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Big question # 4: How and why does lightning strike objects?

Big question # 5-99: What the heck was that?
Lightning Attachment Problem

Exactly how lightning strikes objects on or near the ground is not well understood.

The problem is of great practical importance for lightning safety and protection. More on this during the lightning safety talk.
Lightning propagation Problem

Lightning can travel over 100 miles through storm systems.

It does this by breaking down the air in front of it, forming a hot conductive channel that carries the charges to the tip of the lightning.

Most lightning does not travel continuously. Instead, it moves in discrete steps, about 50 yards long. No one knows how or why lightning moves this way.
Lightning Initiation

Problem

Years of balloon, aircraft and rocket observations have never found large enough electric fields inside thunderstorms to make a spark. And yet lightning strikes the Earth about 4 million times per day.

This has led to the cosmic-ray model of lightning initiation....
Step 1: Blow up one medium to large size star.

Tycho supernova remnant as seen in x-rays by Chandra
Step 2: Have the explosion accelerate cosmic-rays, which then fly around the galaxy for about 10 million years until…

NASA FERMI all sky gamma-ray image
Step 3: One of them slams into the Earth’s atmosphere and carves a conductive path through a thunderstorm.

http://astro.uchicago.edu/cosmus/projects/aires/protonshower.jpg
Step 4: Voilà!

http://www.insidesocal.com
Nice idea, but, unfortunately, air showers alone will not increase the conductivity enough to initiate lightning.

If air showers are involved in lightning initiation then there must be some other mechanism to increase the ionization….

Runaway Electrons

(C.T.R. Wilson, 1925)
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
25 MeV electron moving through air at 1 atm in a 3 kV/cm electric field

Relativistic Runaway Electron Avalanche (RREA)

Gurevich et al., 1992
Inside a thundercloud:
Strong electric fields accelerate electrons to nearly the speed of light. These electrons emit x-rays and gamma-rays.
Some observations would be nice at this point.

Since runaway electrons should make lots of x-rays and gamma-rays, do we see energetic radiation from thunderstorms or 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 &lt;i&gt;et al.&lt;/i&gt; (1994)</td>
<td>space</td>
<td>Yes (Sprites?)</td>
<td>No</td>
</tr>
<tr>
<td>Moore &lt;i&gt;et al.&lt;/i&gt; (2001)</td>
<td>mountain (3288 m)</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Let’s look for ourselves.
Rocket-triggered lightning
Easier to study rocket-triggered lightning
Triggering lightning
Method 2
Instrument used to measure x-rays from lightning at the International Center for Lightning Research and Testing (ICLRT) in FL
X-ray instruments in front of rocket launch tower used to trigger lightning
Rocket-triggered lightning
Rocket Triggered Lightning -- slow motion
Rocket-triggered lightning
Rocket Triggered Lightning—slow motion
X-rays from rocket-triggered lightning

From Dwyer et al. (2004)
The more x-ray detectors the better, especially for catching natural lightning
Distribution of x-rays for natural and rocket triggered lightning

Natural lightning struck just off site

Rocket launch tower

Figure 5(a). Natural Lightning MSE-07-04

Figure 5(b). Triggered Lightning UF-07-07
X-rays from natural cloud-to-ground lightning
We see other strange stuff as well. A gamma-ray flash coming down from the overhead thundercloud.
First x-ray image of lightning, showing descending dart leader
Attachment process as seen in x-rays
Movie of x-rays from lightning. The entire movie records events that last 2.5 millionths of a second.
Lightning is a big spark.
Do all sparks emit x-rays?

1.5 MV, 2 m long spark made by a Marx generator
Discovery of x-rays from long laboratory sparks in air

Using a Marx generator, 1.5 million volt sparks in air make x-rays, very similar to lightning.

This was not known prior to 2005.

From Dwyer et al. (2005)
World’s largest air insulated van der Graaf machine at the Boston Museum of Science
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World’s largest air insulated van der Graaf machine at the Boston Museum of Science
No x-rays detected for either positive or negative polarity sparks

As viewed in x-rays, their sparks look nothing like lightning. Not really a “lightning show.”

9 years after the discovery of x-rays from lightning, it is still not clear why some discharges make x-rays and others do not.
Meanwhile, back inside the thunderclouds…

Photo by Mindi Holcomb
Thunderstorms

- Lightning and some long sparks emit hard x-rays.

- There are a lot of sparks, big and small, made inside thunderclouds.

- Do thunderstorms emit x-rays as well?
Yes. Big time.

Lightning near 21 August Glow

From Kelley et al. 2014
Gamma rays are made inside thunderstorms.
Explosive production of energetic particles seen from space

CGRO/BATSE Terrestrial Gamma-ray Flash (TGF) (Fishman et al. 1994)
Artist’s impression of a terrestrial gamma-ray flash (TGF) and electron-positron beam seen from space

Courtesy NASA
How do thunderstorms make terrestrial gamma-ray flashes?

There are two leading models:

- Lightning leader emission, similar to x-ray emission seen near the ground.
- Dark Lightning!
Dark Lightning

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 $t < 10 \, \mu s$. 

From Dwyer (2007)
Dark lightning

- A new kind of lightning.
- Generates so many high-energy particles that it discharges the thunderstorm faster than normal lightning.
- Makes currents as big as normal lightning, e.g. > 100,000 amps.
- Emits very little visible light, i.e. appears dark.
- Can explain TGFs.
- Cosmic rays are not needed.
Multi-pulsed TGFs

From Dwyer (2012)
Multi-pulsed TGFs

Dark lightning model result

From Dwyer (2012)
What about this?

- A bright TGF was seen by the RHESSI spacecraft in the middle of the Sahara Desert on a nice day. The nearest thunderstorms were ~1000 miles away.

- If thunderstorms generate TGFs deep within our atmosphere, how can we explain this and other similar events (seen by BATSE and Fermi)?

Plot courtesy David Smith
Computer simulation of gamma-rays (red) and electrons (blue) blasting their way out of our atmosphere
Thunderstorms make electron and positron (anti-matter) beams

Courtesy Michael Briggs
Conclusions

- Many mysteries remain about how thunderstorms and lightning work, including how thunderstorms electrify, how lightning gets started and how it moves.

- It was recently established that thunderstorms and lightning produce intense bursts of x-rays and gamma-rays.

- This high-energy radiation may be important for understanding how lightning works.

- X-rays and gamma-rays also give us a new tool for remotely studying thunderstorms and lightning.

- This new field of study is called “High-Energy Atmospheric Physics.”