Lightning - Phenomenology

**Lightning:** A transient electrical discharge (ms), with high electrical current (tens of kA), covering distances of kilometers, that occurs when enough charge builds up in the atmosphere to produce electric fields that exceed the “breakdown field” in the atmosphere (~ MV/m). Normally lightning is associated with thunderstorms, but can also be associated with dust storms and volcanoes.

Types of lightning discharges:
1. Intracloud flashes (within clouds)
2. Intercloud flashes (between clouds)
3. Cloud to Air flashes
4. Cloud-to-ground flashes (between cloud and ground)
   4.1 Negative CG
   4.2 Positive CG
70%

Discharge within cloud between negative base and positive top (intra-cloud)

30%

Discharge between negative and positive charge centers

Typical cloud-to-ground lightning between ground and negative charge centers

Inter-cloud strike (cloud-to-cloud)
Volcanic Lightning
Origin of lightning flashes in thunder clouds

Fig. 1. Distribution of (a) heights above ground level (at 1.43 km amsl) of the origins of 773 flashes, cloud to ground (CG) and intracloud (IC), that occurred in 13 storms; and (b) origin heights of 214 flashes to ground.
Fig. 2. Changes in the thundercloud charge distribution that are caused by CG (open circles) and IC (arrows) lightning as a function of time (10). Charge lowered in coulombs is shown for ground flashes and moment changes in coulombs-kilometers for intracloud discharges. The data are from a portion of an active thunderstorm at the NASA Kennedy Space Center. The open circles show the altitude and magnitude in coulombs of the negative charges removed by various (CG) lightning flashes that occurred during a 20-min period. The arrows show the changes in dipole moment in coulomb-kilometers that were produced by cloud discharges that effectively destroyed separated positive and negative charge. A downward-pointing arrow indicated positive charge was above negative charge before both were effectively neutralized. GMT, Greenwich mean time. [Reprinted from (10) with permission, © 1989 American Geophysical Union]
Fair Weather Charge

- In fair weather we observe an Electric Field of 100V/m pointing downward to the Earth. (Earth has negative charge.

+     +     +     +
Upper atmosphere/ionosphere is positively charged.

-     -     -     -
Ground is negatively charged.
Lightning

- Air is a very good insulator.
- To have lightning:
  - Need to have the charge centers very close to each other
  - Have very large differences in charge “strength”, i.e. large E-fields
- In order to get lightning in a thunderstorm you need to separate large amounts of charge. How is this done? *(Lecture on Th. Electr.)*
Below Thunderstorms the E-field is reversed
(Foul Weather Field)

Cloud-to-Ground Lightning Discharge:

Negative Cloud-to-Ground
(90 %)

Positive Cloud-to-Ground
(5 %)
Ground-to-Cloud flashes

Positive Ground-to-Cloud (3 %)

Negative Ground-to-Cloud (2 %)
• The lightning stroke begins when the electric fields exceed breakdown voltage. At the ground the maximum fields get to ~10 kV/m.

• Initially streams of electrons surge from the cloud base toward the ground in steps of 50 to 100 m.
• Start and stop steps as the **stepped leader** progresses toward ground.
The polarity of a leader is defined by the polarity of its charge – and not by its current.
Fig. 7.1a  Diagram showing general features of streamer mechanism as applied to lightning leader into virgin air in absence of step mechanism. The times $t_3 > t_2 > t_1$. 

- Electric field intensity
- Photon producing photoionization
- Electron avalanche
Fig. 9.1. Stepped leader initiation and propagation. (a) Cloud charge distribution just prior to p-N discharge. (b) p-N discharge. (c)-(f) Stepped leader moving toward ground in 50-yard steps. Time between steps is about 50 millionths of a second. Scale of drawing is distorted for illustrative purposes.

Figure 6.2. Sketch of the time development of a lightning stepped leader and the ensuing return strokes.
The stepped leader is:

- Very Faint
- Essentially invisible to the human eye
- Produces an ionized channel that will allow for the flow of charge during the remainder of the lightning stroke.
### Characteristics of stepped leaders

**Primarily Uman (1969)**

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<th>Item</th>
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<th>Typical value</th>
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<td>Interval of step ($\mu$sec)</td>
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<tr>
<td>Current (A)</td>
<td></td>
<td>2600</td>
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The Attachment Process

• When the stepped leader gets near the ground (~100 m or so):
  – Positive charge moves from the ground up toward the stepped leader -- these are called **streamers**.
  – The streamers may come from almost any pointed object on the ground:
    • Trees
    • Antennas
    • Flagpoles
    • Telephone Poles
    • People
Figure 6.3. Sketch of the luminous processes that occur during a lightning strike. An upward-connecting discharge forms in (c) when the stepped leader is at the striking distance, SD.
Streamers

A streamer rising from a part of the tree. The return stroke was created when the stepped leader met with a streamer from another part of the tree.
Figure 6.4. Photograph of upward streamers near the strike points of two flashes in mountainous terrain. Point d: striking distance; e: junction between the connecting discharge and the leader; a, b, and c: upward discharges that did not contact the leader (Krider and Ladd, 1975).
Return Stroke

- One of the streamers will meet the stepped leader -- not necessarily the one from the tallest object!
- When they meet a pulse of energy flows up toward the cloud (along the ionized path) and toward the ground. Rapid transfer of charge from cloud to ground.
- This luminous pulse of electrical energy is called the **return stroke**.
- Occurs very fast -- we see it as a flash!
Fig. 7.1c  Diagram showing general features of streamer mechanism as applied to return stroke. Times $t_3 > t_2 > t_1$. Note that all current is carried by electrons since the mobility of positive ions is low.
Fig. 9.2. Return stroke initiation and propagation. (a) Final stages of stepped leader descent. (b) Initiation of upward-moving discharges to meet downward-moving leader. (c)-(e) Return stroke propagation from ground to cloud. Return stroke propagation time is about 100 millionths of a second; propagation is continuous. Scale of drawing is distorted.

Fig. 78. Mechanism of return stroke. After Schonland (1938).
Dart Leader

- approximately 0.04 sec after the return stroke
- the dart leader travels down the ionized channel without “steps”
- followed by another return stroke after ~1 msec.
- Another dart leader can occur 0.04 sec after the next return stroke, and so on.…
- May get several sets of dart leader/return stroke pairs.
- Appears as if the lightning “flashes.”
Fig. 7.1b  Diagram showing general features of streamer mechanism as applied to dart leader. The times $t_3 > t_2 > t_1$. 
Fig. 9.3. K-streamers and J-streamers making more negative charge available to the channel top during the 50 thousandths of a second or so following the cessation of current flow in the first return stroke. Scale of drawing is distorted.

Fig. 9.4. Dart leader and subsequent return stroke. (a)-(c) Dart leader deposits negative charge on defunct first-stroke channel during its thousandth-of-a-second trip to ground. (d)-(e) Subsequent return stroke propagates from ground to cloud in about 100 millionths of a second. Scale of drawing is distorted.
Schematic Description of Lightning Flash

Flash (0.2 sec = 200 msec)

stroke (~40 msec)

- 1 msec
- “stepped” leader (30-90 m steps) 1.5x10^7 cm/sec
- Return stroke 1.3x10^10 cm/sec

stroke (~40 msec)

- 40 msec
- “dart” leader 10^9 cm/sec
- Return stroke

stroke (~40 msec)

- 40 msec
- “dart” leader 10^9 cm/sec
- Return stroke

A charged channel descends from cloud to ground ~ 5 C

Transfer of charge to Earth (electrical discharge)

Equipotential lines

- +
Fig. 4.3  Frequency distribution of peak current for lightning strokes initiated by downward-moving leaders. Strokes lowering negative charge and strokes lowering positive charge are both included.
Fig. 5.7. (a) Current at ground due to a typical lightning flash without continuing current — so-called cold lightning. (b) Current at ground due to a typical lightning flash with continuing current — so-called hot lightning.
Fig. 2.—Discharge current variations.

\[
I = A e^{-\alpha t} - B e^{-\beta t} + C e^{-\gamma t}
\]

\[
I = I_0 \left( e^{-\alpha t} - e^{-\beta t} \right)
\]

\[
\alpha = 5 \times 10^2 \text{ s}^{-1}, \quad I_0 = 20 \text{ kA}
\]

\[
\beta = 5 \times 10^5 \text{ s}^{-1}, \quad A = 20 \text{ kA}
\]

\[
\gamma = 7 \times 10^3 \text{ s}^{-1}, \quad B = 25 \text{ kA}
\]

\[
C = 5 \text{ kA}
\]
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<td>135</td>
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<td>μsec</td>
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<td>μsec</td>
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<td>Positive first strokes</td>
<td>μsec</td>
<td>25</td>
<td>230</td>
<td>2000</td>
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<tr>
<td>91</td>
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<td>A^2 sec</td>
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<td>$5.2 \times 10^4$</td>
</tr>
<tr>
<td>26</td>
<td>Positive first strokes</td>
<td>A^2 sec</td>
<td>$2.5 \times 10^4$</td>
<td>$6.5 \times 10^3$</td>
<td>$1.5 \times 10^7$</td>
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<tr>
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<td>Time interval between negative strokes</td>
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<td>150</td>
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<td></td>
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<td>94</td>
<td>Negative (including single-stroke flashes)</td>
<td>msec</td>
<td>0.15</td>
<td>13</td>
<td>1100</td>
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<tr>
<td>39</td>
<td>Negative (excluding single-stroke flashes)</td>
<td>msec</td>
<td>31</td>
<td>180</td>
<td>900</td>
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<tr>
<td>24</td>
<td>Positive (only single flashes)</td>
<td>msec</td>
<td>14</td>
<td>85</td>
<td>500</td>
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*Adapted from Berger et al. (1975).*
Lightning Flash – total discharge ~ 0.2 seconds
Lightning Stroke – individual discharge within flash ~ 10 msec
Multiplicity – number of strokes per flash ~ 3-4 strokes per flash separated by ~40 msec

<table>
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<th>Characteristics of lightning flashes</th>
<th>Minimum</th>
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<td>3--4</td>
<td>26</td>
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<td>100</td>
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<td>Duration of flash (sec)</td>
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<td>0.2</td>
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<tr>
<td>Charge transported (C)</td>
<td>3</td>
<td>25</td>
<td>90</td>
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</table>
Fig. 10. My conception of cloud to ground lightning, which is similar to that of Malan and Schonland [1951]. (Malan and Schonland’s conception appears in figure 21, page 50.) Arrowheads mark channels extending into virgin air. Solid triangle arrowheads mark ionizing wavefronts extending into warm or hot air. Thin solid lines indicate channels carrying tens to hundreds of amperes. Thick solid lines indicate channels carrying kiloamperes. Dotted lines indicate resistive channels (carrying no current).
Fig. 16.2. Streak-camera photograph of a 12-stroke lightning flash taken near Socorro, New Mexico. The first stroke is on the left and is the only branched stroke (see Chapter 9). Increasing time goes from left to right. Continuing current (see Chapter 5), as evidenced by continuing luminosity, flows after the eleventh stroke. (Courtesy, Marx Brook, New Mexico, Institute of Mines and Technology)
Fig. 1.10 Histograms of the number of strokes per flash (a) for 1800 flashes in South Africa studied by Schonland (1956) and (b) for 105 flashes in Florida studied by Thomson et al. (1984). The mean number of strokes per flash in South Africa was 4.1 and in Florida was 4.0.

Fig. 1.11 Histograms of the interstroke time interval for (a) 1482 flashes in South Africa studied by Schonland (1956) and (b) for 105 flashes in Florida studied by Thomson et al. (1984). Note that the horizontal axis in b is logarithmic and that the histogram plotted with that logarithmic axis is roughly symmetrical. Thomson (1980) and Thomson et al. (1984) have shown that the distribution of interstroke intervals follows log normal statistics. The geometric mean interstroke interval in South Africa was 51 msec and in Florida was 69 msec. The arithmetic mean interstroke interval in South Africa was 65 msec and in Florida was 90 msec. A discussion of the log normal distribution, and of the geometric mean, which is also the median value for
Fig. 10.5. Holes melted in two Fiberglas screens by lightning. At least four strokes passed through the screen on the left. One stroke passed through the screen on the right.
Upward lightning

Fig. 6.1a. Lightning initiated by an upward-moving leader from a tower on Mt. San Salvatore near Lugano, Switzerland. The spot directly beneath the bottom of the lightning channel is a tower light. Upward-initiated lightning is branched upward in contrast to the downward branching of the usual cloud-to-ground lightning flash. (Courtesy, Richard E. Orville, State University of New York at Albany)

Fig. 6.1b. Lightning strikes twice! Another upward-going lightning from the San Salvatore tower. (Courtesy, Richard E. Orville)
Lightning triggered by aircraft during takeoff
Horizontal Length of Lightning Channels
Fig. 5.4  A stroke-integrated near-infrared spectrum of lightning obtained by Salanave (1966) using the slitless spectrometer shown schematically in Fig. 5.3. (Courtesy, Institute of Atmospheric Physics, University of Arizona, 1966.)

Fig. 5.10c  Stroke temperature as a function of time for flash A. Horizontal dashed lines indicate the time resolution, vertical bars the error limits. (Adapted from Orville (1998a, 1998).)

Temperature of Lightning
General Characteristics of Thunder:
1. There is a finite time interval between lightning and the start of thunder.
2. Thunder has a long lifetime relative to lightning (~10 sec).
3. Thunder can be heard up to 25 km from the lightning.
4. The frequency of the acoustic wave is between 0.25 – 500 Hz (maximum around 200 Hz). [sensitivity of human ear: 20-20,000 Hz]

The velocity of sound: \( v = \lambda f \)  
\( \lambda \) - wavelength, \( f \) - frequency  
\( v = \sqrt{\frac{\gamma P}{\rho}} \)  
for acoustic waves propagating in an ideal gas

Where: \( \gamma = 1.4 \) (ratio of molar heat capacity of air = \( c_p/c_v = 7/5 \))  
\( P = R/\mu \rho T \)  
\( \mu = 28.8 \) average molecular weight of air  
\( R = 8.3 \times 10^7 \) erg/g/K
The energy produced by a lightning stroke is of the order of
\[ W = 10^5 - 10^6 \text{ J/m} \ (W \sim \frac{1}{2} \frac{QV}{L} \sim \frac{1}{2} QE). \]

The energy is absorbed in different processes:
1. Dissociation of molecules
2. Ionization
3. Kinetic energy (heating) \( \rightarrow \) increase of air temperature
4. Radiation
5. Work \( \rightarrow \) expansion of lightning channel \( \rightarrow \) shock wave (most energy absorbed during this process)

For \( T = 300\text{K} \) \quad v = 350 \text{ m/sec}
For \( T = 30,000\text{K} \) \quad v = 3500 \text{ m/sec}
Thunder starts as a Shock wave due to the rapid heating of the channel, and rapidly cools during expansion. The shock wave is converted to a sound wave at a distance of ~1m from the core of the

Example: For $W=10^5$ J/m

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<th>P</th>
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<tr>
<td>2cm</td>
<td>500 atm</td>
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<tr>
<td>5cm</td>
<td>80 atm</td>
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<td>0.14m</td>
<td>10 atm</td>
</tr>
<tr>
<td>1m</td>
<td>1 atm</td>
</tr>
</tbody>
</table>

The frequency of the acoustic wave is

$$f = \frac{v_o}{\lambda} = \frac{350}{1} \sim 350 \text{ Hz}$$
Fig. 5.10. Thunder signatures of two lightning flashes. Microphone output amplitude is plotted as pressure perturbation, \( \frac{P}{P_0} \), and shows the claps (large spikes) and rumbles of thunder from (a) a nearby cloud-to-ground flash and (b) a long horizontal flash. Time = 0 is the time of lightning. (Adapted from Few 1974: American Geophysical Union, with permission.)
The “rumbling” sound of thunder is due to the different segments of the lightning channel that are orientated in different directions relative to the observer.
Attenuation of Thunder in the Atmosphere

Dependence on frequency, temperature and humidity
Why do we only hear thunder a short distance from the thunderstorm?

The temperature decreases with altitude and therefore so does the propagation velocity of sound in the atmosphere.

\[
\sin \theta_1 = \frac{v_1}{\sin \theta_2} \quad \text{Snell's Law}
\]

\[
\sin \theta_2 = \frac{v_2}{v_1} \sin \theta_1 > \sin \theta_1
\]

\[
\Rightarrow \theta_2 > \theta_1
\]

Therefore the sound wave moving toward the surface is refracted upward.
The ray path can be described as a segment of a parabola:

\[ L^2 = \frac{4 T_o}{\Gamma} h \]

Where:  
- \( L \) is the horizontal distance (x) between the vertex of the parabola and the source 
- \( T_o \) is the maximum temperature along the path (often surface temp) 
- \( h \) is the height of the source above the ground

For \( T_o = 30^\circ C \), \( \Gamma = 9.8^\circ C/km \) and \( h=5km \), we get \( L \sim 25km \).

\[ \rightarrow \] Thunder is seldom heard beyond 25km from the lightning.
Ziggie and Zack: Your Lightning Heroes!

At home

It's a bad idea to go out, a thunderstorm is coming!

The weather looks fine to me!

Remember that thunderclouds can move closer and strike surprisingly fast!

Don't go outside and stay away from all electric appliances!

It's been 30 minutes since the last flash and thunder... yahoo! It's safe to go outside!

In town

I counted less than 30 seconds between the flash and the start of the thunder... This means that the thundercloud is within 10 km from us! We have to find shelter!

It's dangerous to stay close to a car or a building if we can't enter...

Don't touch the radio or any metal parts... it can be dangerous! Let's close the window!

No worries mum, we are safe inside the car!

If you are in danger, use your mobile to call the emergency number!

At the park

Let's run! All pointy structures can attract lightning!

At a distance of about the height of the structure, we're safe!

Get out of the water, it's dangerous!

Let's stay away from the metal fence! We have to avoid small groups of trees... they can attract lightning. It's safer to enter the forest!

Guys, don't stand up! If lightning strikes, crouch down or bend over!

...And we should be 5 m apart!

Yep! Let's go in the forest... away from the hill-top where lightning could strike!