X-ray Emission from Thunderstorms and Lightning

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Lightning facts

- Lightning strikes the Earth about 4 million times every day.
- Lightning costs the US about $4-5 billion per year in losses and damages.
- Every year lightning kills about 100 people in the US alone, more than hurricanes or tornados.
Despite its familiarity, lightning remains a mystery

- Big question #1: What microphysical processes are responsible for thunderstorm electrification?

- Big question #2: How does lightning get started with the relatively low electric field strengths inside thunderstorms?

- Big question #3: How does lightning travel through tens of kilometers of air?
Since we are still struggling to understand how lightning works 250 years after Franklin’s kite experiment, perhaps we are missing something important....

Runaway Electrons
25 MeV electron moving through air at 1 atm
25 MeV electron moving through air at 1 atm in a 3 kV/cm electric field
Energy loss and gain experienced by an electron in air
Extensive air showers trigger lightning?

For a typical thunderstorm electric field $\lambda \sim 100$ m.

If the high field region has a depth of 2000 m then $\exp(20) \sim 10^8$ runaway electrons are produced for each energetic seed particle.

An extensive air shower with $10^7$ particles passing through such a thunderstorm would produce $10^{15}$ relativistic electrons and many more low energy electrons.

Maybe extensive air showers and runaway breakdown initiate lightning.

The average energy of runaway electrons is 7 MeV.

The runaway breakdown threshold electric field $E_{th} = 284$ kV/m at STP.
Relativistic Breakdown due to x-ray and positron feedback.

The central avalanche is due to the injection of a single, 1 MeV seed electron. All the other avalanches are produced by x-ray and positron feedback. The top panel is for times, $t < 0.5 \, \mu s$. The middle panel is for $t < 2 \, \mu s$, and the bottom panel is for $t < 10 \, \mu s$. 
Relativistic Breakdown limits the electric field that can be achieved in air and prevent large avalanche multiplication.
Does runaway breakdown actually occur?

One signature of runaway breakdown is x-ray emission.

Many researchers have searched for such x-rays associated with thunderstorms and lightning.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Location</th>
<th>X-rays in thunderstorms?</th>
<th>X-rays in lightning?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appleton &amp; Bowen (1933)</td>
<td>ground</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Macky (1934)</td>
<td>balloon</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Clay et al. (1952)</td>
<td>ground</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Hill (1963)</td>
<td>300 m tower</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>McCarthy &amp; Parks (1985)</td>
<td>aircraft</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Fishman et al. (1994)</td>
<td>space</td>
<td>Yes (sprites?)</td>
<td>No</td>
</tr>
<tr>
<td>Moore et al. (2001)</td>
<td>mountain (3288 m)</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Rocket-triggered lightning
Instrument used to measure x-rays from lightning at the UF/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL
X-ray instruments in front of rocket launch tower used to trigger lightning
Triggering lightning
Method 2
Rocket-triggered lightning
Rocket-triggered lightning
Rocket-triggered lightning
Rocket Triggered Lightning -- slow motion
Rocket Triggered Lightning—slow motion
X-rays from rocket-triggered lightning dart leaders
X-Rays from Lightning

New research shows that lightning is a surprisingly complex and mystifying phenomenon

By Joseph R. Dwyer

Lightning is a particularly unsettling product of bad weather. It causes more deaths and injuries in the U.S. than either hurricanes or tornadoes do, and it strikes without warning, sometimes with nothing but blue sky overhead. In central Florida, where I live, thunderstorms are a daily occurrence during the summer, and so, ironically, people in the Sunshine State often spend their afternoons indoors to avoid the risk of death from the sky.

Worldwide, lightning flashes about four million times a day, and bolts have even been observed on other planets. Yet despite its familiarity, we still do not know what causes lightning. It is a misconception that Benjamin Franklin solved the puzzle when he conducted his famous kite experiment in 1752.

Credit: J. R. Dwyer, Sci. American, May, 2005
Energy of x-rays from triggered lightning
X-rays from natural cloud-to-ground lightning
TERA at the UF/Florida Tech International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, FL
TERA Instrument Design
X-rays from triggered lightning using TERA
Detector response fits to x-ray pulse from lightning
Radial fall-off of the x-rays from the triggered lightning channel

Radial energy distribution

Deposited energy (keV/m²)

Radial distance (m)

\( \frac{-r}{120} \times \exp \left( \frac{r}{120} \right) \)

UF-05-01
UF-05-03
UF-07-07
Schematic of Monte Carlo simulation
Model fits to x-ray data for different runaway electron energies

-64 < t(μs) < -7
287 > z(m) > 87

Isotropic electron source

Deposited energy (keV/m²)

Radial distance (m)
Best model fit to x-ray data

1000 keV Isotropic

-164 < t(μs) < 0
797 > z(m) > 17

Reduced $\chi^2 = 1.09$

Unshielded (Model)
Shielded (Model)
Shielded (PMT)
Unshielded (PMT)
Model fits to x-ray data for different lightning leader altitudes
Energetic electron luminosity from lightning (electrons/sec)
A ground level gamma-ray flash observed during the initial stage of rocket-triggered lightning
CGRO/BATSE Terrestrial Gamma-ray Flash (TGF)
Terrestrial Gamma-Ray Flash (TGF) spectrum and results of Monte Carlo simulation for different source altitudes
Monte Carlo simulation showing runaway electron trajectories, injected by lightning, inside a thundercloud at 5 km altitude.
The effective dose produced by one lightning leader inside a thundercloud and a TGF versus the radius of the energetic electron beam.
Future Work:
Schematic of XL-cam

- 3-inch NaI/PMTs (102)
- 0.5-inch lead sheets
- Adjustable pinhole
- 2 m
Simulated movie of lightning made with x-rays.  
25 microsecond of data shown. The lightning leader channel from a high speed optical camera is superimposed. For this simulation the emission is assumed to come from the bottom of the newly formed leader segment.
Conclusions

• Lightning is not simply a conventional discharge.

• It involves an exotic kind of discharge called runaway breakdown, during which electrons are accelerated to nearly the speed of light and large numbers of x-rays are created.

• Since the standard models of lightning do not include runaway breakdown nor do they predict x-ray emission, clearly we need to revisit these models.

• How lightning works has remained a great mystery. Perhaps runaway breakdown is the missing pieces that we need to solve the puzzle.

• Finally, x-rays give us a new way to look at lightning.