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HIGH-ENERGY ATMOSPHERIC PHYSICS AND TERRESTRIAL GAMMA-RAY FLASHES

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Abstract

Thunderstorms have been recently established as the most energetic natural particle accelerators on Earth. Starting from the early work by Wilson in 1925 suggesting the acceleration of electrons up to relativistic energies in thunderstorms electric fields, it took about 75 years to build up a sufficiently large observational frame and reach a general consensus on the existence of this phenomenon. The most violent manifestation of this process are Terrestrial Gamma-ray Flashes, sub-millisecond bursts of gamma-rays with energy up to several tens of MeV produced in thunderstorms and typically detected from space by detectors designed for high-energy astrophysics. First discovered in 1994 by the BATSE instrument onboard the NASA CGRO spacecraft, TGFs are now entering a golden age thanks to the wealth of observations delivered by the AGILE, RHESSI and Fermi satellites. Despite a general consensus on the underlying physical mechanism, several questions are still open, namely on the TGF-lightning relation, the maximal energy, and the pervasiveness of the phenomenon. In addition to TGFs observed from space, impulsive bursts

of radiation as well as long-lasting emissions have been observed by detectors onboard research airplanes and deployed on ground, suggesting that the production of energetic radiation within thunderstorms is a much more pervasive phenomenon than previously thought.

1 Introduction to high-energy atmospheric physics

In recent years it has been established that thunderstorm environment is the site of energetic particle acceleration, capable to produce and accelerate electrons, positrons, photons and neutrons with energies up to several tens of MeV. In fact, thunderstorms are the most energetic natural particle accelerators on Earth, see 1) for a recent extensive review. The production of energetic radiation in thunderstorms was first foreseen in the work by C.T.R. Wilson in 1925 2), describing the mechanism of runaway electron production in air. A free electron in air, in the presence of an external electric field, may gain more energy by the ambient field than the energy lost by friction force with the air molecules. The requirement for the electron is to be energetic enough so that the Bethe-Bloch equation describing the friction force in air at the electron energy is decreasing, and the ambient field is above a certain threshold level, which is about one tenth of the conventional breakdown field and is close to the maximum electric field observed in thunderstorms. When these initial conditions are satisfied, the electron gains energy as long as it's moving within the field region, and can become relativistic. Energetic electrons can then undergo photon production by Bremsstrahlung in air, then photons can further produce energetic electrons and positrons by Compton scattering and pair production, and eventually neutrons by photo-production. Successive theoretical development 3) showed that runaway electrons interacting with air molecules by Møller scattering can produce knock-on electrons with sufficient energy to run into the runaway regime as well, therefore starting an avalanche multiplication process (Relativistic Runaway Electron Avalanche, RREA) that greatly enhance the total number of energetic particles.

It took almost 75 years to reach a general consensus on the effective manifestation of this mechanism, since the early experimental evidences were controversial. It is now established that significant X- and gamma-ray fluxes can be produced by thunderstorms on different time scales, from minutelong quasi-stationary fluxes (gamma-ray glows or Terrestrial Ground Enhancements, TGEs) to sub-millisecond bursts of gamma-rays (Terrestrial Gamma-ray Flashes, TGFs). Although the production of runaway electrons is believed to be at the basis of all these phenomena, the conditions at the acceleration site (field magnitude and spatio-temporal behaviour, source size) appear to be different.

The first unambiguous observation of a long duration emission of hard X-rays associated to thunderstorm came in 1985 4) with pioneering aircraft observations. Later, balloon measurements provided information on both ionizing radiation and electric fields inside active thunderstorms 5). Recent airplane observations of gamma-ray glows were reported by the ADELE experiment 6), suggesting that RREA mechanism is responsible for this emission. Unambiguous ground based observations of long duration X- and gamma-ray emissions were first reported in 2000 7), followed by a wealth of observations mostly carried out on Japan winter thunderstorms 8) or high-altitude sites 9). Although aircraft observations suggest the RREA mechanism to be at the basis of the glow phenomenon 6), ground-based observations point out the possible contribution of charged cosmic rays, whose spectrum is modified by the thunderstorm electric field and overcomes the RREA contribution to the gamma-ray flux above few tens of MeV 10).

2 Terrestrial Gamma-ray Flashes

In addition to long duration emissions, gamma-rays emission from thunderstorms can take the form of sub-millisecond, bright bursts of gamma radiation extended up to several tens of MeV in energy and associated to lightning activity, known as Terrestrial Gamma-ray Flashes (TGFs). Since their discovery in the early nineties by the Burst and Transient Source Experiment (BATSE) detector on-board the NASA Compton Gamma-ray Observatory (CGRO) 11), a wealth of observations have been provided by the three currently operative space instruments capable of TGF detection: the Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) 12), the Gamma-ray Burst Monitor (GBM) on-board the *Fermi* satellite 13) and Astrorivelatore Gamma ad Immagini LEggero (AGILE) 14, 15, 16, 17, 18, 19). In addition to space observations, one TGF has been observed onboard an aircraft by the ADELE experiment 20), and recently a claim for ground observation of TGFs has been reported [21].

Although runaway electrons are believed to be at the basis of the TGF phenomenon, it has been shown [22] that the RREA mechanism alone acting on seed electrons produced by natural radioactive background or extensive air showers is not enough to account for the high fluence observed from space. Two competing models have thus emerged to overcome this theoretical limitation: either the relativistic electron flux is further enhanced by the Relativistic Feedback mechanism [23] acting within the large-scale electric field of thunderstorms, or the multiplication and acceleration of electrons takes place in the high field region associated to the tip of upward propagating lightning leaders [24]. This latter scenario implies a tight link between TGFs and lightning propagation, and seems to be supported by recent observations based on ground-based radio observations [25] and optical measurements from satellite [26].

3 Outlook: a global perspective

The study of TGFs and related phenomena is now carried out mostly on a local perspective, i.e. trying to understand the single event source mechanism and properties. This is basically unavoidable since many pieces of the puzzle to understand these phenomena are still missing. However, it is worth looking at these phenomena also from a global perspective, trying to understand their potential contribution to the coupling between atmospheric layers and, eventually, their impact on climate. This is even more important now that recent studies have suggested that observed TGFs might be just the tip of the iceberg and these phenomena may be much more pervasive than previously expected.

Considering the Earth global energy budget, of the 341 W/m^2 delivered on average by incoming solar irradiance, about 28% is transferred from the Earth's surface to the atmosphere as sensible heat (energy transfered by conduction and convection, 17 W/m^2) and latent heat (80 W/m^2) [27]. This energy transfer is driven by winds that carry heat and moisture out of the surface and ultimately drive atmospheric circulation and thunderstorm activity. This energy powers the ≈ 2000 thunderstorms active on average every second on Earth, which act as electric current generators keeping charged the surface-ionosphere capacitor and ultimately driving the Earth global electric circuit (GEC) [28]. Given the finite conductivity of the atmosphere, the surface-ionosphere capacitor would discharge in a finite time if the charging provided by thunderstorms were not at play. Indeed, the observed fair weather current of ≈ 2 pA/m^2 requires an average energy flux of 5×10^{-7} W/m^2 to maintain the average +250 kV potential difference between the ionosphere and Earth surface steady on the long term. This is indeed a tiny fraction (about 5×10^{-9}) of the total energy flux available from sensible and latent heat, but it is sufficient to maintain the GEC active. A larger, but still small fraction of energy is dissipated by lightning activity in thunderstorms. There are ≈ 44 lightning flashes per second on average on Earth 29), each of them dissipating about $10^9 - 10^{10}$ J 30), corresponding to $0.3 - 3 \times 10^{-3}$ W/m^2 average energy flux. The vast majority of this energy is delivered as heat and kinetik energy associated to the mechanical blast wave. However, how much energy is released in the radio-frequency and high-energy channel (relativistic electrons and gamma-rays) is regarded as one of the top ten questions in lightning research 31). Given the TGF intensity observed from space and the transport of photons from the production region close to thundercloud top through the atmosphere, one may estimate the average TGF energy at the source to be of order 10 kJ. If every lightning is associated to a TGF 32), the total energy flux delivered in the TGF channel would be $\approx 3 \times 10^{-9}$ W/m^2. Again, this is a very small fraction (about 3×10^{-11}) of the total energy flux available. However, this crude estimate does not consider gamma-ray glows, for which the paucity of measurements does not allow a reasonable estimate of the average energy flux. In principle, these long duration emissions, despite less bright than TGFs, thanks to the larger spatial extension and quasi-stationary behaviour may deliver a larger amount of energy in the high-energy channel. Although the energy delivered in the high-energy channel is a very small fraction of the total available energy, we cannot neglect its contribution to the coupling between the atmosphere and the ionosphere and eventually as a feedback factor for climate processes. The long interaction length of this radiation (the minimum cross section for gamma-rays in air is at ≈ 20 MeV) makes gamma-rays a suitable mean for coupling the top of the troposphere and the ionosphere, tens of kilometers above.

Climate is a highly complex and interconnected system, where all variables at play couple together in a non-linear fashion. In this scenario, even factors accounting for a small fraction of the total available energy budget can give a feedback with substantial amplification of the effects. For example, galactic cosmic rays flux at Earth accounts for about 10^{-9} the total solar irradiance, equivalent to that of starlight. Although the influence of cosmic rays on climate is still under debate, there is a growing set of observations suggesting a correlation between galactic cosmic rays flux and climate variation at the centuries - millennia time scales 33). The proposed mechanism for providing the required substantial feedback to the climate system is the influence of ionizing radiation on aerosol nucleation and the formation of cloud condensation nuclei 34). This feedback ultimately influences cloud coverage and the rediative balance, hence the climate 35).

Although the rough estimate of the energy flux delivered as ionizing radiation by thunderstorms and reported above is a factor ≈ 30 lower than that due to galactic cosmic rays, it is worth exploring the possibility that such energy flux may provide a feedback to climate as well. Unlike cosmic rays, ionizing radiation from thunderstorms would be an *internal* forcing agent, directly linked to thunderstorm activity. Ionizing radiation produced by thunderstorms may act on aerosol nucleation exactly like cosmic rays, moreover it can affect the GEC by directly modifying the air conductivity by ionization, both locally, close to the production region, and at a larger distance, given the large interaction length. To address this issue it is mandatory to assess a better estimate of the total amount of energy delivered as ionizing radiation, increasing the amount of observations for both TGFs and long duration glows, both at ground level, airplane, balloon and satellite altitude. Important information will come from the two forthcoming space missions ASIM and TARANIS, specifically designed for the observation of TGFs and related phenomena.

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