Lightning and energetic radiation: recent work at the University of Bergen

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Abstract

Lightning and energetic radiation in the atmosphere have been the subject of an increasing amount of research over the past few years. This talk summarizes recent activity at the University of Bergen on instruments, data analysis, and modeling of energetic radiation in the atmosphere, including terrestrial gamma-ray flashes, lab sparks, and lightning.

1 Introduction

Despite centuries of study, lightning is poorly-understood. Key questions include the mechanism of thunderstorm electrification and the resulting charge structure (*Stolzenburg and Marshall*, 2008), the process by which lightning channels are initiated (*Petersen et al.*, 2008), and the mechanism of lightning channel extension (*Gallimberti et al.*, 2002). The consensus on such questions is growing, but the details are crucial and there is still much debate. Recently, the role of energetic particles in such processes has become the subject of intense study with the discovery of terrestrial gamma-ray flashes (*Fishman et al.*, 1994), x-ray emissions by natural and triggered lightning (*Dwyer*, 2005b; *Dwyer et al.*, 2003), lab sparks (*Dwyer*, 2005a), and streamer discharges (*Nguyen et al.*, 2010), and the possibilities raised by the physics of runaway electrons.

To summarize the physics, the key facts are the instabilities present in gases in strong electric fields (see *Moss et al.* (2006) for an extensive discussion, the following is a summary). A free electron in an gas under an applied electric field can gain energy from the field and lose energy to collisions with gas molecules. When the free electron has low energy ($<$ 100 eV), as it gains energy from the field it experiences larger and larger frictional forces. For electrons with energies above 100 eV, however, this trend reverses and as the electron gains energy from the field, it experiences *less* friction. If the electric field is above 275 kV/m but below 10 MV/m, a low-energy electron will eventually reach an energy where frictional forces equals electric force, while a high-energy electron will "run away" to very high energies, an effect first predicted by *Wilson* (1924). This tends to separate free electrons in a gas into two populations, low-energy or "thermal" electrons, and high-energy or "runaway" electrons. Both thermal and runaway electrons experience collisions with gas molecules. If the applied electric field is strong enough, both low-energy and runaway electron populations will grow exponentially. Interestingly, the electric field necessary to drive avalanche growth of runaway electrons is an order of magnitude lower than that necessary to drive avalanche growth of low-energy electrons.

These processes combine with the electric fields produced in thunderstorms to produce a variety of recently-discovered sources of radiation. First, terrestrial gamma-ray flashes (TGFs) are brief ($<$ 1 ms duration) bursts of gamma-rays produced by thunderstorms and lightning that are not only bright enough to be detected by satellites orbiting hundreds of km away, but bright enough to effectively blind those detectors, producing large "dead time" in the satellite electronics (*Fishman et al.*, 1994; *Grefenstette et al.*, 2009; *Briggs et al.*, 2010; *Marisaldi et al.*, 2010). Second, balloon observations of energetic particles within thunderstorms have detected long-duration "glows" of gamma-rays that must somehow result from background electric fields

(*McCarthy and Parks*, 1985). Third, lightning discharges themselves produce bursts of x-ray pulses as the channel extends (*Dwyer et al.*, 2003; *Dwyer*, 2005b). These processes seem also to be active in smaller-scale discharges in the lab (*Dwyer*, 2005a).

These observations, together with the physics of runaway electrons and the possibility of relativistic runaway electron avalanche (RREA) growth, especially at relatively low threshold electric fields, suggests that runaway electrons may play an important role in thunderstorm dynamics. Energetic electrons must be present in order to explain energetic radiation observed in association with thunderstorms and lightning, either as short-duration bursts such as TGFs or the x-ray bursts produced by lightning leaders or as long-duration glows emitted by thunderstorms.

These unexpected possibilities have stimulated an increasing amount of interest over the past few years. The University of Bergen (UiB) has been active in much of this research. With a strong background in space physics, balloon and satellite instrument design, and associated data analysis, UiB is a natural place for such work to take root. Researches at UiB have published useful results on the properties TGFs (*Østgaard et al.*, 2012; *Collier et al.*, 2011; *Gjesteland et al.*, 2011), the implications of their observations (*Carlson et al.*, 2011a, 2012a), and detailed analysis of satellite observations (*Østgaard et al.*, 2008; *Gjesteland et al.*, 2010). More recently, UiB researchers ...

- ... are building an instrument for TGF observations, together with groups from Denmark, Spain, and Poland: the Modular X-ray and Gamma-ray Sensor (MXGS), part of the Atmosphere-Space Interactions Monitor (ASIM) to be deployed on the International Space Station.
- ... doubled the number of known TGFs by applying an improved search algorithm to existing TGF data (*Gjesteland et al.*, 2012).
- ... ran spark experiments with a novel detector to map the properties of energetic radiation produced by sparks in the lab (*Carlson et al.*, 2012b).
- ... modeled satellite observations to determine the fluence distribution of TGFs (*Østgaard et al.*, 2012).
- ... modeled the geometry necessary to detect TGFs from aircraft or balloon platforms (*Hansen et al.*, 2012).
- ... modeled the possible connection of such processes to lightning behavior (*Carlson et al.*, 2010, 2011b).

These activities are described in more detail below and in the accompanying slides.

2 University of Bergen Research

2.1 Atmosphere-Space Interactions Monitor

The Atmosphere-Space Interactions Monitor (ASIM) is an experiment to be deployed on the International Space Station (ISS) composed of energetic radiation detectors, cameras, and photometers. The energetic radiation detector, the Module X-ray and Gamma-ray Sensor (MXGS), is designed to observe TGFs in two ways: a coded mask imager will be used to determine the position and angular size of the source in x-rays, and a high-energy gamma-ray spectrometer will determine the energy distribution of higher-energy photons. The instrument design is completed, the project has passed preliminary design review (PDR), and is now in phase C. At the time of this writing, the expected launch to the ISS is in 2015.

2.2 TGF Data Search

UiB has also recently completed a reanalysis of existing TGF data from the Reuven-Ramaty High-Energy Solar Spectroscopic Imager (RHESSI) spacecraft (*Gjesteland et al.*, 2012). The algorithm complements a preliminary TGF catalog released by the RHESSI group by refining their criteria such that the threshold can be lowered without significantly contaminating the results with false events. The improved algorithm more than doubles the number of TGFs while retaining the same quality of signal as seen in the geographic distribution of events an in the fraction of events that can be directly associated with lightning as measured by the World-Wide Lightning Location Network (WWLLN).

2.3 Spark Experiments

UiB, in collaboration with the Technical University of Eindhoven (TU/e) in the Netherlands has also carried out a set of spark experiments with a 2 MV Marx Generator (*Carlson et al.*, 2012b). These experiments were carried out with a novel detector design using scintillating optical fiber coupled to well-shielded photomultiplier tubes. The non-conductive detectors can be placed very near the high voltage electrode and can easily be repositioned, allowing UiB researches to map out the distribution of signals as produced by energetic electrons and photons produced by the spark. Analysis is ongoing.

2.4 TGF Fluence Distribution Determination

One of the unknowns in TGF physics is the fluence distribution of TGFs at satellite altitude. This is difficult to determine from the satellite data as all observations to date have been significantly affected by dead time and detection efficiency. These effects are difficult to correct with a single satellite, but results from multiple satellites can be combined to infer the properties of this distribution. UiB researches have recently published a comparison of RHESSI and Fermi observations of TGFs (*Østgaard et al.*, 2012). The two instruments differing sensitivities and effective areas can be used to constrain the fluence distribution at satellite altitude. The results of such an analysis indicate that TGF fluence at satellite altitude follows an approximate power law distribution with index -2.3 and also suggests that TGFs may be much more common than previously assumed.

2.5 Aircraft/Balloon Observation Modeling

Satellite observations of TGFs must contend with atmospheric attenuation, uncertain geometry, and require a good deal of luck. Balloon or aircraft instruments offer significant advantages in this regard, as the observations can be carried out in regions of high thunderstorm activity and detailed lightning and meteorological observations can also be ensured. The ideal conditions for such observations are not simple, however, so UiB researchers are modeling TGF observation at balloon and aircraft altitudes (*Hansen et al.*, 2012). The model results help determine the necessary geometry for balloon and aircraft observations, and help understand the existing rarity of TGF observations by such instruments.

2.6 Lightning Modeling

The UiB group is also developing a model of the lightning discharge to help determine the associated electric fields relevant to energetic radiation production (*Carlson et al.*, 2010, 2011b). This model, the time-domain fractal lightning model (TDFL) is an advanced solution to the time-domain electric field integral equation on conducting or resistive channels, including the effects of channel conductivity evolution and the corona sheath. Preliminary results are very encouraging, and development is ongoing.

3 Future Projects

The UiB group includes several masters students, and graduate students, and postdocs who are working on energetic radiation and lightning, including modeling bremsstrahlung, runaway electron avalanche feedback (self-seeding), continued lab spark experiments, analysis of the new RHESSI data, and preparation for ASIM science. The group is also very interested in further collaborations on the topics described above or any related topics. Energetic radiation associated with lightning and thunderstorms is turning out to be a far more interesting and important topic than initially envisioned, we hope such research will continue, and we hope to make UiB an active player in future work.

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