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## New Mechanism for Lightning Initiation

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### Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). To distinguish radio-frequency (rf) signals generated by lightning from the electromagnetic pulse produced by a nuclear explosion, it is necessary to understand the fundamental nature of thunderstorm discharges. The recent debate surrounding the origin of transitionospheric pulse pairs (TIPPs) detected by the BLACKBEARD experiment aboard the ALEXIS satellite illustrates this point. We have argued that TIPP events could originate from the upward propagating discharges recently identified by optical images taken from the ground, from airplanes, and from the space shuttle. In addition, the Gamma Ray Observatory (GRO) measurements of x-ray bursts originating from thunderstorms are almost certainly associated with these upward propagating discharges. When taken together, these three measurements point directly to the runaway electron mechanism as the source of the upward discharges. The primary goal of this research effort was to identify the specific role played by the runaway-air-breakdown mechanism in the general area of thunderstorm electricity and in so doing develop lightning models that predict the optical, rf, and x-ray emissions that are observable from space.

### 1. Background and Research Objectives

Mechanisms for the initiation of lightning discharges have been proposed and studied for decades. In all cases air breakdown is assumed to occur as a result of acceleration of thermal seed electrons to ionizing energies in the presence of thunderstorm electric fields. However, the threshold electric field necessary for this process exceeds all

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measurements of large scale electric fields in thunderstorms and it is necessary to invoke complex scenarios (such as field enhancement around water droplets) for the initiation of lightning. In a recent paper Gurevich, Milikh, and Roussel-Dupré [1] describe a new process for air breakdown in which high-energy electrons in the tens of keV range (produced by cosmic-ray ionization of air) are accelerated by thunderstorm electric fields to relativistic energies (approximating 'runaway'), producing secondary electrons (in the 10 keV range) which, in turn, runaway in energy to produce additional secondaries. The net result is an avalanche of the high-energy electron population and the formation of an electron beam.

The runaway breakdown mechanism possesses a number of advantages over existing theories. The threshold electric field is calculated to be ten times less than that needed for thermal air breakdown and less, by a factor of two or three, than the maximum large scale fields measured in active thunderstorms. In addition, the formation of a high-energy electron beam is accompanied by large scale breakdown of the air, which results in a current of cold electrons that cancels the positive charge left behind. This permits the electron beam to propagate and avalanche over larger distances. A sufficient amount of charge is deposited in a small volume, producing a field that exceeds the threshold for runaway. Hence, a new beam can be formed and in this way a breakdown or ionization front can propagate over large distances.

One of the unique signatures of runaway breakdown is the strong  $\gamma$ -ray flux produced by the beam interaction with air. Unfortunately,  $\gamma$ -rays are also readily absorbed in air and the detection of such emissions necessitates a distance to the discharge of less than several hundred meters to a kilometer at sea level, depending on the strength of the discharge. At high altitudes above 25 km, the atmosphere becomes transparent to these emissions and remote detection becomes feasible. In addition, because the frictional drag on electrons decreases exponentially with height and the dipole field from thunderstorms decays slowly (as  $1/r^3$ ), the threshold for runaway is more easily exceeded over larger distances at high altitude. As a result, runaway breakdown is more likely to be detected in high altitude discharges.

Observational support for the runaway mechanism comes from recent measurements by McCarthy and Parks [2] of sharp increases in the X-ray flux from 5 to 110 keV prior to lightning strokes. Even more intriguing are the recent measurements (see e.g., Sentman and Wescott [3]) of high-altitude optical flashes over the tops of thunderstorms and the satellite measurements of  $\gamma$ -ray and radio flashes that appear to be associated with thunderstorms. First results from the BLACKBEARD experiment aboard the ALEXIS satellite yielded the measurement of Trans-Ionospheric Pulse-Pair (TIPP)

events. These events, previously not documented in the literature, consist of a time-correlated pair of VHF sferics, separated in time by from several tens of microseconds to more than 100  $\mu$ s, but having individual full-widths at half maximum of from 3 to 10  $\mu$ s.

Another newly discovered phenomenon may also be related to upward lightning but, again, corroborating optical observations were not available to make a definitive association. Bursts of intense, hard gamma-ray emission from the atmosphere were observed by the Burst and Transient Signal Experiment (BATSE) aboard the Compton Gamma-Ray Observatory (CGRO) when the subsatellite point was above large thunderstorm complexes near the equator (Fishman et al. [4]). The association of these emissions with upward discharges stem not only from the proximity of the subsatellite point to thunderstorm activity but also to the fact that strong atmospheric absorption and scattering limits the source region to altitudes above 25 km, which happens to coincide well with the altitude range of the optical measurements. If the  $\gamma$ -ray measurements obtained by BATSE can be directly linked to the upward discharge process defined by the optical observations, then we must rule out any model that is based on conventional air-breakdown. An alternative solution for the initiation of upward discharges is rooted in the runaway air breakdown mechanism.

Our primary objective was to develop a theoretical model for lightning that is based on the runaway air-breakdown mechanism. When completed, this model would treat the stepped-leader and/or beta streamer phase of lightning discharges but could also be adapted to study the case of upward propagating discharges. In addition, the model would predict the optical, radio frequency (rf), and  $\gamma$ -ray emissions to be expected from lightning discharges. A secondary goal was to undertake experiments and analyze existing data to verify the presence of runaway breakdown in thunderstorm discharges.

## **2. Importance to LANL's Science and Technology Base and National R&D Needs**

The analyses performed as part of this effort yielded a new, fundamental understanding of the plasma processes involved in the development of lightning discharges. The results of our research has provided valuable input to environmental, commercial, industrial, and military concerns interested in predicting and protecting against lightning strikes and interested in the overall global electrical circuit and global climate change. Direct programmatic interest in this subject stems from a desire to characterize the rf, optical, and  $\gamma$ -ray backgrounds associated with lightning emissions observed from space and to discriminate the rf signals produced by lightning discharges from the electromagnetic

pulse produced by a nuclear explosion. The BLACKBEARD and FORTE projects (funded by the Department of Energy) have benefited and will continue to benefit directly from the research performed as part of this LDRD effort.

### 3. Scientific Approach and Results to Date

The first year of our project focused on development of a kinetic theory for runaway air-breakdown. A detailed paper was published [5] describing the results of a time-dependent, numerical solution of the relativistic Boltzmann equation and including a computation of the expected Bremsstrahlung emission. A second report, which included a discussion of the role of runaway breakdown in lightning initiation, was published as a Los Alamos report [6].

In the second year we focused on the development of a two-dimensional fluid model (using the results of the kinetic calculations) to allow for the finite spatial distribution of thunderstorm electric fields and in order to study the details of electron beam formation and charge deposition. A paper discussing an initial analytic treatment of the spatial evolution of the runaway electron beam was published [7]. The results were incorporated in our fluid model. We also initiated a series of experiments to look for  $\gamma$ -ray emissions from cloud-to-ground lightning. The measurement of optical flashes over the tops of thunderstorms by researchers in the lightning community during the first and second years prompted us to take a more detailed look at high-altitude discharges in the context of runaway breakdown. We decided to apply our fluid theory to model upward discharges. At the same time we modified our existing kinetic code to include the effects of the geomagnetic field. A paper on the latter subject is nearly complete and will be submitted for publication in Physical Reviews E.

In the second year we also initiated an analysis of satellite  $\gamma$ -ray data obtained from the Army Beam Experiment (ABE; Feldman et al. [8]). An initial analysis of this data reveals the presence of bursty emissions (similar to that recorded by GRO) and the frequent occurrence of Trimpie-type precipitation events.

The third year of the project proved to be quite prolific as much of the results obtained in the previous two years bore fruit. With our fluid model of runaway breakdown we were able to successfully simulate upward propagating discharges and reproduce many of the temporal and spatial characteristics of the measured optical flashes termed sprites and blue jets. Results of our model calculations are shown in Figure 1. In addition, we pointed out that the  $\gamma$ -ray pulses recorded by GRO probably originated from the same phenomenon and that only runaway breakdown could account for the magnitude and

temporal characteristics of the observations. Our model and the corresponding results are described in a paper submitted for publication [9]. In a second paper submitted for publication on upward propagating discharges, we review the general theory of runaway breakdown and present a simplified model for upward discharges including a calculation of the expected optical,  $\gamma$ -ray, and VHF radio emissions [10]. The radio emissions calculated with our model were able to reproduce many of the characteristics of TIPPs including the double pulses, their intensity, the time separation between pulses, and the duration of each pulse.

Three papers [11-13] describing the ABE  $\gamma$ -ray measurements have been submitted for publication. GRO-type pulses were detected, further supporting the runaway breakdown mechanism as the source of upward discharges.

The ground-based experiments to look for  $\gamma$ -ray emissions from lightning are described in another paper submitted for publication [14]. The results so far are inconclusive. However, measurements recently obtained in the Ivory Coast, Africa, have yielded some interesting temporal coincidences between rf and  $\gamma$ -ray measurements that could confirm the presence of runaway discharges in stepped-leader processes. We also participated this year in an experiment in the Ivory Coast with Elisabeth Blanc of the Laboratoire de Detection et Geophysique, Commissariat a L'Energie Atomique to detect ionization from upward propagating discharges by means of HF sounding and to obtain broadband rf measurements of lightning. We were successful in measuring echoes from ionization columns produced in the stratosphere and lower mesosphere on several occasions. The measurements are described in a paper in preparation and further confirm that runaway breakdown is the driving mechanism for upward discharges.

We have had an extremely successful project not only in terms of the scientific impact of our findings but also because of the interest that our work has generated in the scientific community and in the popular press. Several programs have been spawned directly at Los Alamos as a result of this project. Some examples are the MCG (magnetocumulative generator) Balloon project funded by DOE with several follow-on experiments as well as the analysis of ABE data described in this report.

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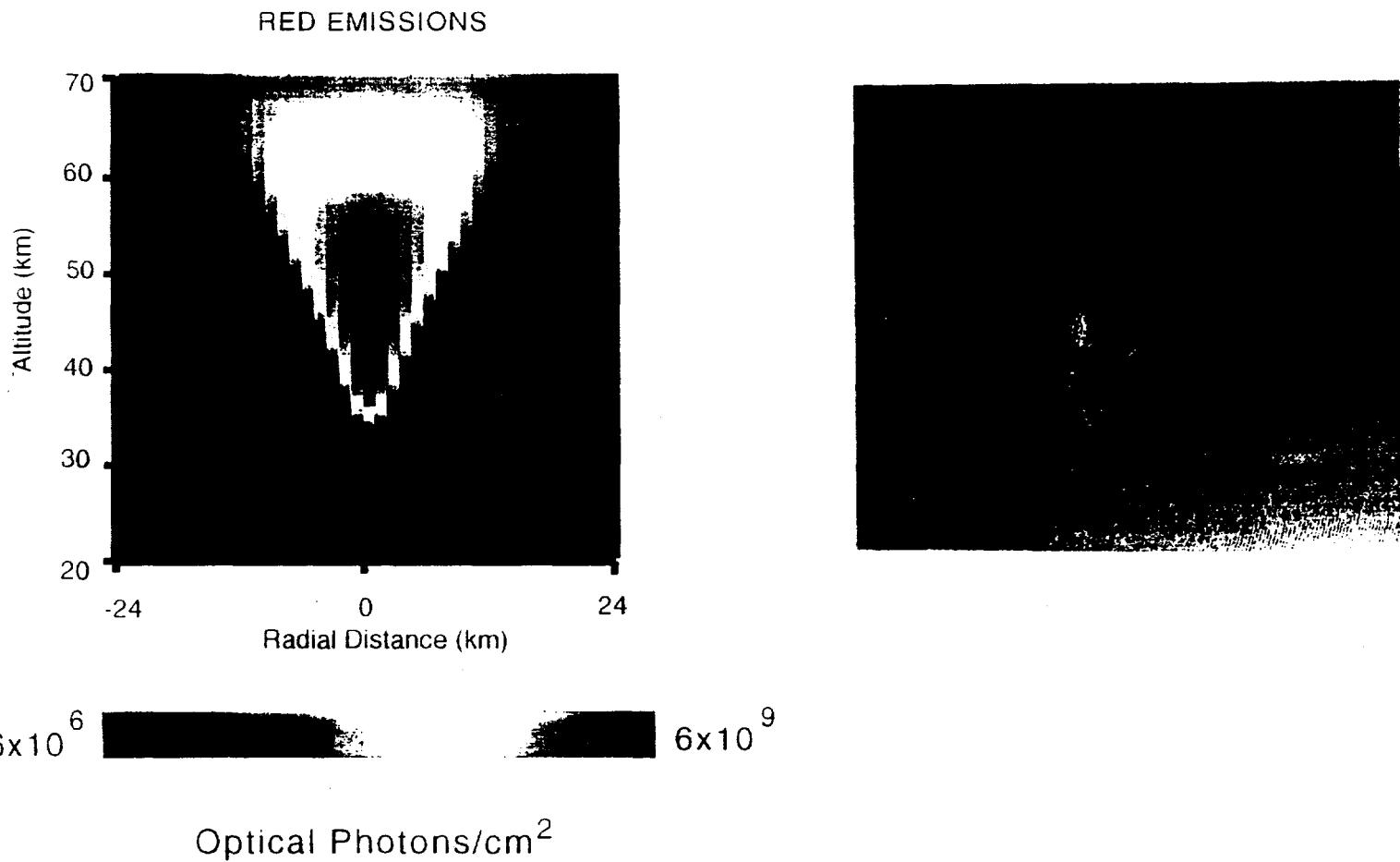


Figure 1. Runaway Simulation of Sprite Emissions Compared with Observations. The results of a two-dimensional, fluid simulation of an upward propagating discharge is shown in the left hand image. The computed irradiance in the red part of the visible spectrum from 6000 - 6500 Å is shown. An actual photograph taken of a red sprite is shown on the right. The photograph was obtained from a movie produced by the Geophysical Institute, University of Alaska (Courtesy of Dave Sentman and Gene Wescott).