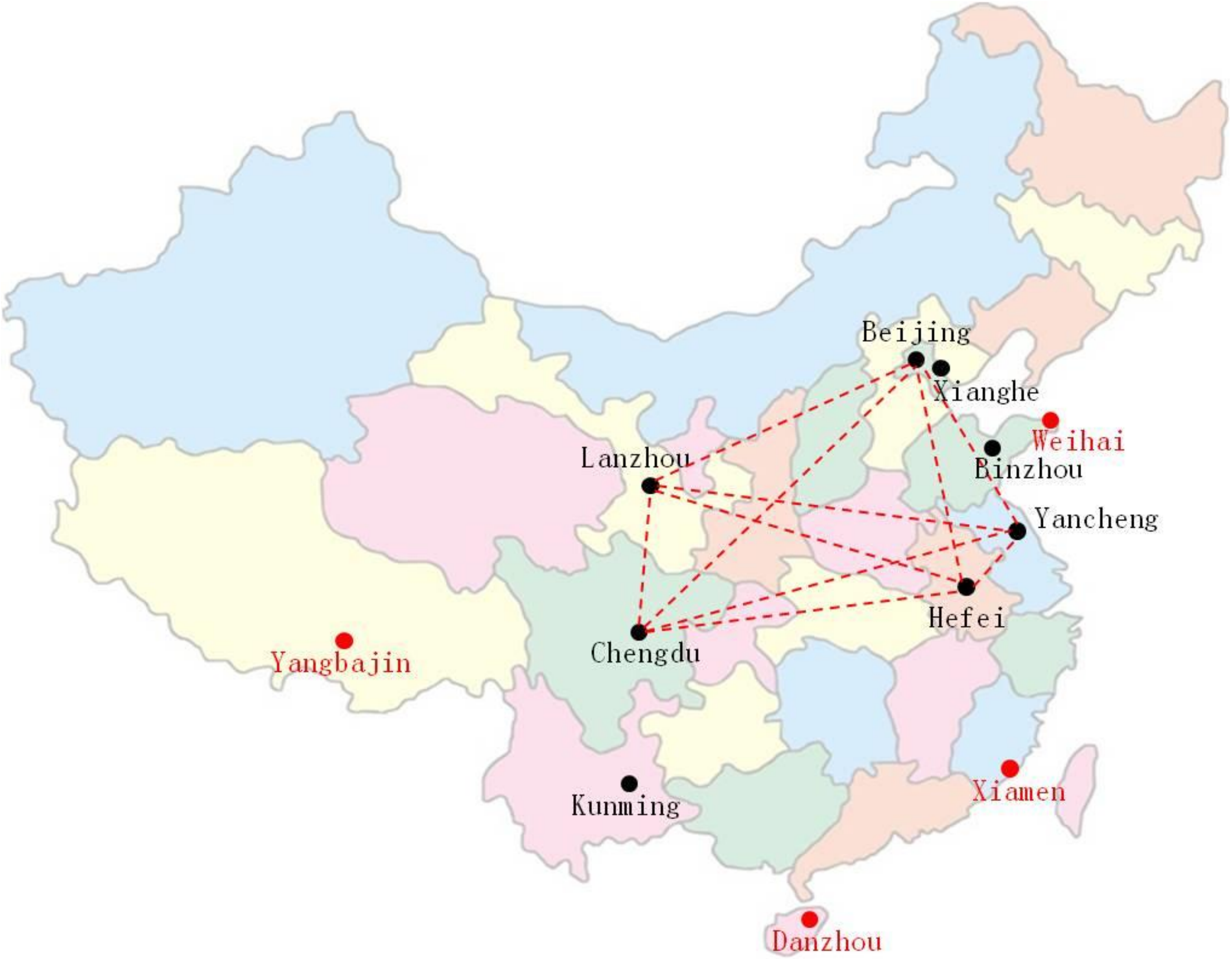
World Wide Lightning Location Network



Rodger et al.

University of Washington in Seattle operating a network of lightning location sensors at VLF (3-30 kHz). Most ground-based observations in the VLF band are dominated by impulsive signals from lightning discharges called “sferics”. Significant radiated electromagnetic power exists from a few hertz to several hundred megahertz, with the bulk of the energy radiated at VLF.

Lightning Detection Network of China

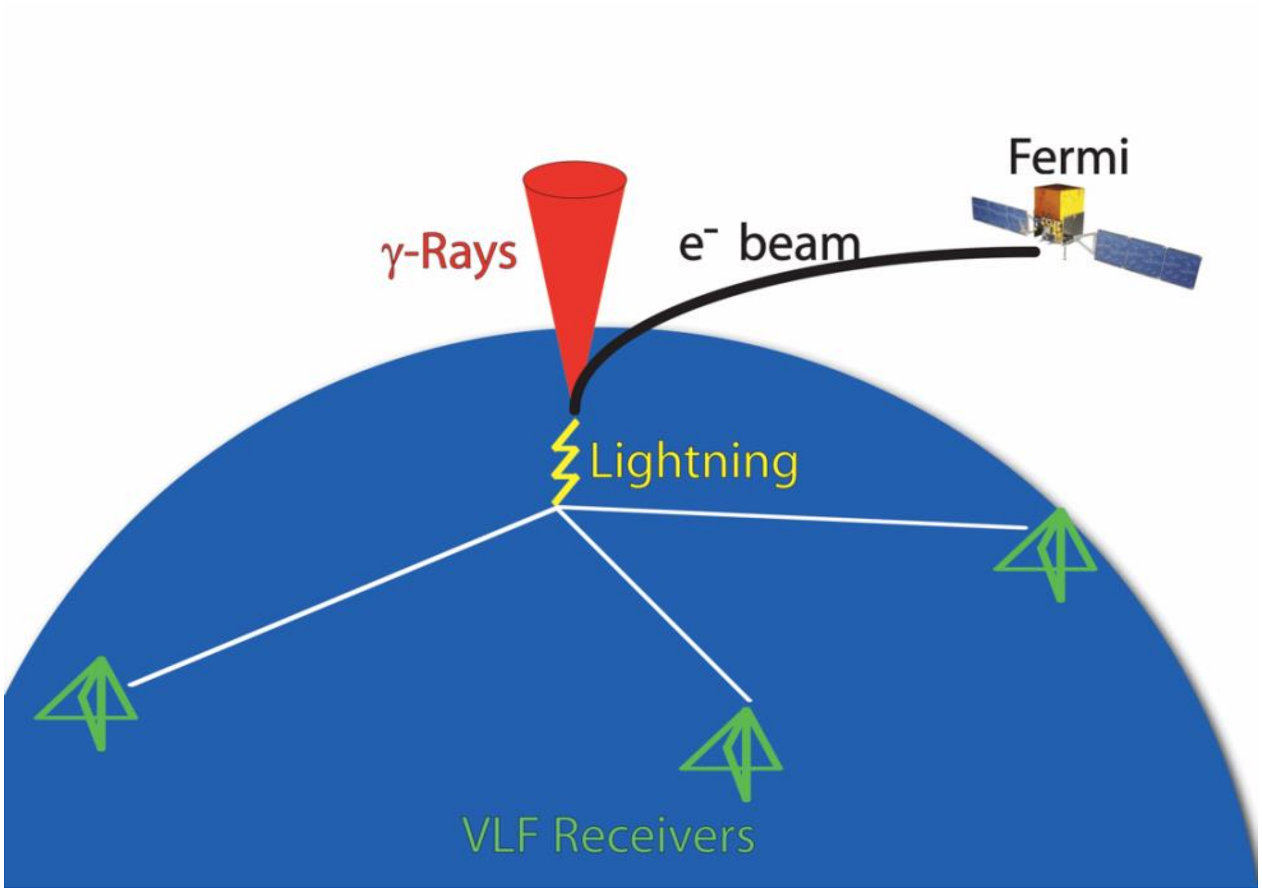


Lu et al.

Lightning Detection Network of China) that will detect and locate lightning discharges across the eastern Asia

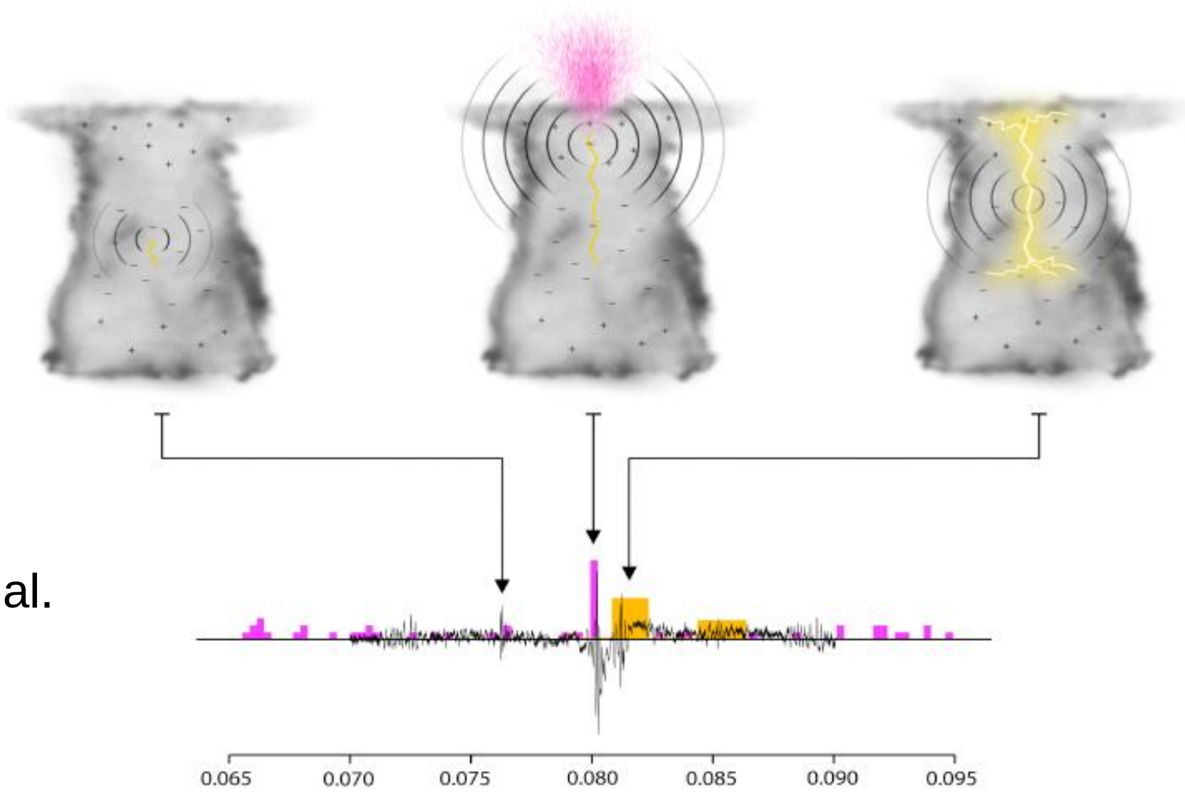
Terrestrial Gamma-ray Flashes-TGFs

Fishman, G.J., et al. (1994), Discovery of intense gamma-ray flashes of atmospheric origin, Science, 264, 1313-1316.



First simultaneous observations of optical lightning and terrestrial gamma flash from space

Ostgaard et al.



30 ms window

We find that the TGF was produced inside the thundercloud at the initial stage of an intracloud (IC) lightning just before the leader reached the cloud top and extended horizontally. A strong radio pulse was produced by the TGF itself.

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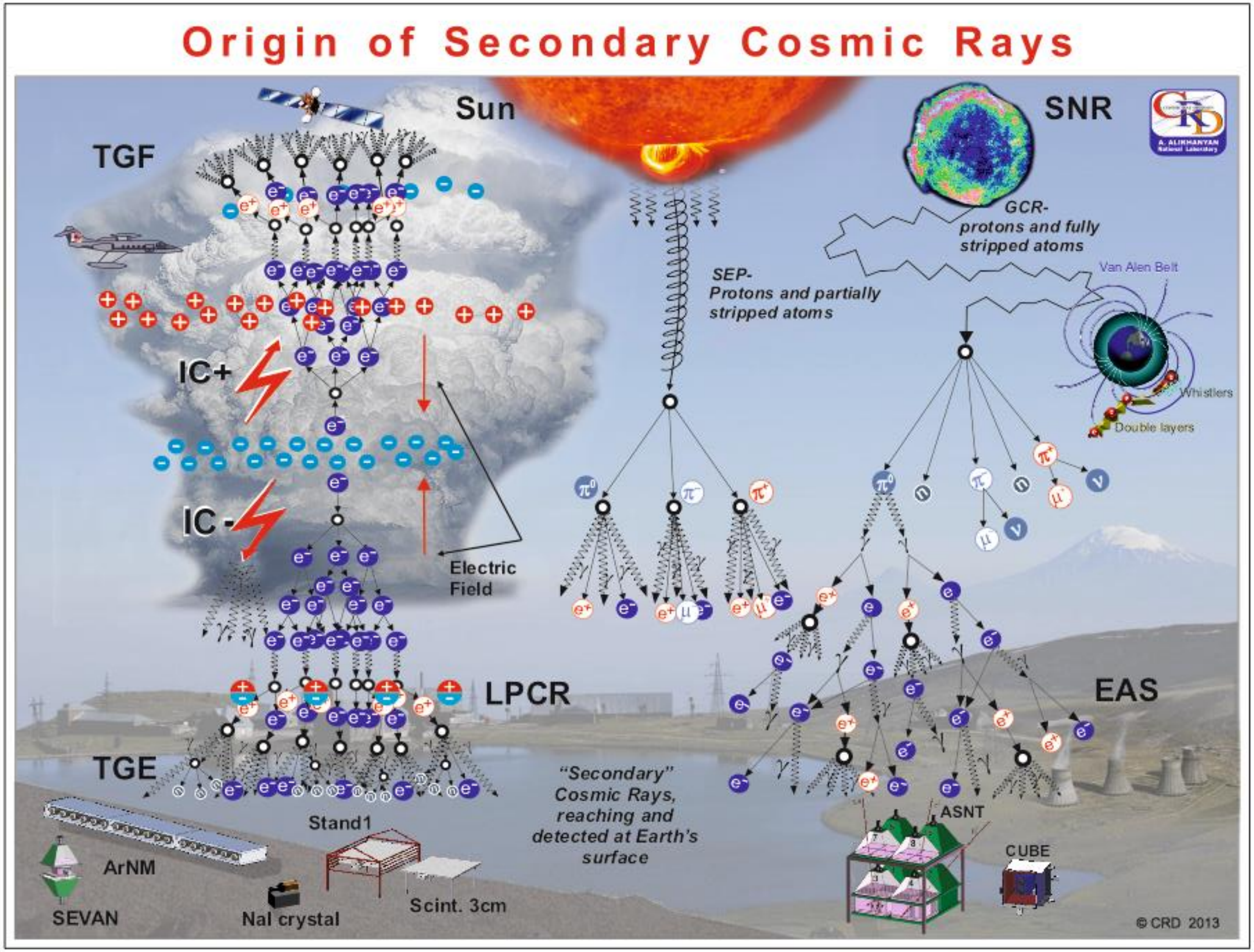
In-flight measurements of high-energetic radiation from thunderstorms

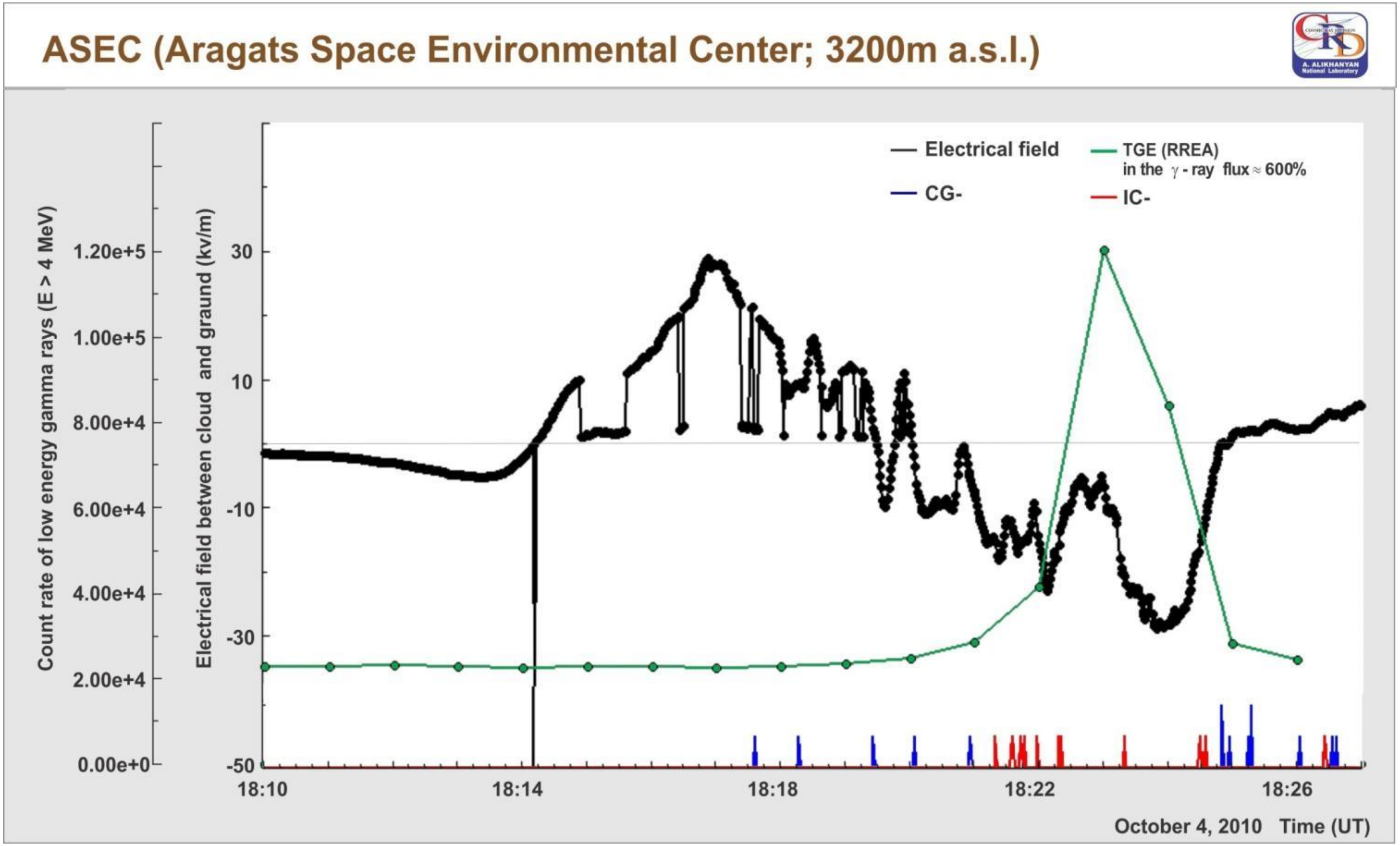
In-flight Lightning Strike Damage Assessment System ILDAS is developed in an EU FP6 project (http://ildas.nlr.nl/) to provide information on threat that lightning poses to aircraft. It consists of 2 E-field sensors, and a varying number of H-field sensors. It has recently been modified to include two LaBr3 scintillation detectors. The scintillation detectors are sensitive to x- and gamma-rays above 30 keV. The entire system is installed on A-350 aircraft and digitizes data when triggered by lightning. A continuously monitoring channel counts the number of occurrences that the X-ray signal exceeds a set of trigger levels. In the beginning of 2014 the aircraft flies through thunderstorm cells collecting the data from the sensors.

Van Deursen et al.

Relativistic Runaway Electron Avalanches (RREA), TGFs and Thunderstorm Ground Enhancements (TGEs)



TGE are detected at large negative near-surface electrical field; at the same time CG- are suppressed.



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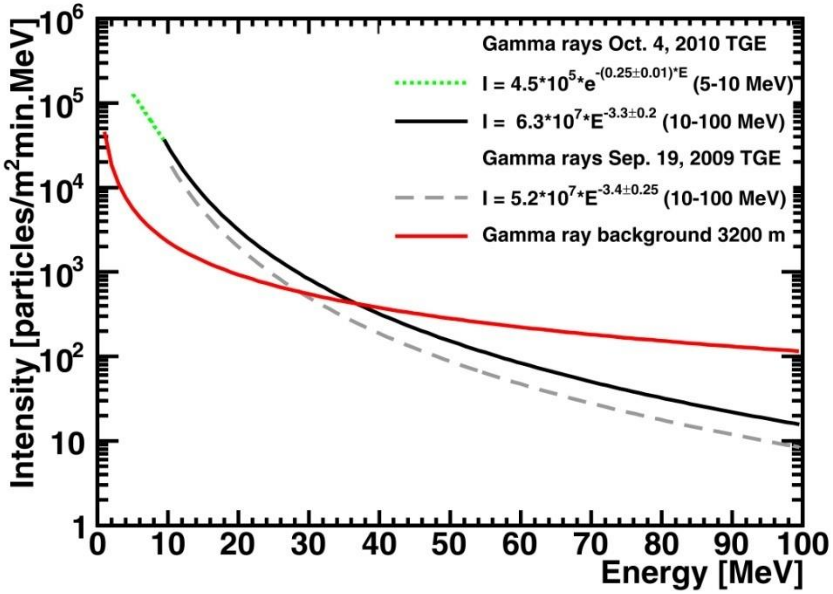
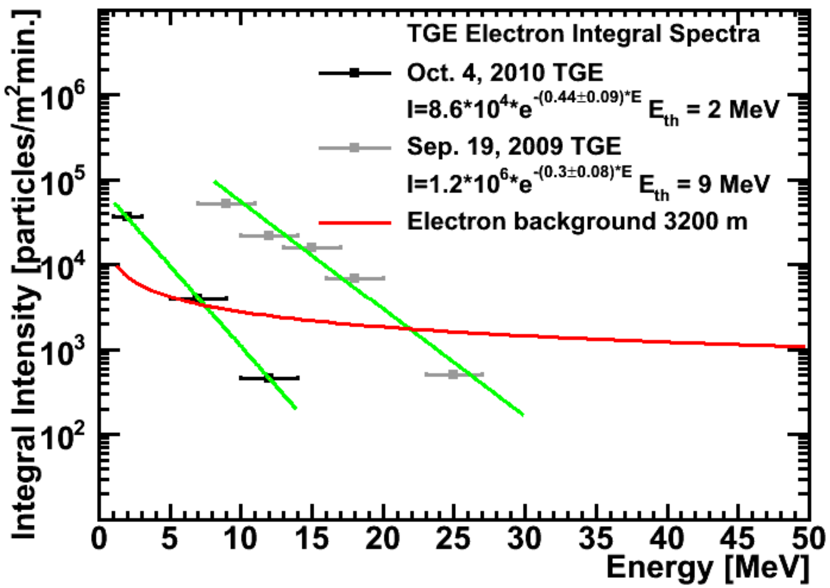
The energy spectra of the largest detected TGEs

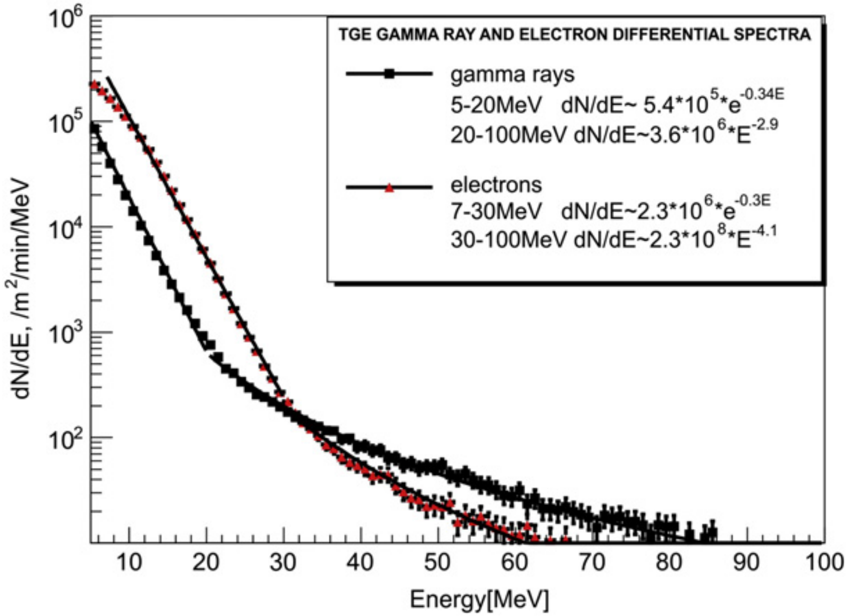


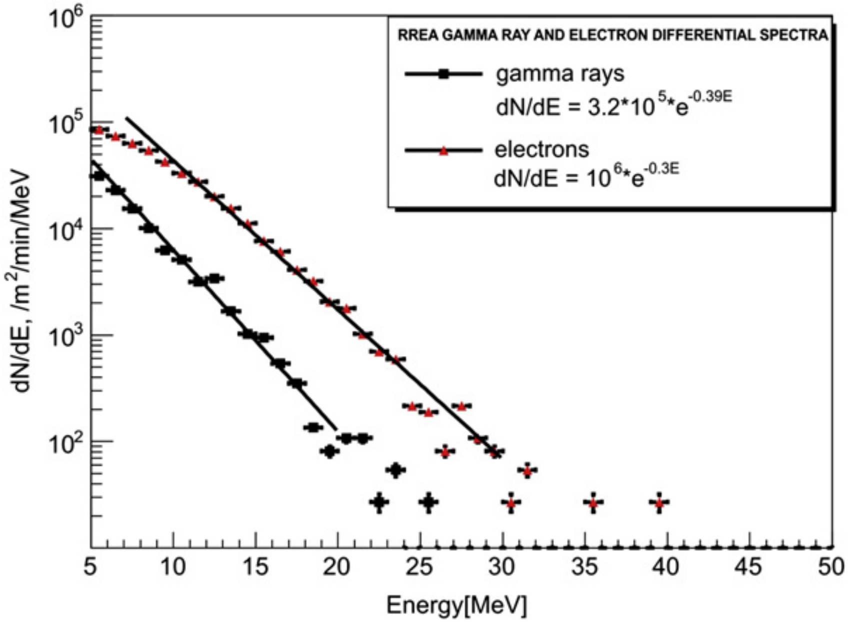


Average energy of TGE electrons ~2.5-3.5 MeV

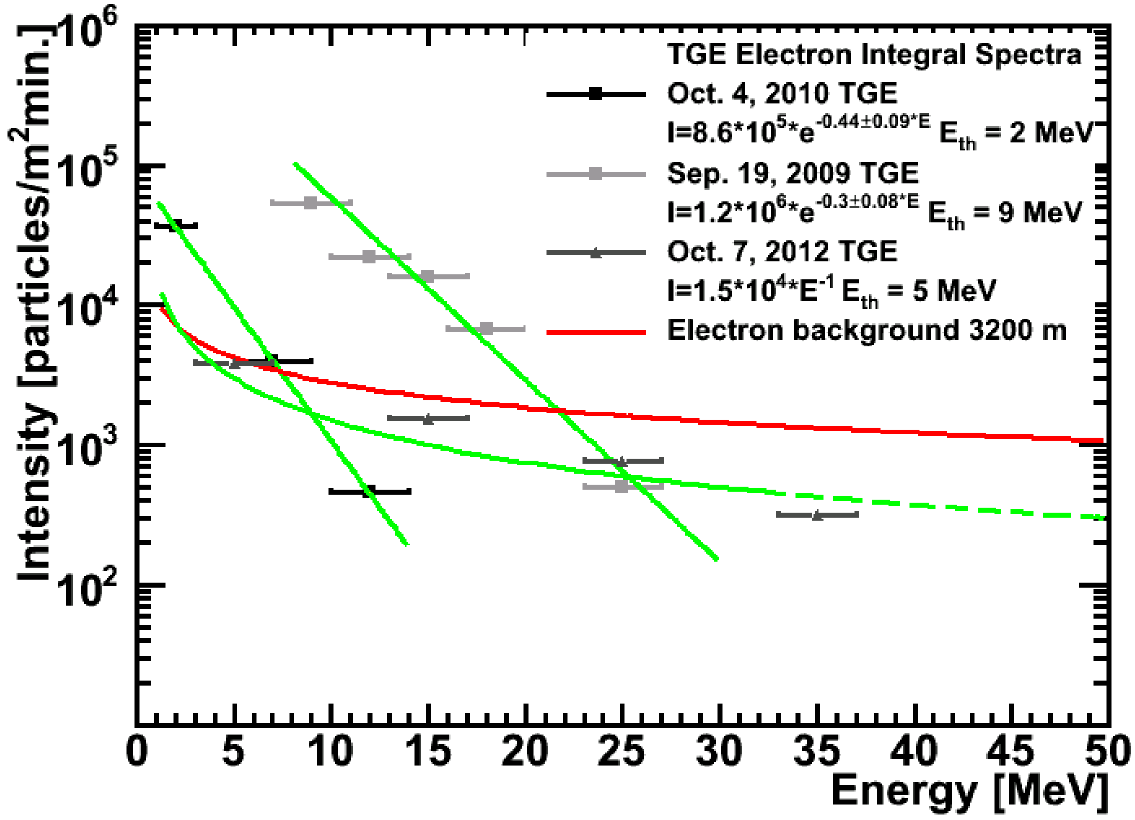
Maximal energy of gamma rays can reach ~100MeV

TGE gamma ray and electron spectra(right) and RREA gamma ray and electron spectra (left) 1500 m field length and 1.8.kV/cm field strength



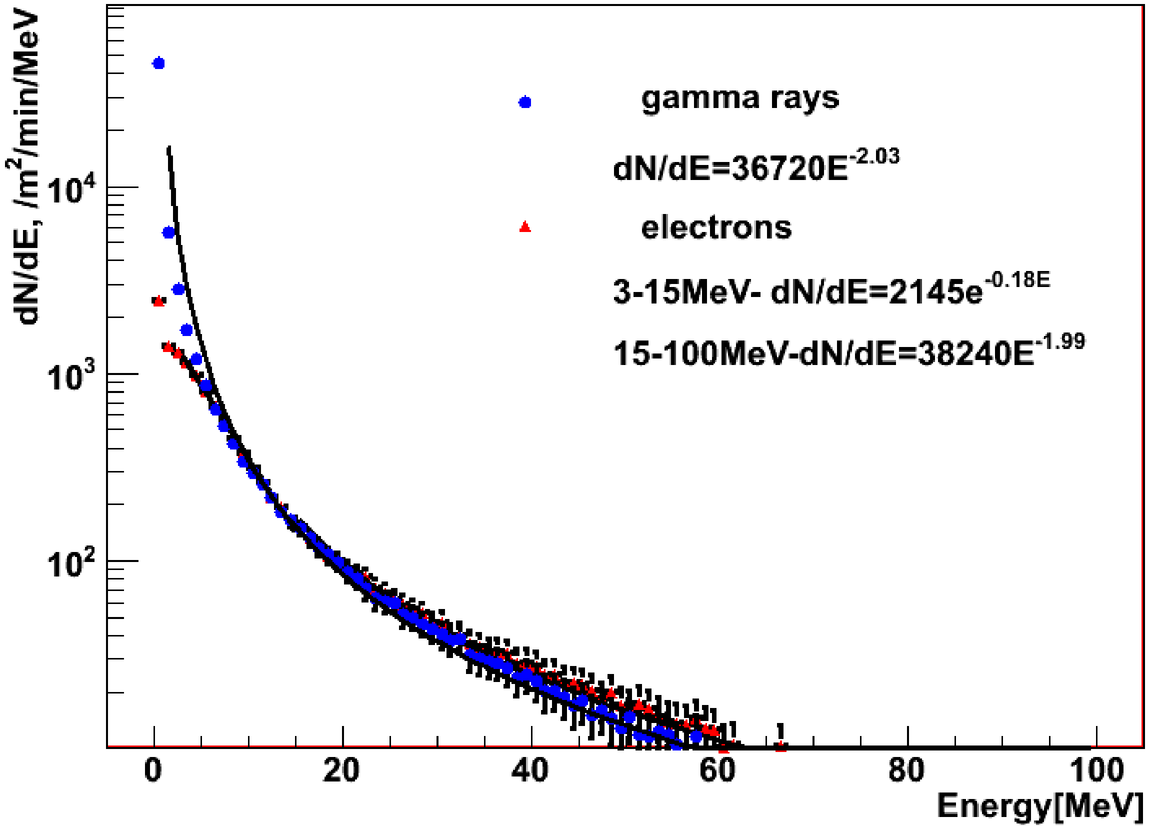


The electron spectra of the TGEs



The total number of RREA electrons estimated is $\sim 10^{11}$ and $\sim 10^{13}$ for the October 7 and the largest TGEs respectively. Thundercloud heights ~50-150m.

Simulations of RREA process in 500m electric field



Model formation

When taking place in strong electric fields, relativistic runaway electron avalanches (RREAs) energy distributions are characterized by an exponential cutoff of ~7 MeV [Dwyer et al., Space Sci. Rev., 173, 133, 2012]. However, in electric fields lower than ~2δ, where δ is defined as the ratio of the applied electric field *E* to the runaway threshold electric field E_{run} (~2.1 kV/cm in air at ground level), the electron energy distribution function (EEDF) is found to differ from this exponential trend. Moreover, in weak fields, the EEDF is more sensitive to differences in the cross sections corresponding to elastic and ionization collisions. We have therefore chosen to compare the results given by two independently developed codes.

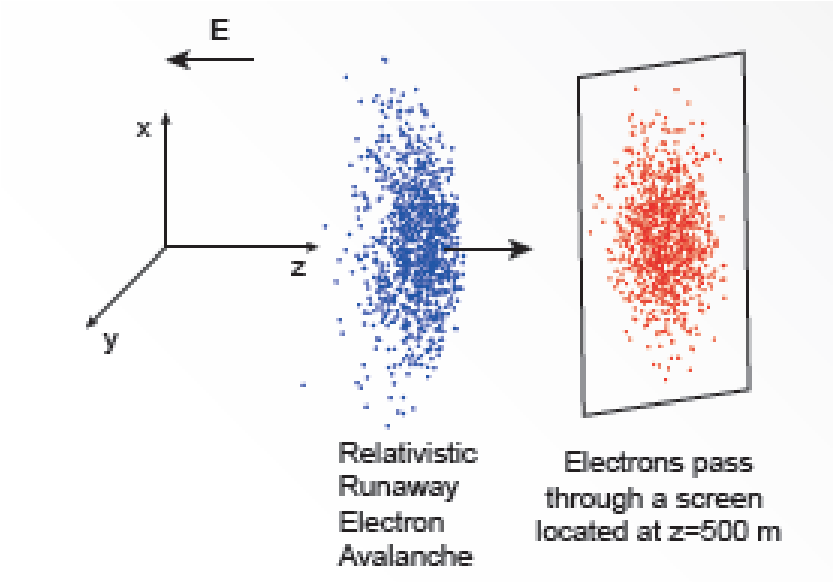
Because of the scattering of electrons, the true RREA threshold field E_{th} (~2.86 kV/cm in air at ground level) is slightly stronger than E_{run}. For this reason, it is convenient to introduce the ratio $\xi=E/E_{th}$. In the present study, we have used ξ=1.1,1.2, 1.3, and 1.5.

Model formation

In-house Monte Carlo model for electrons: This Monte Carlo model is used in this study to simulate the propagation and collisions of electrons in air (80% N2 and 20% O2). This model simulates electrons from sub-eV to GeV (e.g., see [Celestin and Pasko, 2011]). Ionization is taken into account using the using the RBEB model [Kim et al., Phys. Rev. A, 62, 052710, 2000; Celestin and Pasko, J. Phys. D: Appl. Phys., 43, 315206, 2010]. For the sake of comparison, the elastic differential crosssection is taken from [Dwyer, Phys. Plasmas, 14, 042901, 2007]. The friction caused by bremsstrahlung collisions (so-called radiative friction) has been observed to be of importance in the present study. A continuous radiative friction is included based on the NIST database ESTAR.

GEANT4 (LBE package): GEANT4 is a standard simulation tool developed at CERN with various applications from high energy particle physics to nuclear medicine [Agnsotelli et al., Nucl. Instrum. Methods Phys. Res. Res. Sec. A, 506, 2003]. There are few studies using GEANT4 to model the passage of electrons through the air in the presence an electric field [e.g., see Chilingarian et al., Atmos. Res., 114, 2012]. LBE physics list of GEANT4 is used, which takes into account all standard electromagnetic processes and is suitable for the studies at the relatively low energy region.

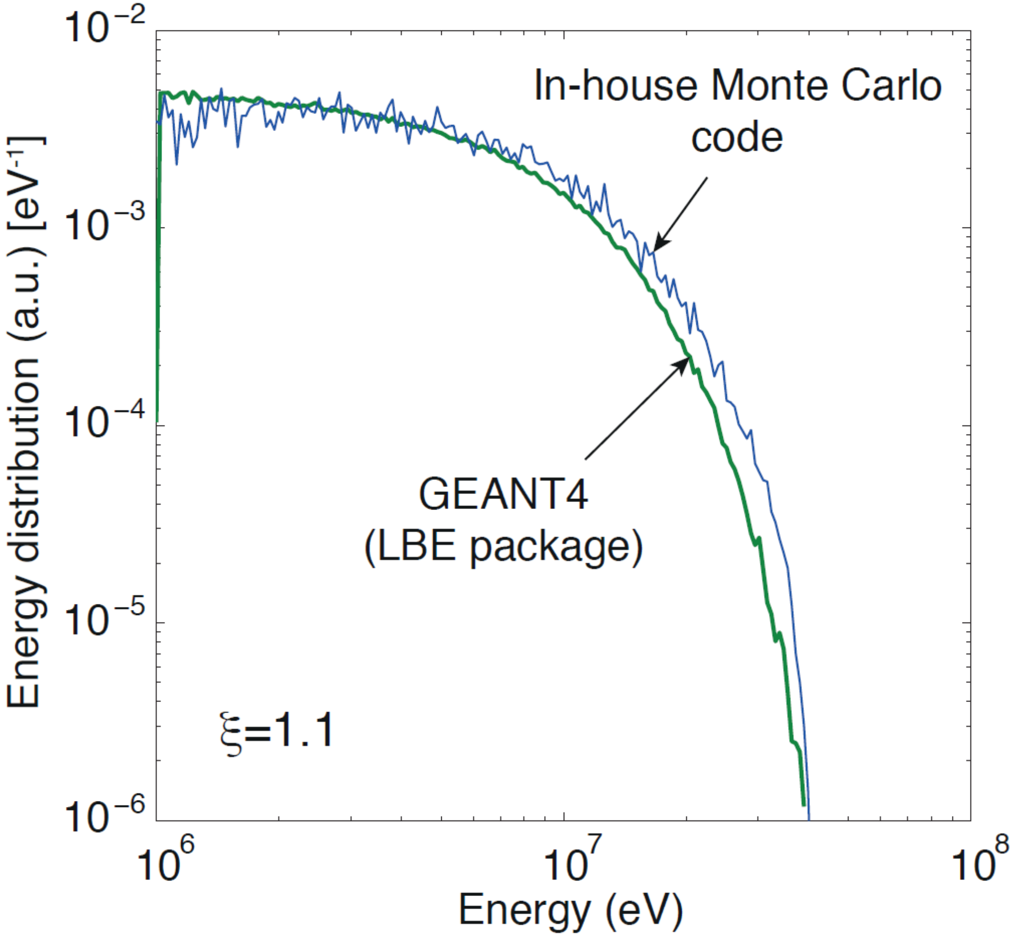
Configuration



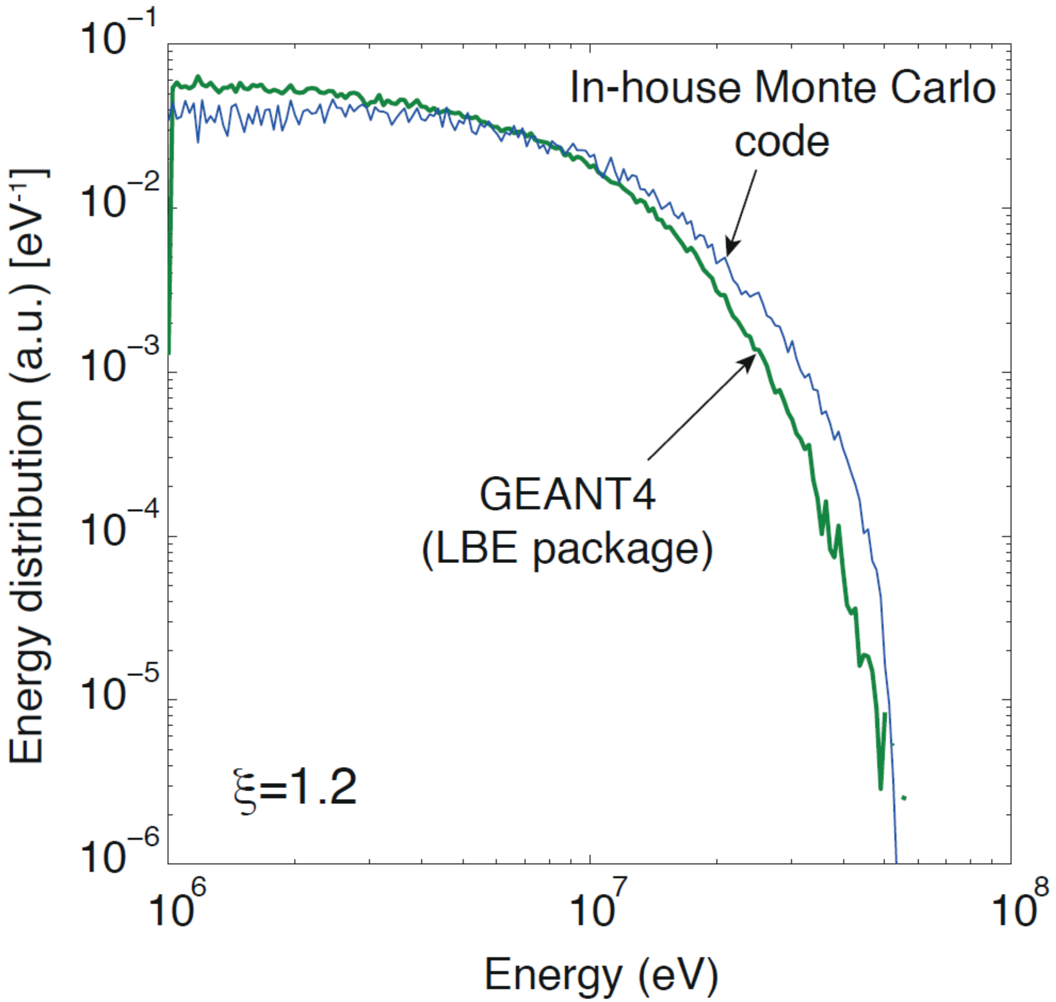
In this study, we inject a number of electrons with energy 1 MeV in the antiparallel direction of a homogeneous weak electric field. The physical properties of electrons are obtained once they reach a fictitious "screen" located at *z*=500 m.

The number of runaway electrons with energy greater than 1 MeV reaching the screen per electron initially injected under electric fields magnitudes defined by ξ=1.1, 1.2, 1.3, and 1.5, is respectively ~60, ~205, ~500, and ~65,000 in the in-house code results, and ~10, ~132, ~890, ~1.3x106 in the GEANT4 (LBE) results.

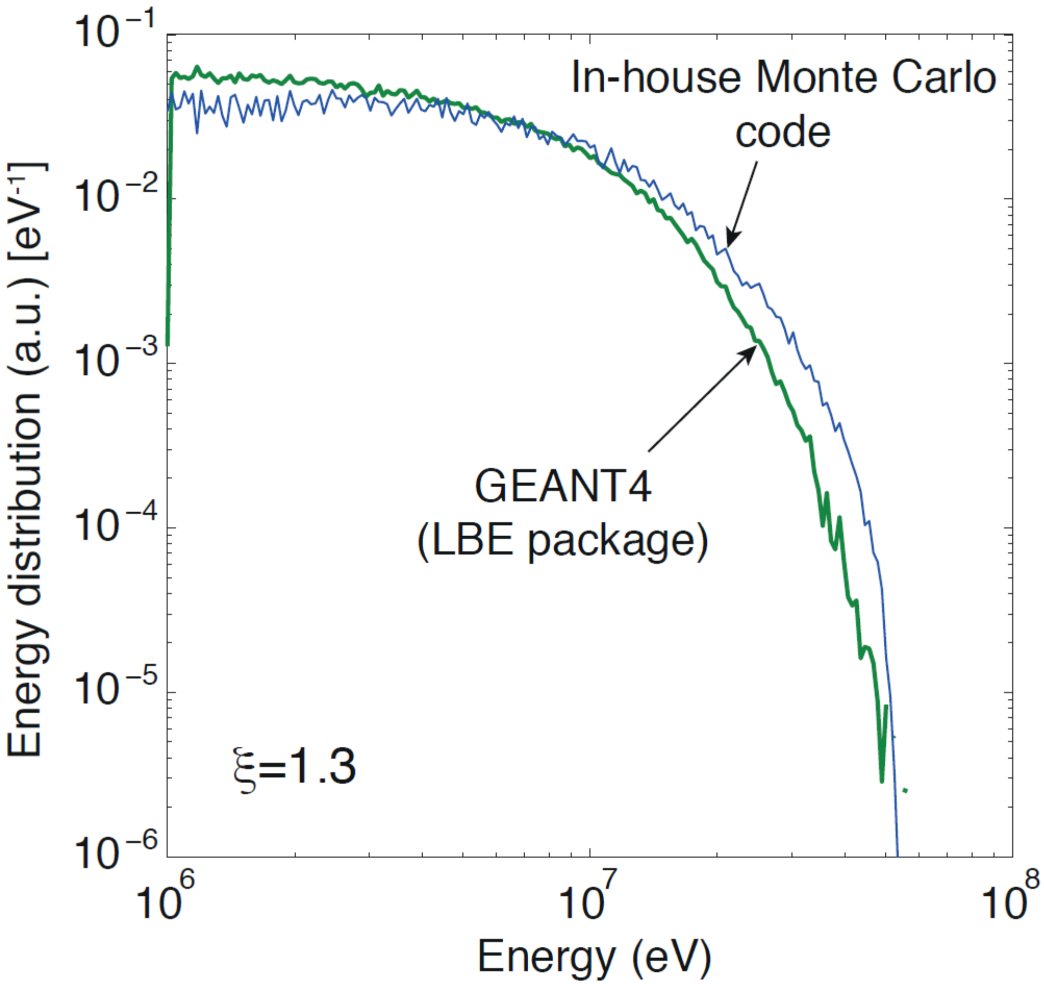
Renormalized EEDFs. In this figure, the in-house Monte Carlo EEDF is multiplied by 0.2 and the number of electrons >1 MeV at 500 m is 59.4 per injected seed electron.



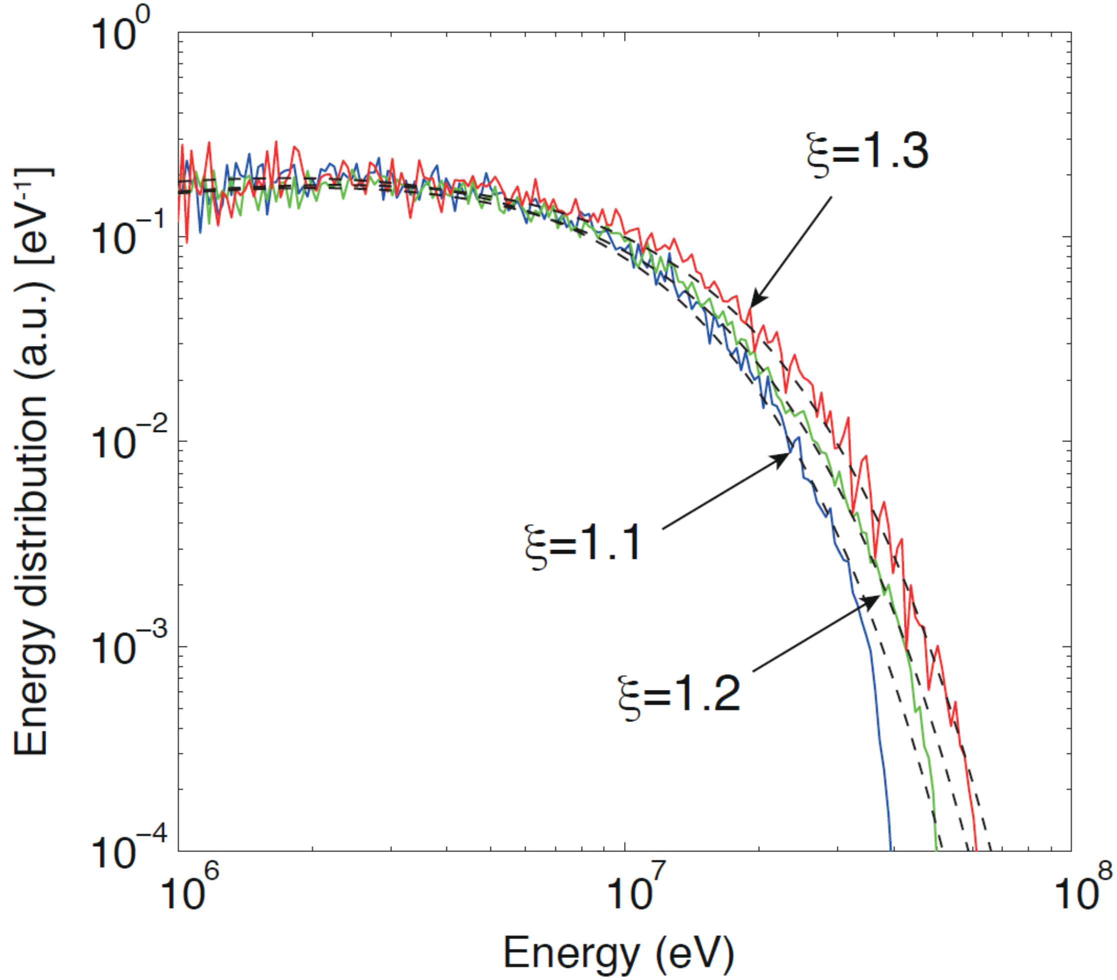
Renormalized EEDFs. In this figure, the in-house Monte Carlo EEDF is multiplied by 0.65 and the number of electrons >1 MeV at 500 m is 205.3 per injected seed electron.



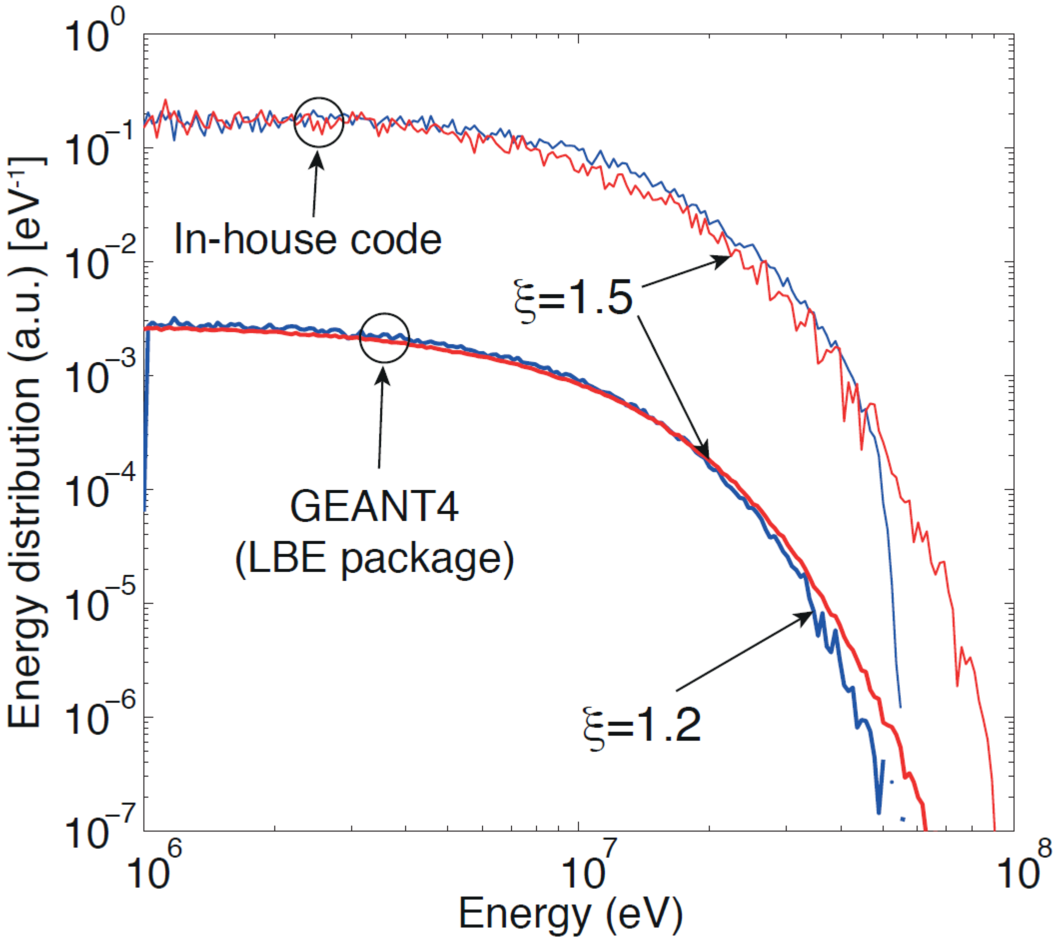
Renormalized EEDFs. In this figure, the in-house Monte Carlo EEDF is multiplied by 1.84 and the number of electrons >1 MeV at 500 m is 498.3 per injected seed electron.



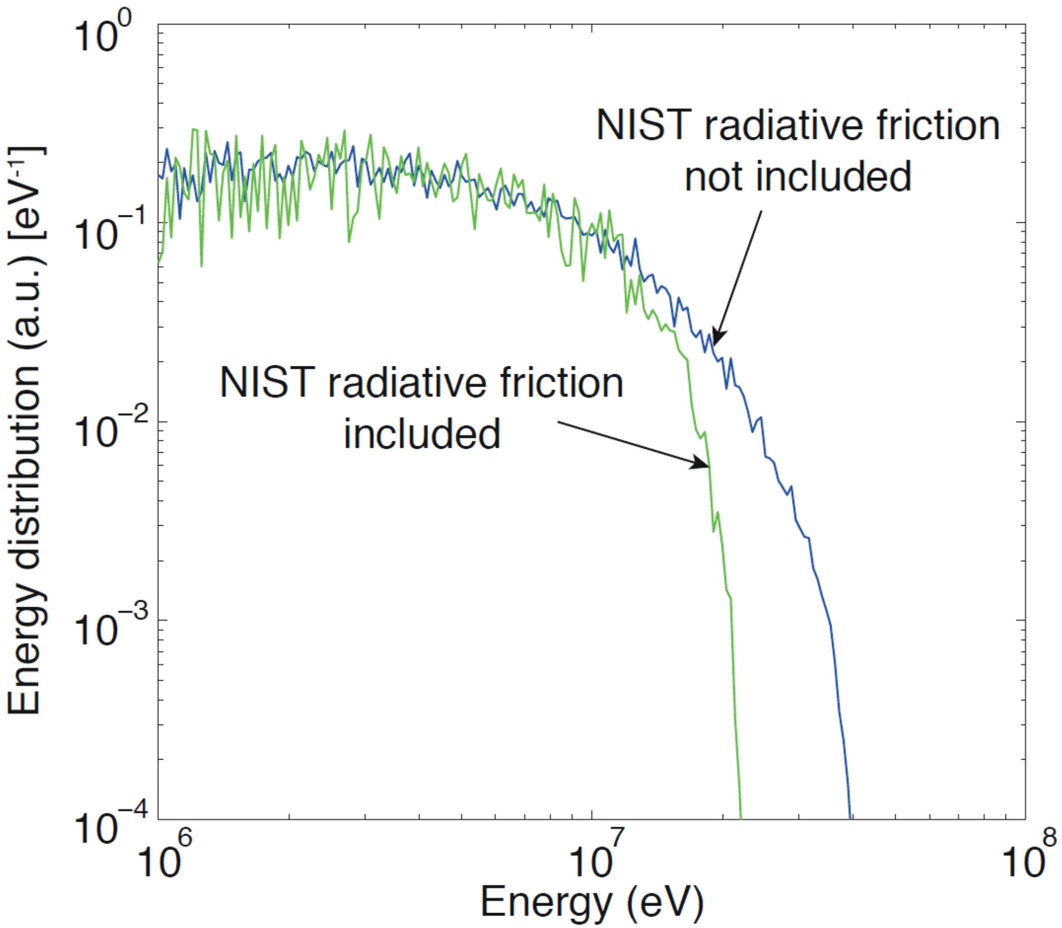
Renormalized EEDFs obtained by the in-house code for three different magnitudes of the electric field. It seems that these distributions can be fit by functions of type $K^{0.3}\exp(-K/K_c)$, where K is the kinetic energy of electrons and K_c=6 MeV, 6.5 MeV, and 7.5 MeV, for ξ=1.1,1.2, and 1.3, respectively.



The EEDFs obtained for ξ=1.5 partially overlap those for ξ=1.2. The normalization is arbitrary.



Effect of the radiative friction on the EEDF (in-house code).



Conclusions

• We have carried out comparisons between the EEDFs in RREAs obtained by GEANT4 (LBE) and an in-house Monte Carlo code. Results are in good general agreement, but further work is needed to understand the origin of the differences obtained.

• The electron energy distribution in RREAs developing in thunderstorms, and therefore the corresponding photon spectra,contain information on the magnitude of the electric field. It might be possible to use this property to infer the value of the electric field inside thunderstorms producing TGEs for fields $\xi<1.5$.

• We have found that the radiative friction strongly affects the energy distribution in RREAs propagating under weak electric fields $\xi<1.5$.


Thank you for your attention!