PLASMA PHYSICS 2

8. LEADER MECHANISMS, DISCHARGES AND PLASMAS IN PLANETARY ATMOSPHERES

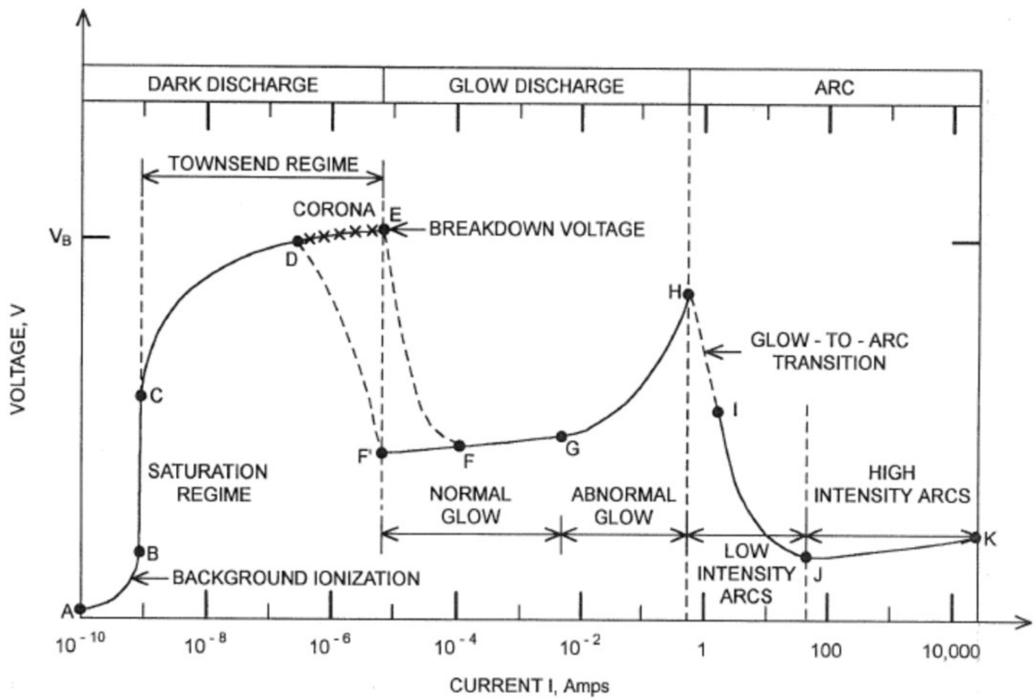
Lecture series contents

1. Townsend breakdown theory, Paschen‘s law
2. Glow discharge
3. Electric arc at low and high pressures
4. Magnetized low-pressure plasmas and their role in material deposition methods.
5. Brief introduction to high-frequency discharges
6. Streamer breakdown theory, corona discharge, spark discharge
7. Barrier discharges
8. **Leader discharge mechanism, ionization and discharges in planetary atmospherres**
9. Discharges in liquids, complex and quantum plasmas
10. Thermonuclear fusion, Lawson criterion, magnetic confinement systems, plasma heating and intertial confinement fusion.

Opakování

- We know that E-field deformations lead to different ignition mechanisms / structures
- We talked about filaments, streamers, etc…

But on what distances does this work? How far can a streamer travel?

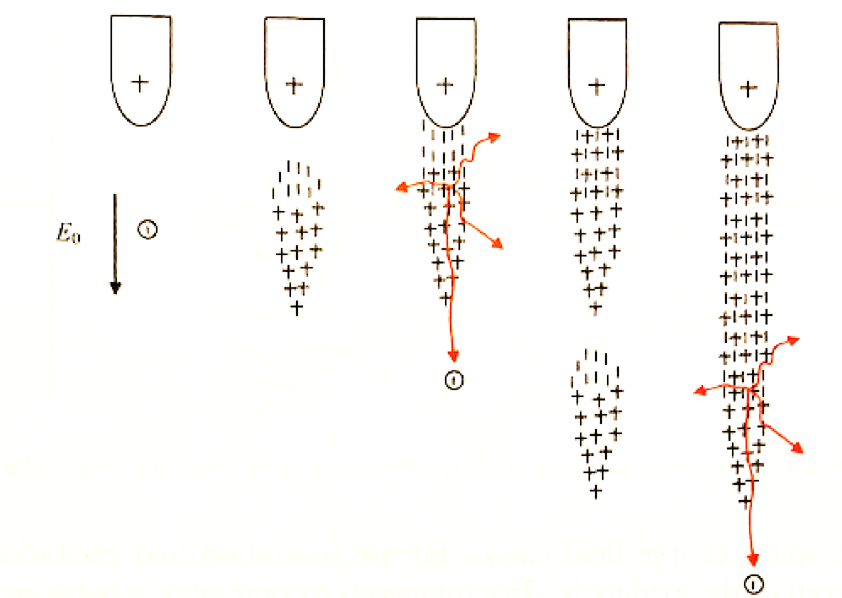


Key reference for this talk: Beroual a Fofana 2016 Discharge in long air gaps: modelling and applications, IOP Publishing, Bristol UK

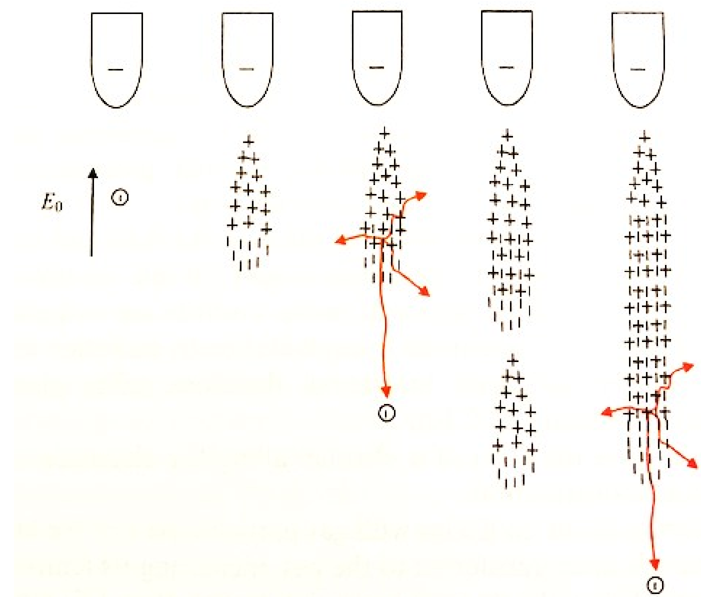
Streamers - review

- Let us remind ourselves about the existence and mechanism of the positive and negative streamers

Positive streamer



Negative streamer



- Secondary electron avalanches and photo-ionization are important

Streamers - review

- Let us remind ourselves about the existence and mechanism of the positive and negative streamers

Positive streamer

Negative streamer

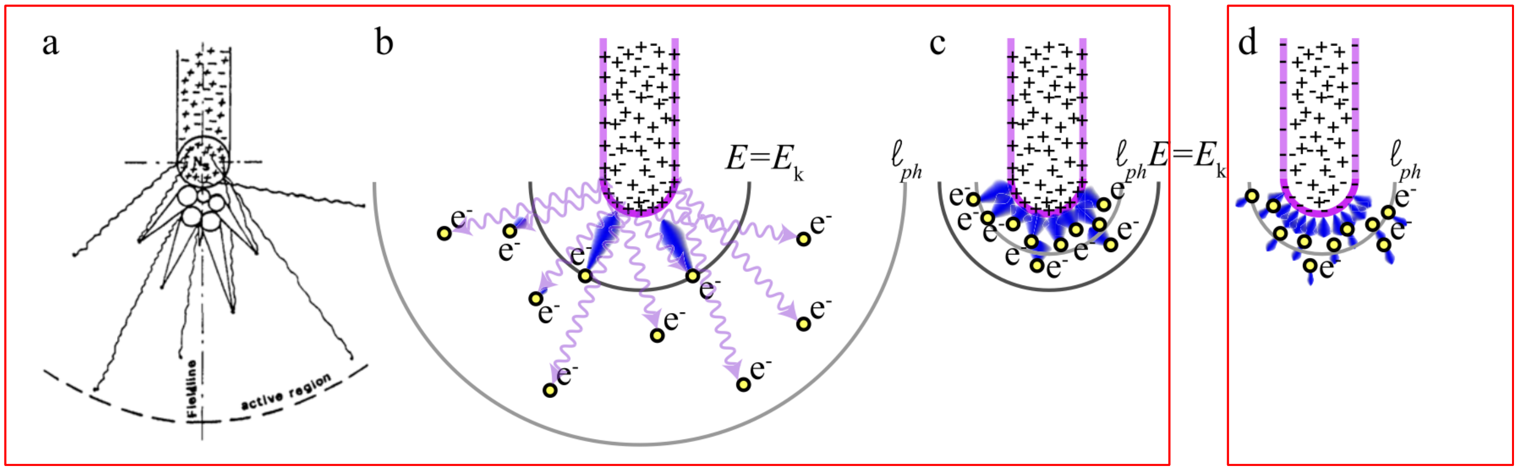


Figure 11. Schematic depictions of streamer propagation. (a) Illustration of positive streamer propagation in air based on the original concept of Raether [74], published in English by Loeb and Meek [75]. Picture taken from [37]. Panels (b)–(d) show an updated scheme for (b) positive streamers with few photons with a long mean free path, (c) positive streamers in air and (d) negative streamers in air. Photon trajectories are drawn as purple wiggly lines. Avalanches start from a yellow electron and are indicated in blue, ℓ_{ph} indicates the photo-ionization range and $E = E_k$ indicates the active region. Note also that panel (a) shows a net positive charge in a spherical head region, while panels (b)–(d) show surfaces charges around the streamer head and along the lateral channel.

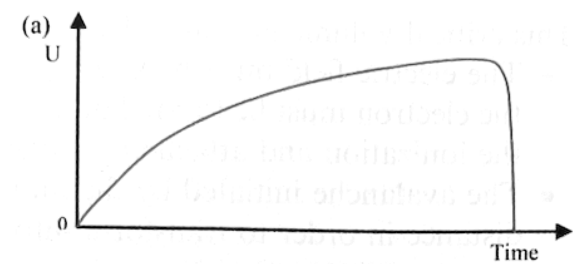
- Secondary electron avalanches and photo-ionization are important

Nijdam et al. 2020 PSST

[redacted]

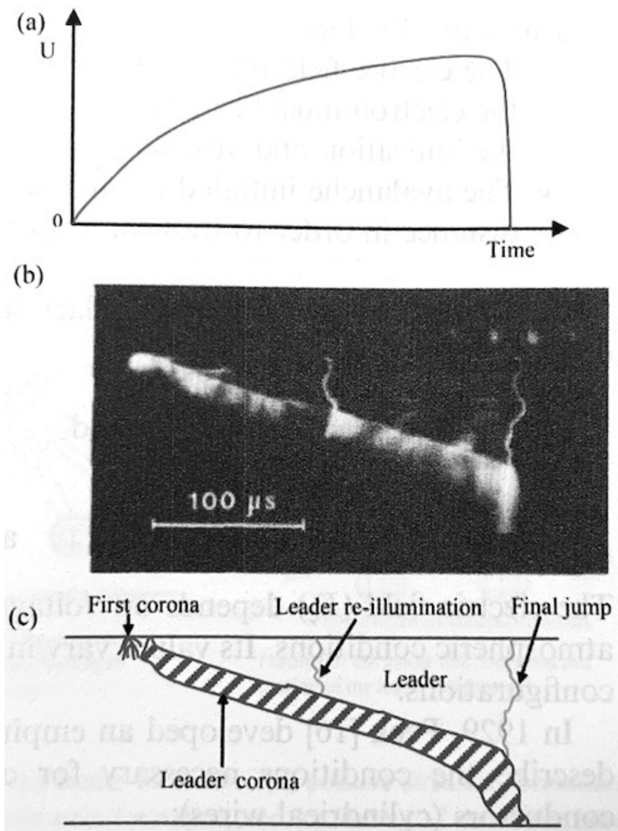
Leader mechanism

- „Leader discharges“ appear in atmospheric-pressure air **over distances longer than 1 m**.
- The new mechanism appears because the **streamer is not conductive enough and as it gets very long, it does not maintain a sufficient E field** in its head.
- It is not entirely clear why the streamer transitions into leader discharge but their **macroscopic properties and qualitative mechanisms are generally well known**.
- Leader mechnism proposed by Meeke a Loeb and helped to understand lightning propagation.
- Experimentally, researches use the so-called **lighting pulse**: for 10m electrode distance, V_{max} = 2.5 MV, t = 500 us



- Just like with streamers, we know **positive and negative leaders** – positive originate from the positive electrode (anode) and negative originate from the negative one (cathode).

Positive leader - overview



čas

- Starts at the positive tip
- Typical leader discharge on the left:
  a) voltage, b) streak camera recording, c) mechanism

Mechanism

1) The discharge beings with corona discharges near the tip
2) The corona ionizes the gas which extends the anode and ignites a new corona at its end.
3) The leader corona (consisting of streamers) is more luminous than the leader body.
4) After the final jump, arc discharge is ignited because a conductive channel is formed.

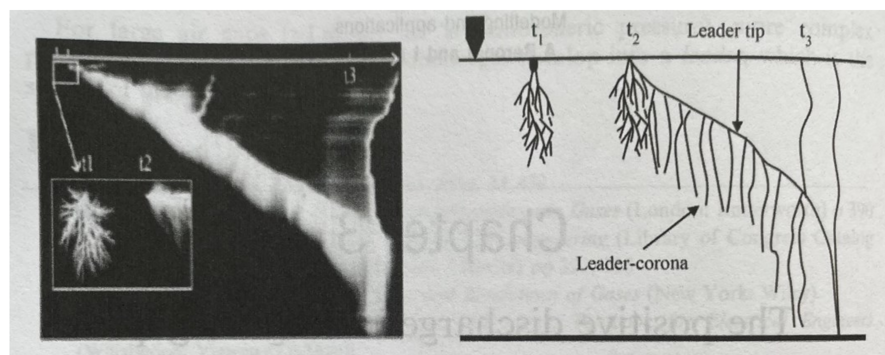
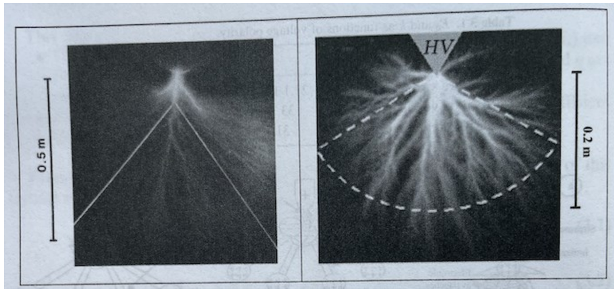


Figure 3.1. Streak photograph and sketch showing the development of a laboratory positive discharge (10 m gap, t_m = 500 μs, V_{max} = 2.5 MV) [11].

[redacted]

Positive leader – the initial corona (1+2)



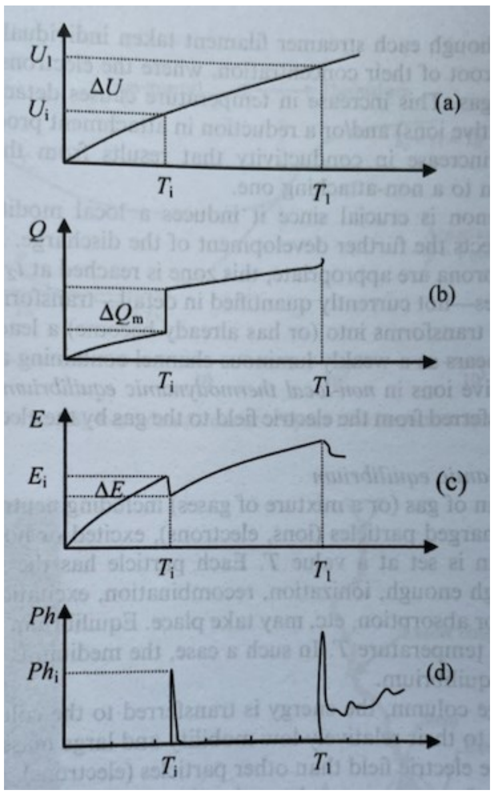


Figure 3.6. Typical oscillograms of phenomena related to first corona [1]: (a) applied voltage; (b) charge injected into the gap; (c) electric field measured at the HV electrode; and (d) emitted light.

- The positive leader is initiated by intense corona discharges in the so-called **active zone.**
- The leader mechanism follows the ignition of the first corona but often, **there is a delay (dark phase)**, which depends on the rise time of the voltage pulse.

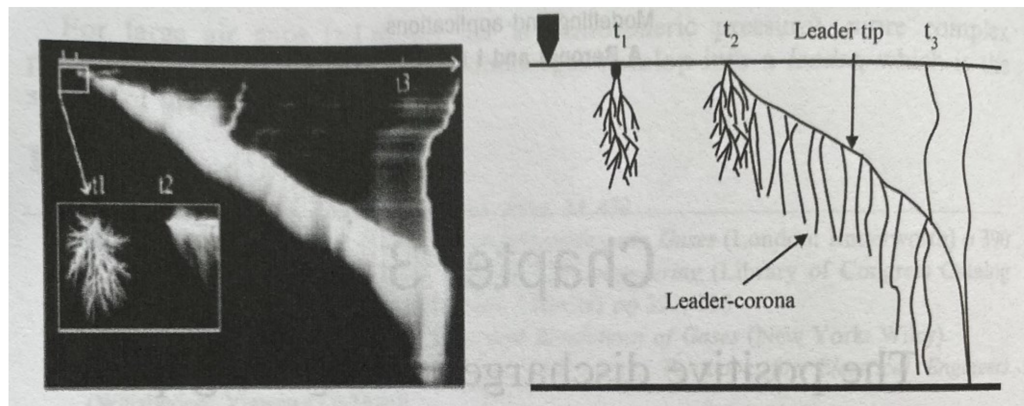
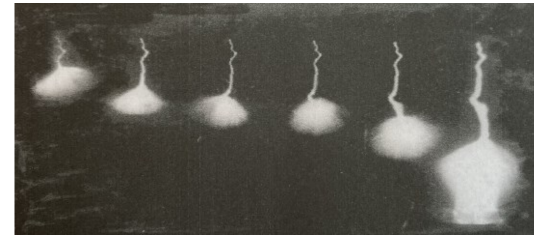
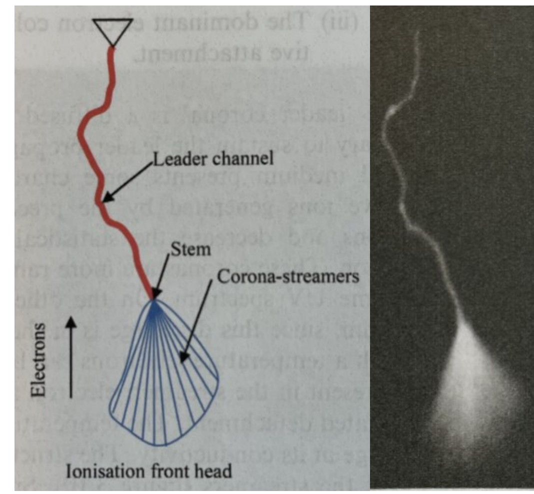


Figure 3.1. Streak photograph and sketch showing the development of a laboratory positive discharge (10 m gap, t_m = 500 μs, V_{max} = 2.5 MV) [11].

[redacted]

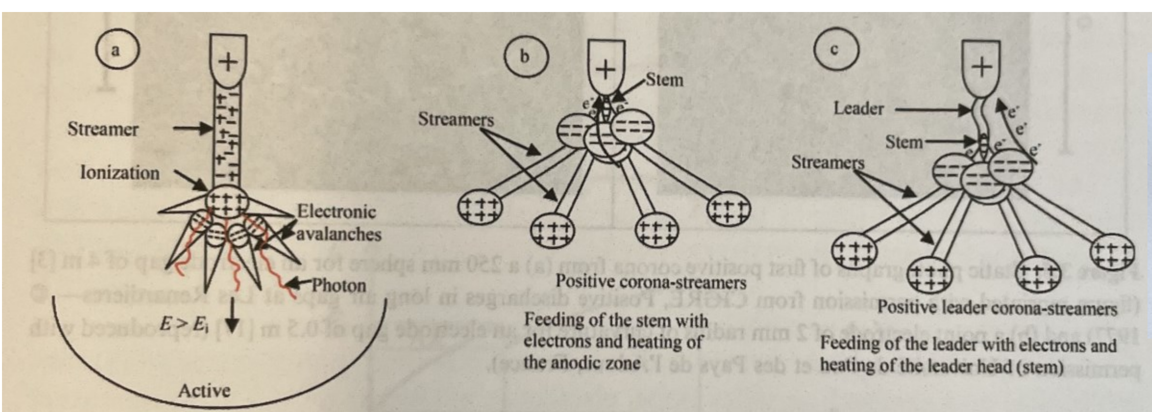
Positive leader – stochastic propagation (3)

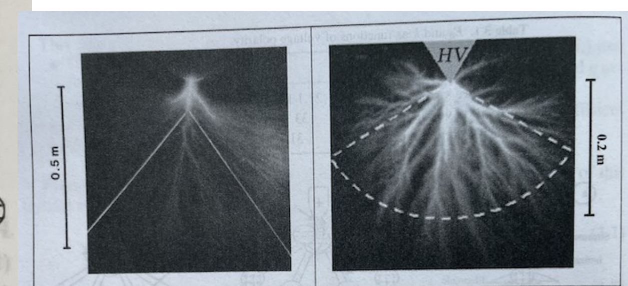




1) The discharge beings with corona discharges near the tip
2) The corona ionizes the gas which extends the anode and ignites a new corona at its end.
3) **The leader corona (consisting of streamers) is more luminous than the leader body.**
   => This is a stochastic phenomena because streamers ignite in all directions but the plasma ignites through only one of them => hence the clasical zig-zag pattern.

4) After the final jump, arc discharge is ignited because a conductive channel is formed.

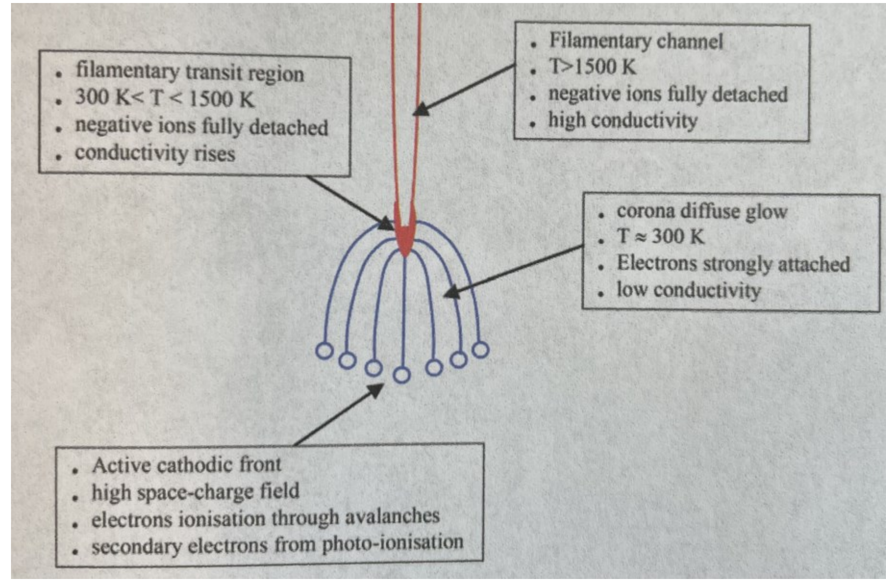




Positive leader – transition to arc (4)

- Parameters of a leader discharge shown on the right

1) The discharge beings with corona discharges near the tip
2) The corona ionizes the gas which extends the anode and ignites a new corona at its end.
3) The leader corona (consisting of streamers) is more luminous than the leader body.
4) **After the final jump, arc discharge is ignited because a conductive channel is formed.**
    1) Streamers reach the cathode surface
    2) Rapid secondary emission occurs on the cathode
    3) Cathode and anode are connected and a „return stroke“ follows – intense current pulse that ionizes the entire pre-ionized channel and discharges all the available charge.
    4) The discharging takes tens of microseconds and current reaches kA-range



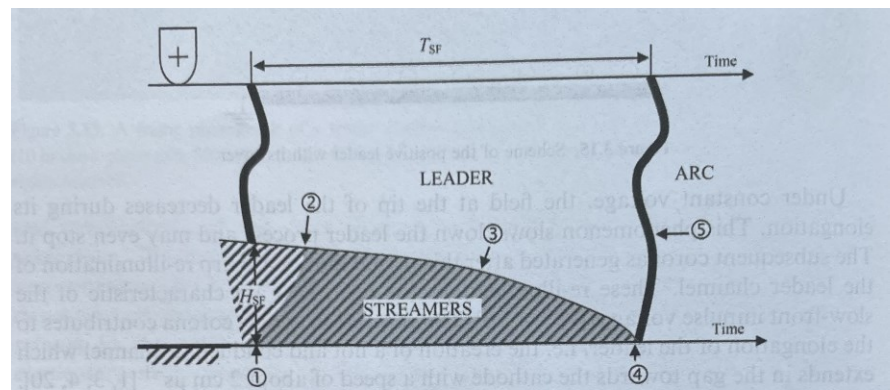


Figure 3.16. Schematic representation of the final jump: 1. Streamers' arrival at the grounded plane. 2. Streamers' re-illumination. 3. Head of the leader. 4. Leader's arrival at the grounded plane. 5. Return stroke.

Negative leader

- Propagates from the negative electrode?
- Typical development shown in the figure
- More complex physics compared to positive leader…

What is the mechanism?

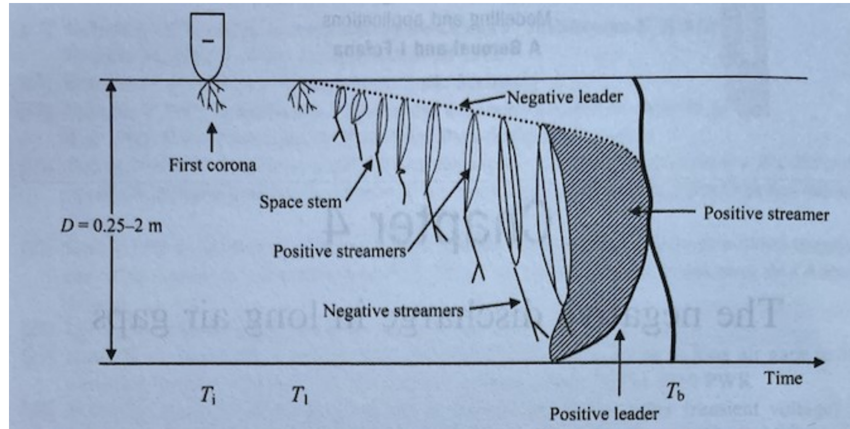


Figure 4.1. The sequence of the different phases of negative air gap breakdown; for distances lower than 2 m. Reproduced from [6] with permission of Université de Pau et des Pays de l'Adour, France.

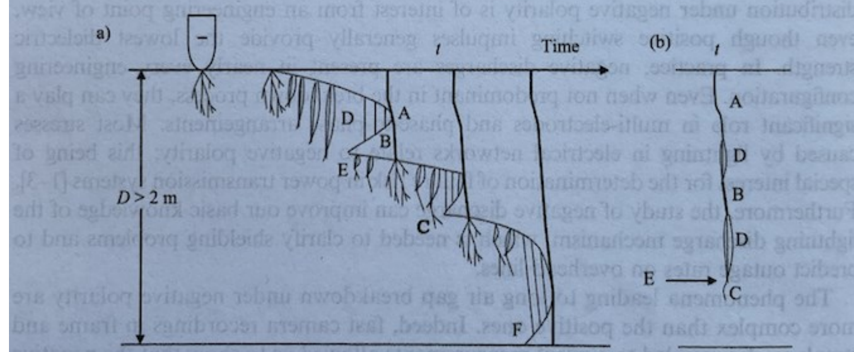


Figure 4.2. Schematic representation of the spatiotemporal evolution of a discharge in a long air gap under a negative polarity impulse voltage, for distances higher than 2 m. (a) A simplified sketch showing the stepping elongation mechanism of the negative discharge. (b) Spatial representation of the negative channel at the time t. A: negative leader; D: positive streamers; B: the space leader; E: space stem; C: negative streamers; and F: positive leader. Reproduced from [6] with permission of Université de Pau et des Pays de l'Adour, France.

Negative leader - overview

- Propagates from the negative electrode?
- Typical development shown in the figure
- More complex than a positive leader – it is not simply about prolonging the electrode.
- The negative leader has to be „fed“ by positive streamers originating from the anode and increasing the plasma density there.
- This gradually increases the length of the conductive volume in front of the cathode. The positive „super-streamers“ feeding the negative leader are called „stems“
- Negative and positive streamers are moving towards each other.
- When this structure approaches the anode, streamers – and possibly also the positive leader – start propagating towads it.
- After both leaders connect and a conductive channel is established, system goes to arc.

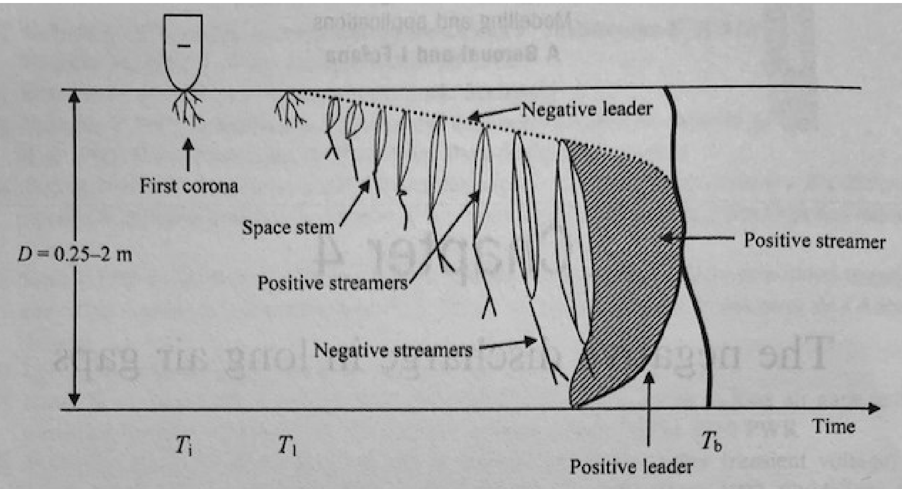


Figure 4.1. The sequence of the different phases of negative air gap breakdown; for distances lower than 2 m. Reproduced from [6] with permission of Université de Pau et des Pays de l'Adour, France.

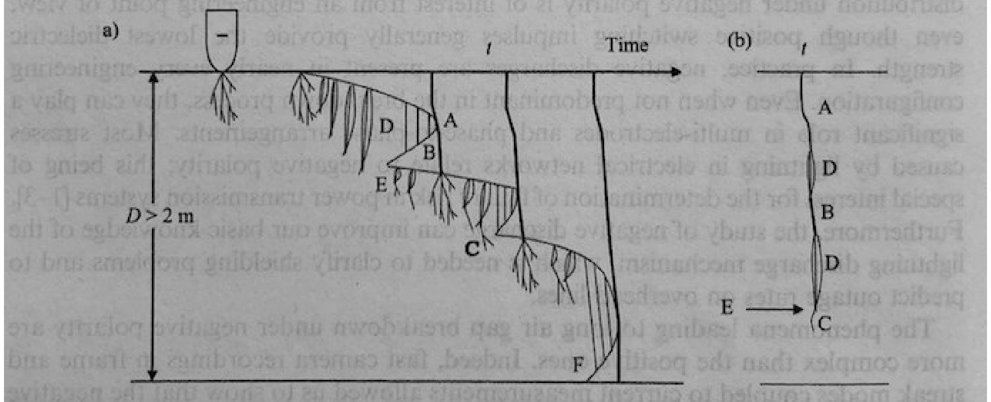


Figure 4.2. Schematic representation of the spatiotemporal evolution of a discharge in a long air gap under a negative polarity impulse voltage, for distances higher than 2 m. (a) A simplified sketch showing the stepping elongation mechanism of the negative discharge. (b) Spatial representation of the negative channel at the time *t*. A: negative leader; D: positive streamers; B: the space leader; E: space stem; C: negative streamers; and F: positive leader. Reproduced from [6] with permission of Université de Pau et des Pays de l'Adour, France.

Negative leader – mechanism of a stem, pilot system

Charge separation in space

Positive streamer propagates between positive space charge areas and negative tip

Negative streamers propagate the other way

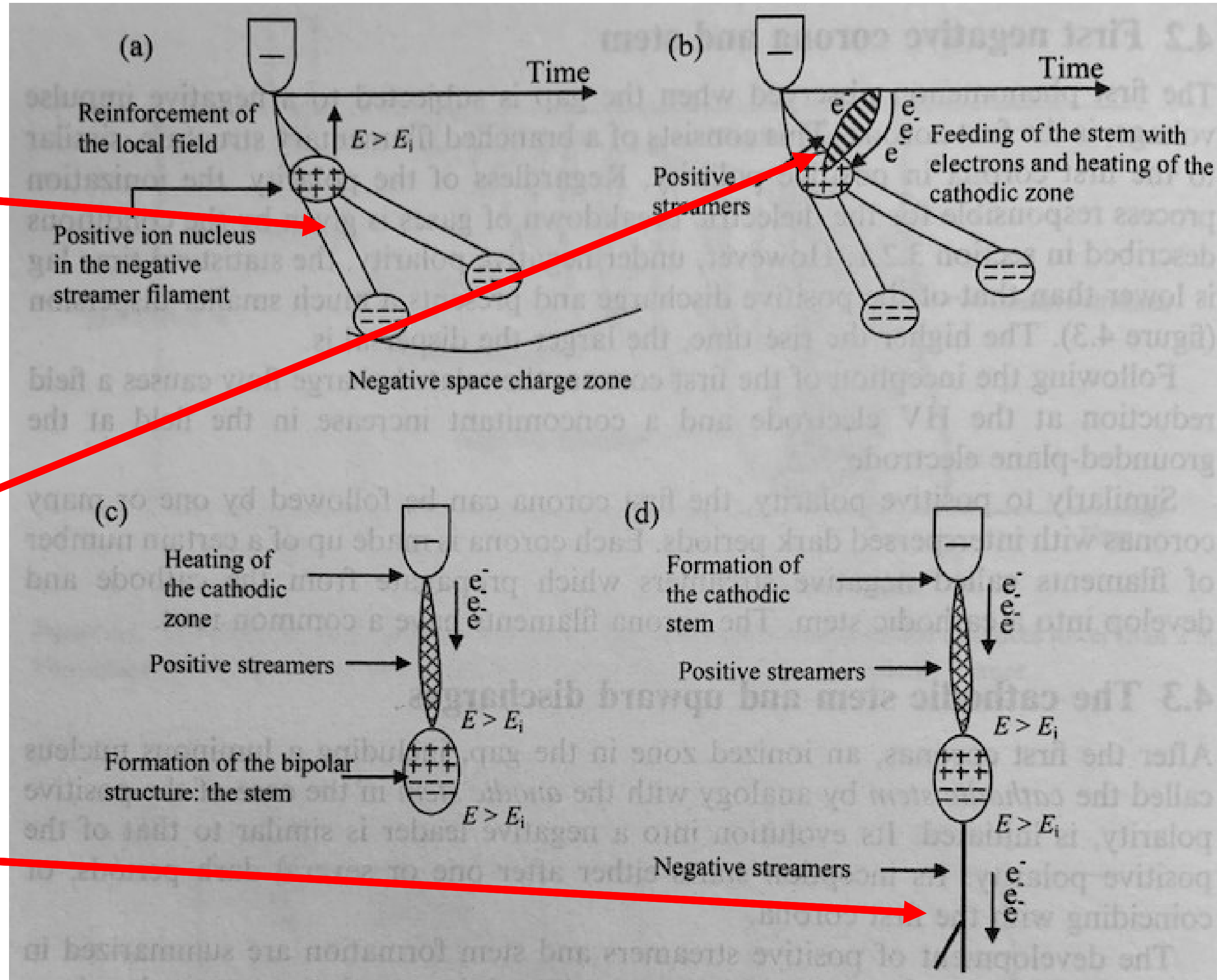


Figure 4.4. Schematization of the sequences leading to the formation of the pilot [6]: (a) positive space charge in the filament of the negative streamer; (b) positive streamers emission from the positive charge; (c) feeding of the stem in electrons and formation of the dipole; and (d) emission of a negative streamer and formation of the pilot.

Negative leader – mechanism of a stem, pilot system

The “stem” structure replicates in individual steps.

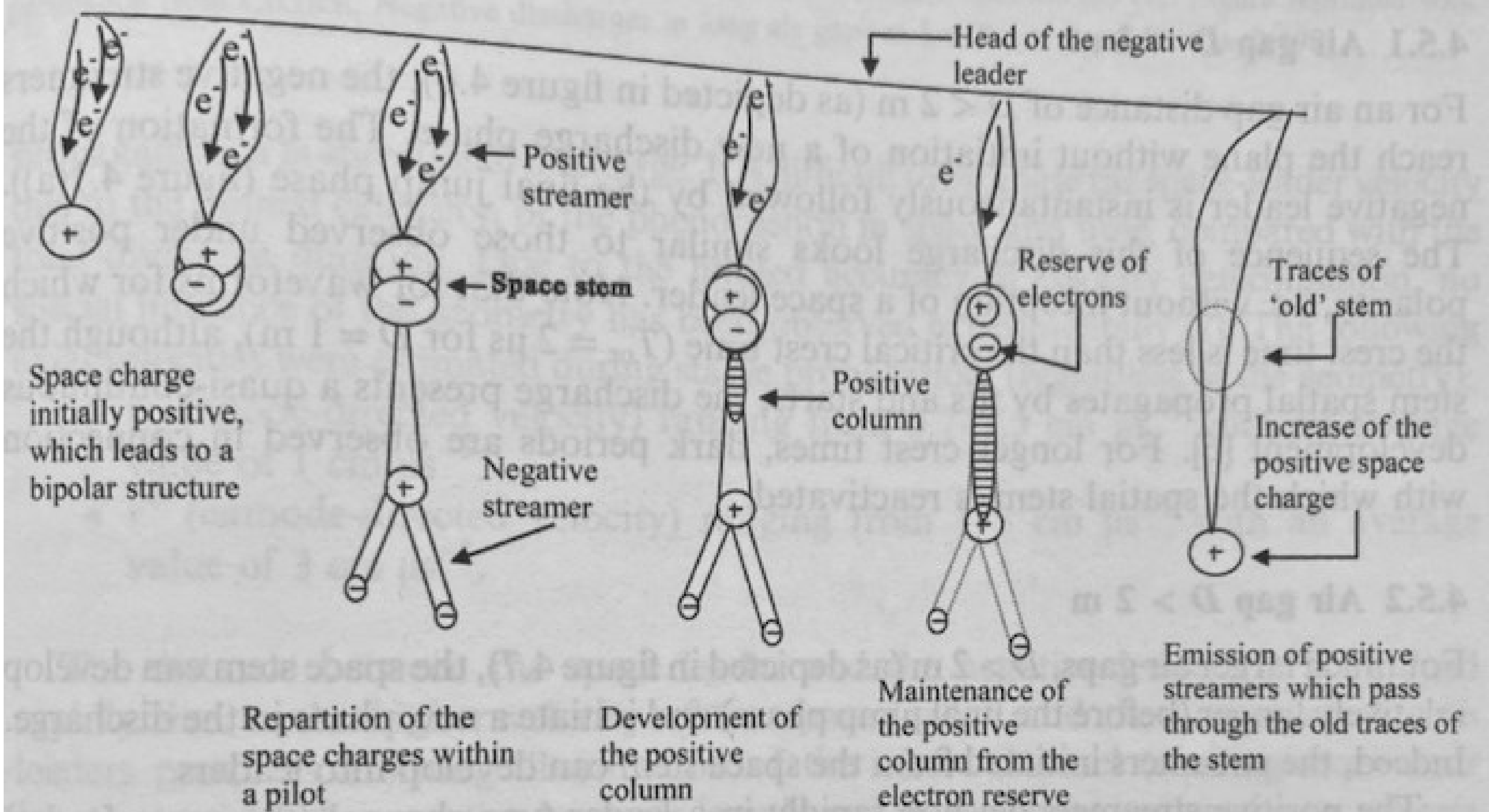


Figure 4.5. A sketch of the sequences leading to the mechanisms of replication of the space stem. Reproduced from [6] with permission of Université de Pau et des Pays de l’Adour, France.

[redacted]

Negative and positive leaders - comparison

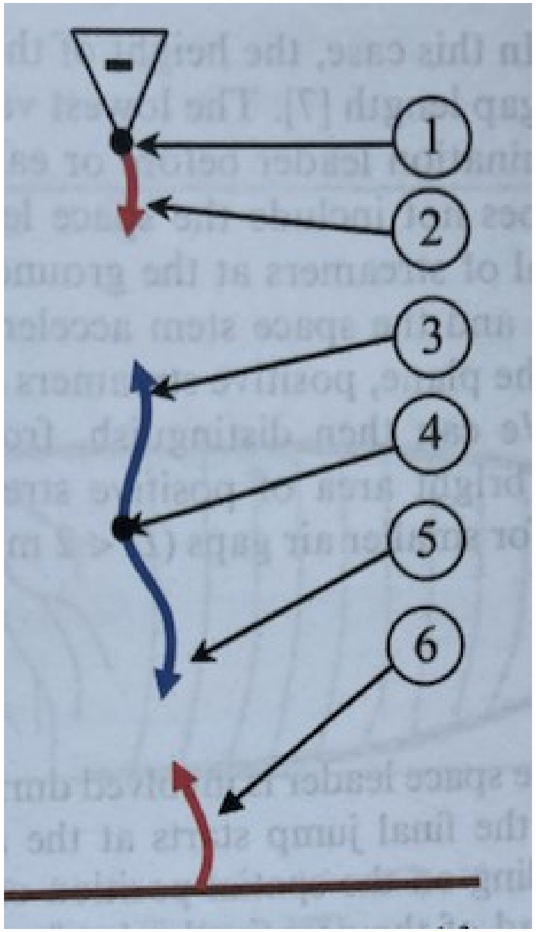
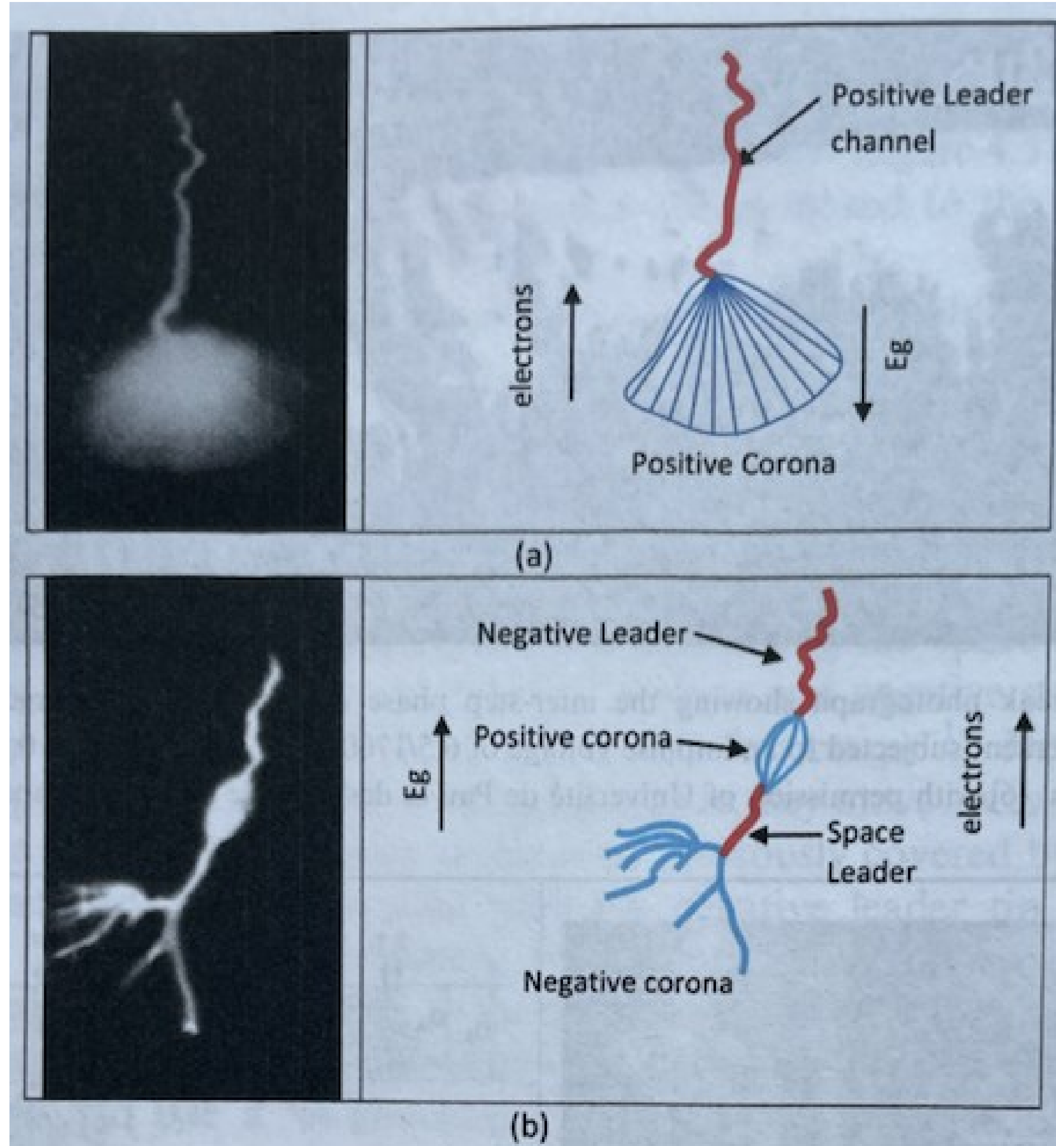


Figure shows the negative leader (2) issued from the stem (1), the space leader (3,4,5) elongating towards the cathode (3) and the anode (5) and the upward positive leader (6)



Negative leader – final jump phase

- There are three ways how the final leader can be shorted / terminated

1. For inter-electrode distances below 2m, the final jump is 70-90% of the entire distance. The positive leader is observed as well.
2. For larger distances, there is usually a spatial leader that connects with the positive or negative leader before the final jump.
3. Finally, it can happen that the spatial stem does not transfer to a spatial leader and you get very long and branching streamers.

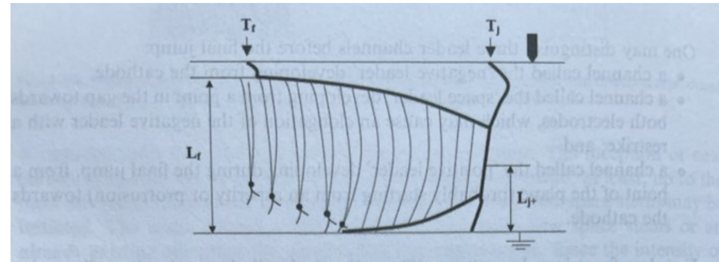


Figure 4.10. Schematic of the type A final jump reprinted from [7] with permission from CIGRE, Negative discharges in long air gaps at Les Renardieres Electra © 1981.

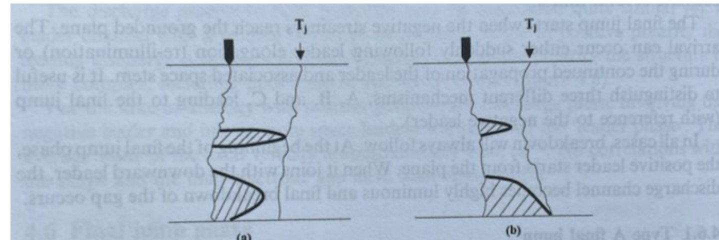


Figure 4.11. Schematic of the type B final jump: the space leader may join the positive leader (a) or the negative leader (b) reprinted from [7] with permission from CIGRE, Negative discharges in long air gaps at Les Renardieres Electra © 1981.

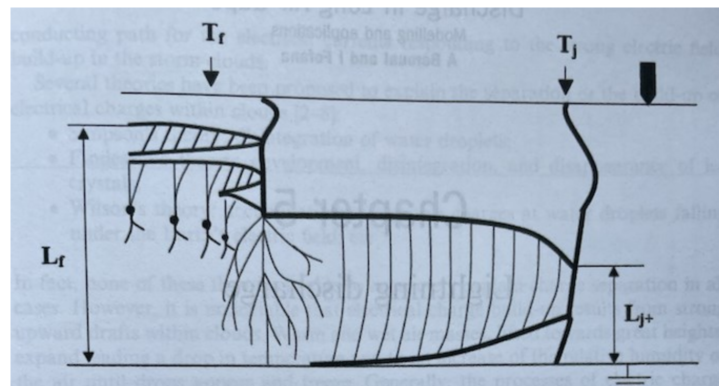


Figure 4.12. Schematic of the type C final jump reproduced from [7] with permission from CIGRE, Negative discharges in long air gaps at Les Renardieres Electra © 1981.

[redacted]

Classical lightning

- One of the most well-known manifestations of electrical activity in Earth's atmosphere is lightning; there are various types of lightning, see the images below ('v' is the direction of discharge spread, and 'i' is the direction of current, that is, opposite to the direction of electron drift).
- The polarity of lightning is determined according to the polarity of the leader mechanism leading to the breakdown.
- In temperate climates, the majority of lightning (up to 80%) is negative, carrying negative charge to the ground. Positive lightning is more common on winter days. In tropical climates, up to 90% of lightning is positive.

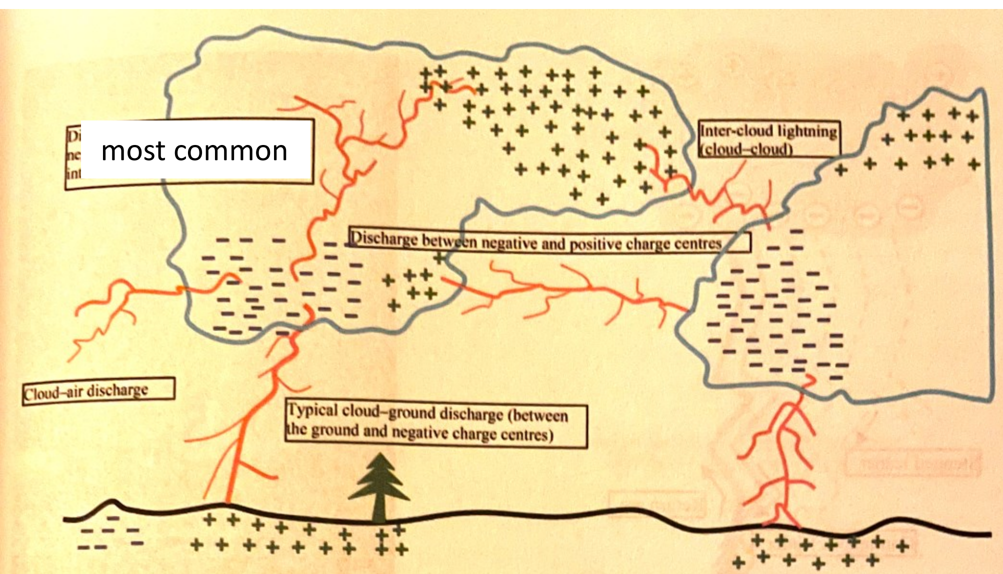


Figure 5.2. Schematic representation of typical atmospheric discharges. The lower part of a thundercloud is usually negatively charged in temperate regions while the upward area is usually positively charged.

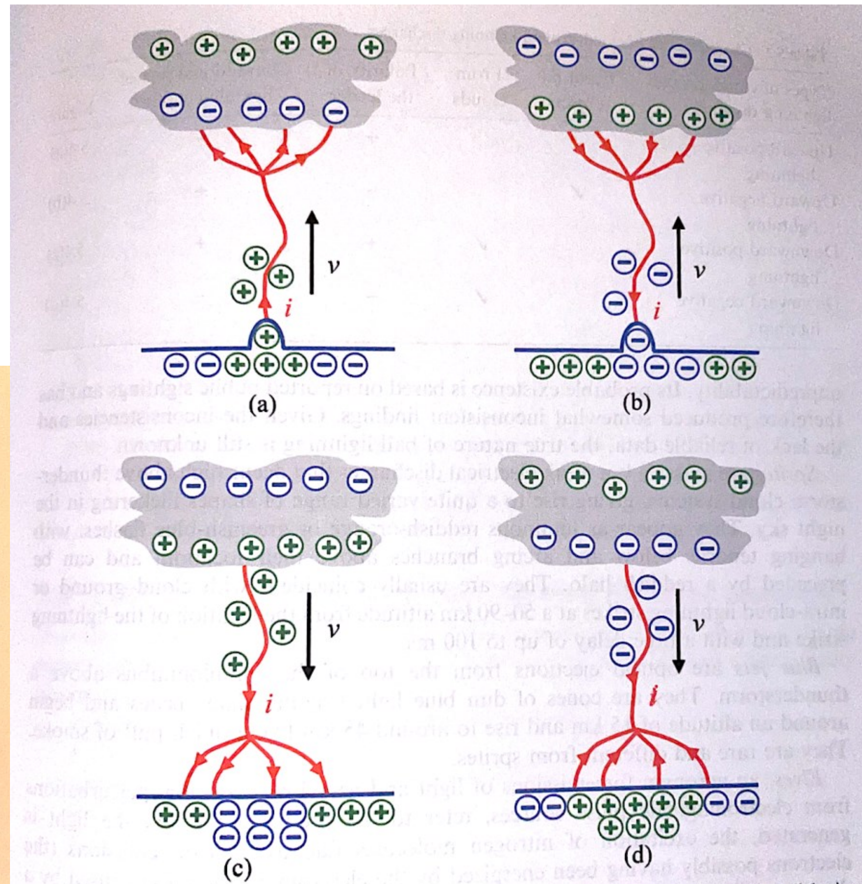


Figure 5.4. Cloud–ground lightning classification: (a) upward positive lightning (ionized channel +, lightning current –); (b) upward negative lightning (ionized channel –, lightning current +); (c) downward positive lightning (ionized channel +, lightning current +); and (d) downward negative lightning (ionized channel –, lightning current –).

Stages of lighting evolution

Lightning has the following typical phases:

1. Formation of a thundercloud
2. Generation of free charge in the thundercloud
3. Initial corona and leader spread
4. Return stroke and arc discharge phase
5. Dart (continuous) leader
6. Subsequent additional return strokes

Formation of a thundercloud:

- This refers to the so-called cumulonimbus cloud (also known in Czech as 'dešťová kupa'), which grows vertically due to the upward flow of air heated by the sun-warmed Earth's surface (heat storm), or by a so-called front storm, where a flow of cold air and warm/moist air collide.
- **A heat storm** (thermal storm) is typical for tropical regions; thermally driven rising air lifts moist air which condenses at about 2km, forming the cloud, first as droplets and at higher altitudes then as ice crystals. The formation of a thundercloud by this mechanism can be very rapid, from one to three hours. The conditions for the creation of such a storm depend much on the properties of the Earth's surface – for example, its ability to heat up.
- **A front storm** (storm created by an atmospheric front) is dominant in milder climates, typically reaching larger dimensions than the former, up to 23km. The creation of thunderclouds by this mechanism can take several days.

heat storm

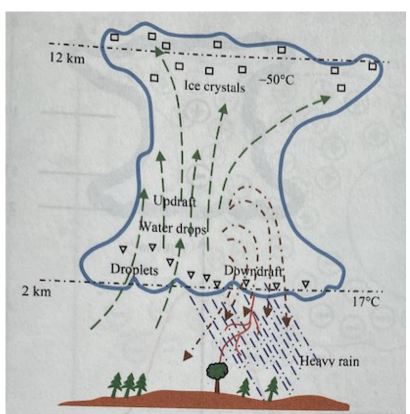
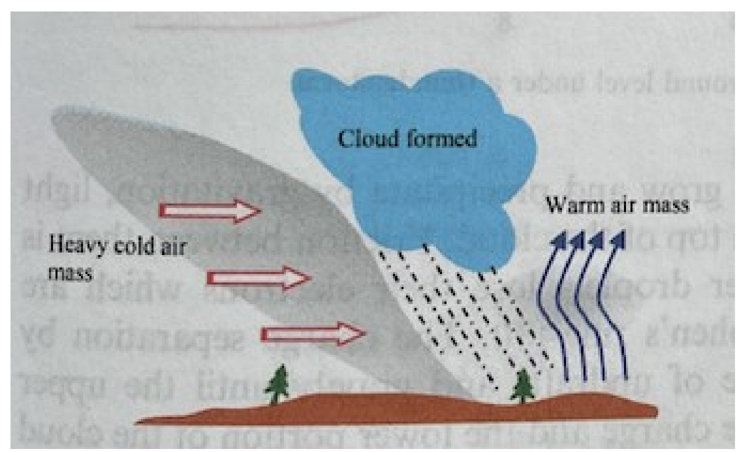


Figure 5.6. Heat storm formation.



front storm

[redacted]

Origin of free space charge during cloud charge-up

- **The exact mechanism of charge separation and the formation of high electric fields in thunderclouds is not precisely known.**
- Various hypotheses exist, which do not always apply (such as the breakup of raindrops, formation of ice crystals, etc.). But it is **known that ice crystals become positively charged, and raindrops carry a negative charge** – this imbalance arises from the friction of water particles in the cloud, these particles are referred to as hydrometeors. The friction is a result of the turbulent movement of air in the cloud, up to 20m/s.

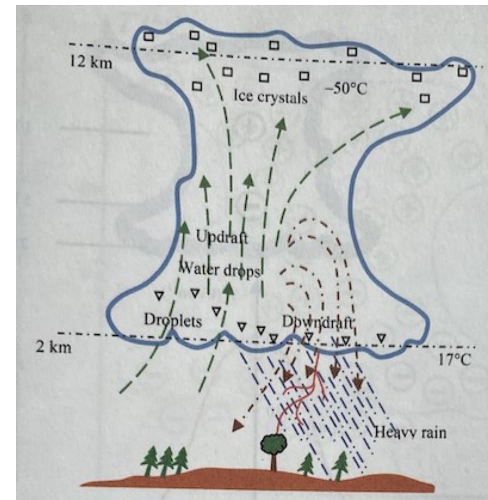


Figure 5.6. Heat storm formation.

- During friction in the cloud, water droplets lose their electrons in favor of frozen droplets of water. The result of the charging in the cloud is a charge separation such that the top of the cloud is positive and its bottom part is negative.
  The potential between these areas can then be up to millions of volts.

- Here is a possible E field of a cloud

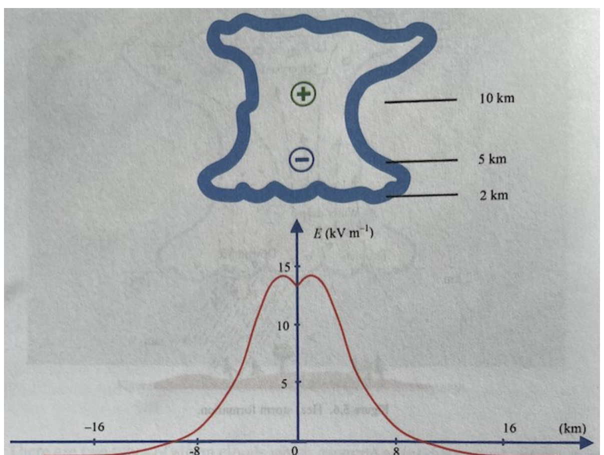


Figure 5.8. The electric field at ground level under a thunderstorm.

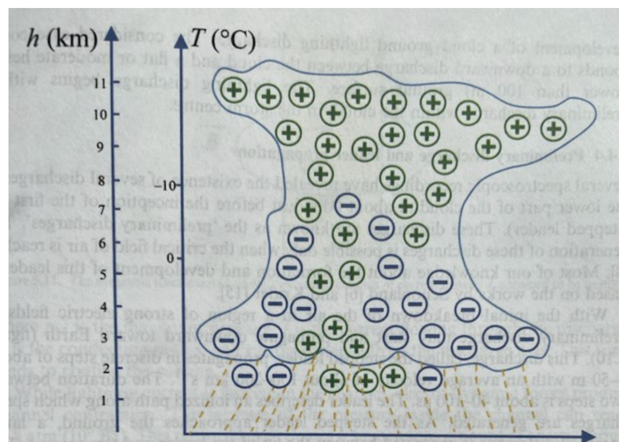


Figure 5.9. Schematic representation of a storm cloud and its electrical charge distribution.

- **If the average electric field between the cloud and the ground reaches values between 15 and 20 kV/m (elsewhere values above 100 kV/m are reported), lightning occurs.**

Lightning discharge time sequence, frequency of ocurrence

The sequence of a lightning discharge for a distance of up to 100 m, negative cloud-to-ground lightning:

- In the first few milliseconds, the initial corona discharges occur, even among different domains of free charge in the cloud, akin to the corona before the leader.
- After the initiation of the leader discharge, it moves towards the ground at **speeds of up to 200 km/s** with the length of individual jumps ranging from 4 to 50 m.
- The **pause between individual jumps** (necessary to create another segment of the leader) is **40 to 100 microseconds**.
- When the leader reaches a distance of 20 to 200 m from the ground, the "selection" of the impact site occurs, which depends on the geometry of the surface and the size of the charge in the leader.
- The return stroke propagates at speeds of up to a tenth of the speed of light, its currents reach **10 to 200 kA**, and it transfers a charge of **5 to 15 C**, with the **dissipated energy reaching up to 500 MJ**. As the current passes, pinching of the ionized channel occurs (remember arc lecture).

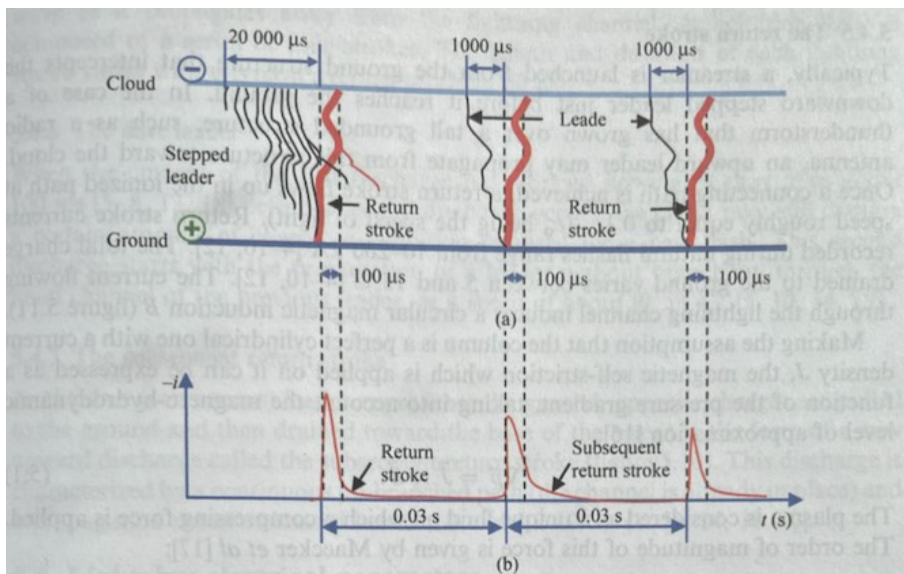


Figure 5.10. Lightning discharge development in the case of flat ground or a structure of moderate height at the ground: (a) a streak-camera-like sketch of the negative lightning discharge mechanism and (b) time variation of negative lightning discharge.

Lightning discharge time sequence, frequency of ocurrence

The sequence of a lightning discharge for a distance of up to 100 m, negative cloud-to-ground lightning:

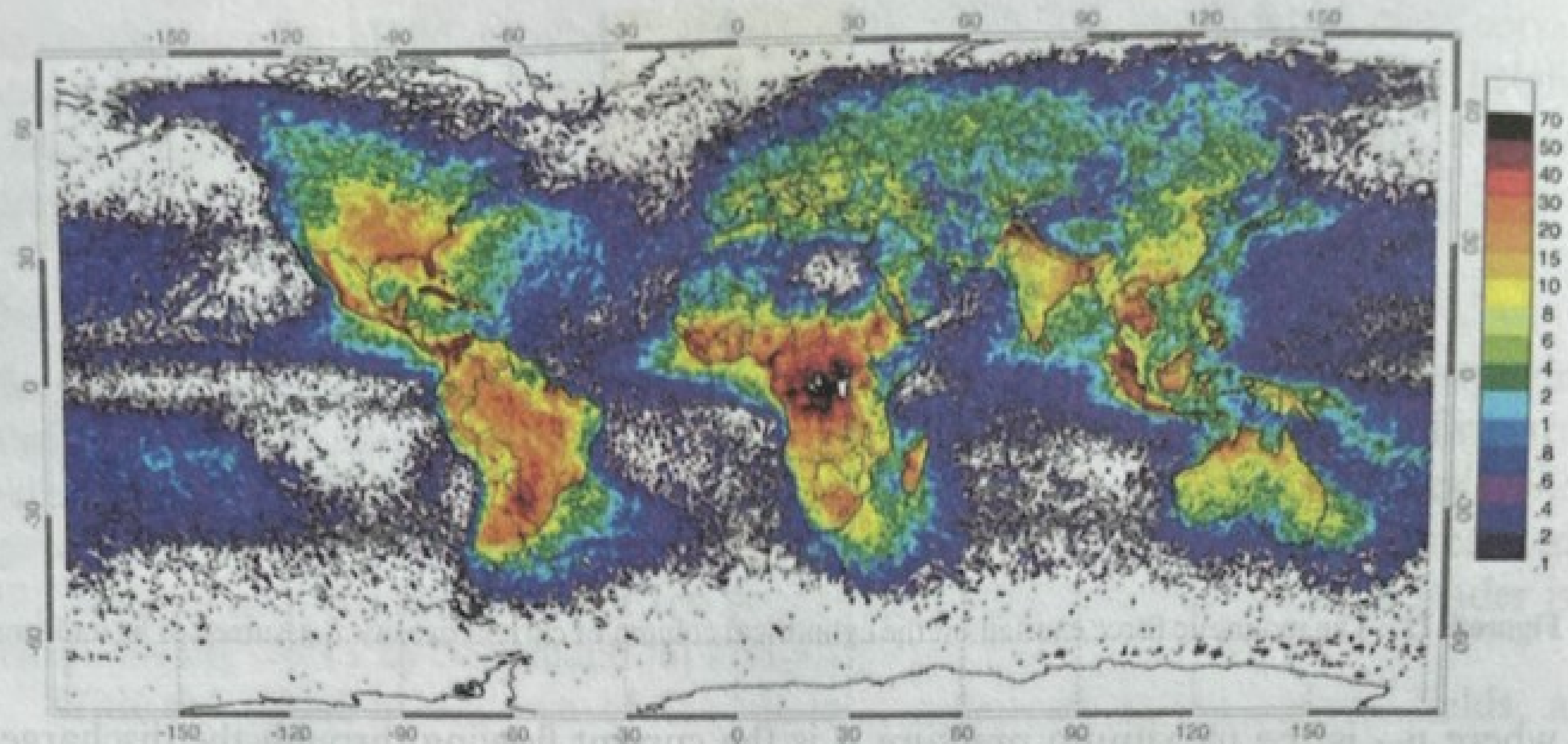
- In the first few milliseconds, the initial corona discharges occur, even among different domains of free charge in the cloud, akin to the corona before the leader.
- After the initiation of the leader discharge, it moves towards the ground at **speeds of up to 200 km/s** with the length of individual jumps ranging from 4 to 50 m.
- The **pause between individual jumps** (necessary to create another segment of the leader) is **40 to 100 microseconds**.
- When the leader reaches a distance of 20 to 200 m from the ground, the "selection" of the impact site occurs, which depends on the geometry of the surface and the size of the charge in the leader.
- The return stroke propagates at speeds of up to a tenth of the speed of light, its currents reach **10 to 200 kA**, and it transfers a charge of **5 to 15 C**, with the **dissipated energy reaching up to 500 MJ**. As the current passes, pinching of the ionized channel occurs (remember arc lecture).

Details of the discharging:

- During the pinch, the pressure in the channel increases to **2 to 8 atm**. The **temperature rapidly reaches up to 30,000 °C**, and due to the expansion of the gas, pressure sound waves are created, resulting in thunder.
- After **typically four return strokes**, a substantial part of the cloud's charge is discharged, with each stroke lasting up to 30 microseconds.
- Even **after another 100 ms, there can be further discharging of the cloud's charge through what is known as a dart leader** (continuous leader), which is almost an entirely new discharge without a branched structure but propagates along the pre-ionized path of previous strokes at speeds of up to 10^7 m/s. The return strokes following the dart leader propagate at speeds of up to 10^8 m/s.

Positive lightning often occurs in the form of a single strike without return strokes and typically lasts one to two tenths of a second.

Frequency of lightning, measured currents



High Resolution Full Climatology Annual Flash Rate

Figure 5.12. Global distribution of lightning April 1995–February 2003 from the combined observations of the NASA OTD (4/1995–3/2000) and LIS (1/1998–2/2003) instruments. The map is based upon the average yearly count of lightning flashes per square kilometre reproduced from [21] courtesy of NASA.

Frequency of lightning, measured currents

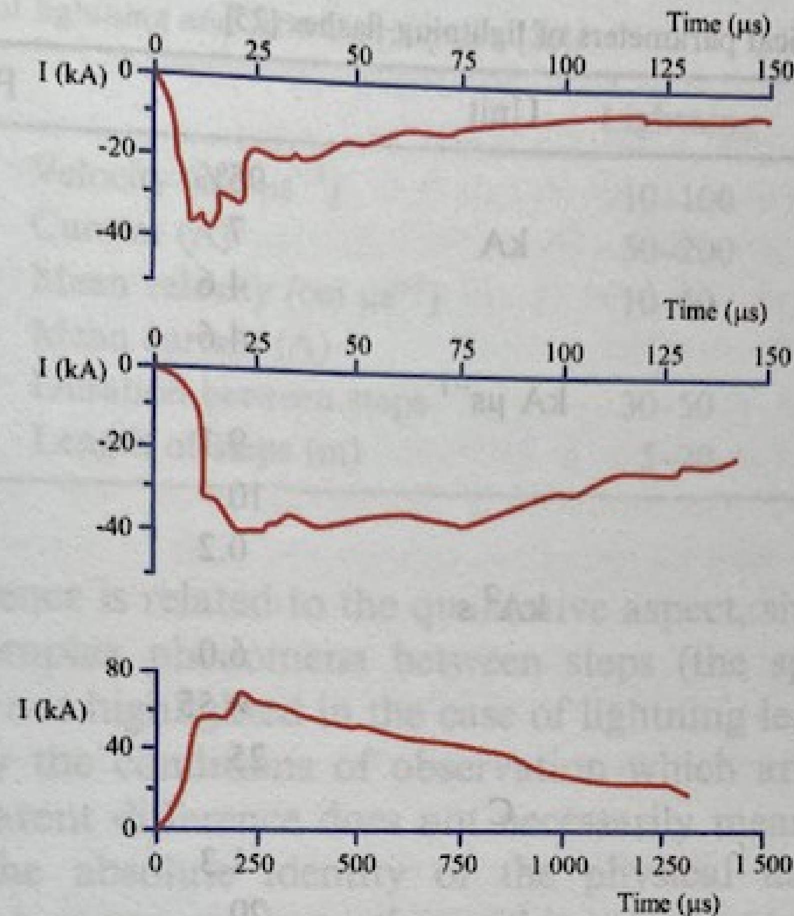
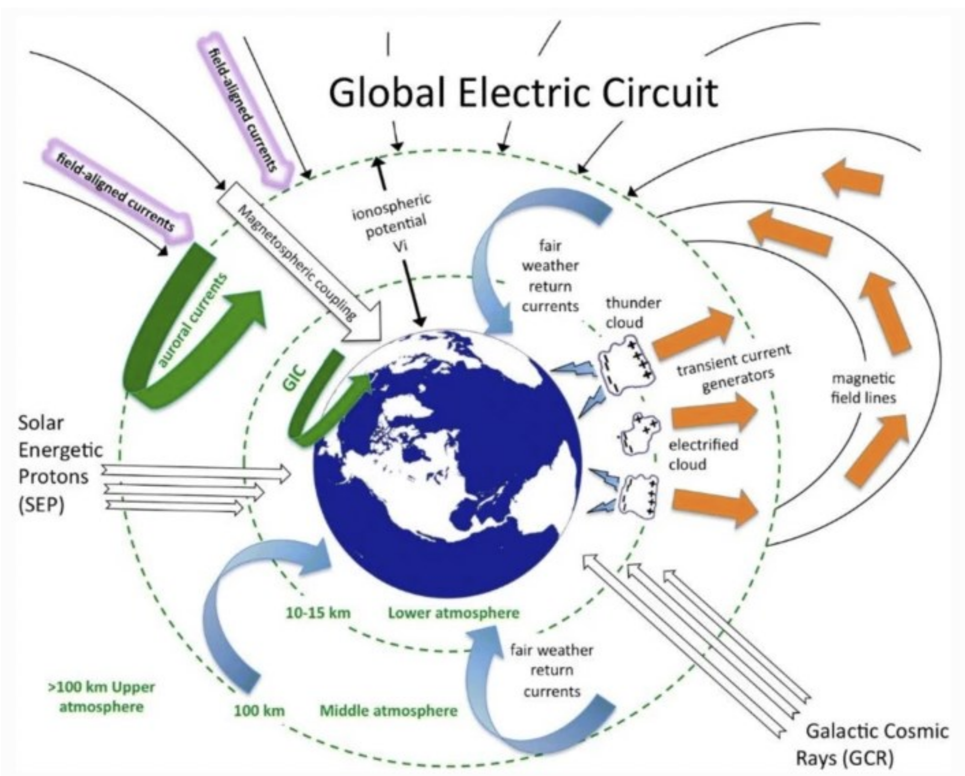
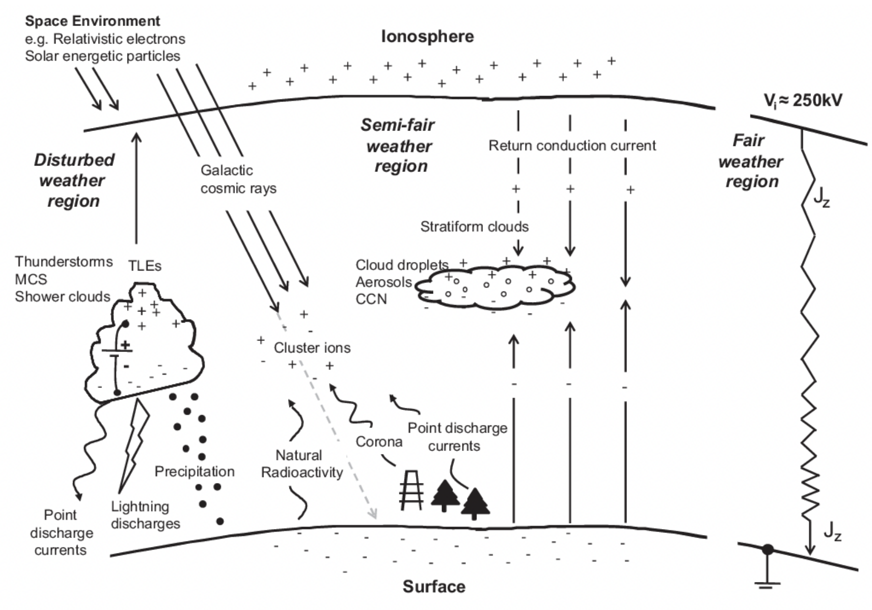


Figure 5.13. Positive and negative lightning current measured at Mt San Salvatore in Lugano (Switzerland) reprinted with permission from [24].

Global electrical circuit

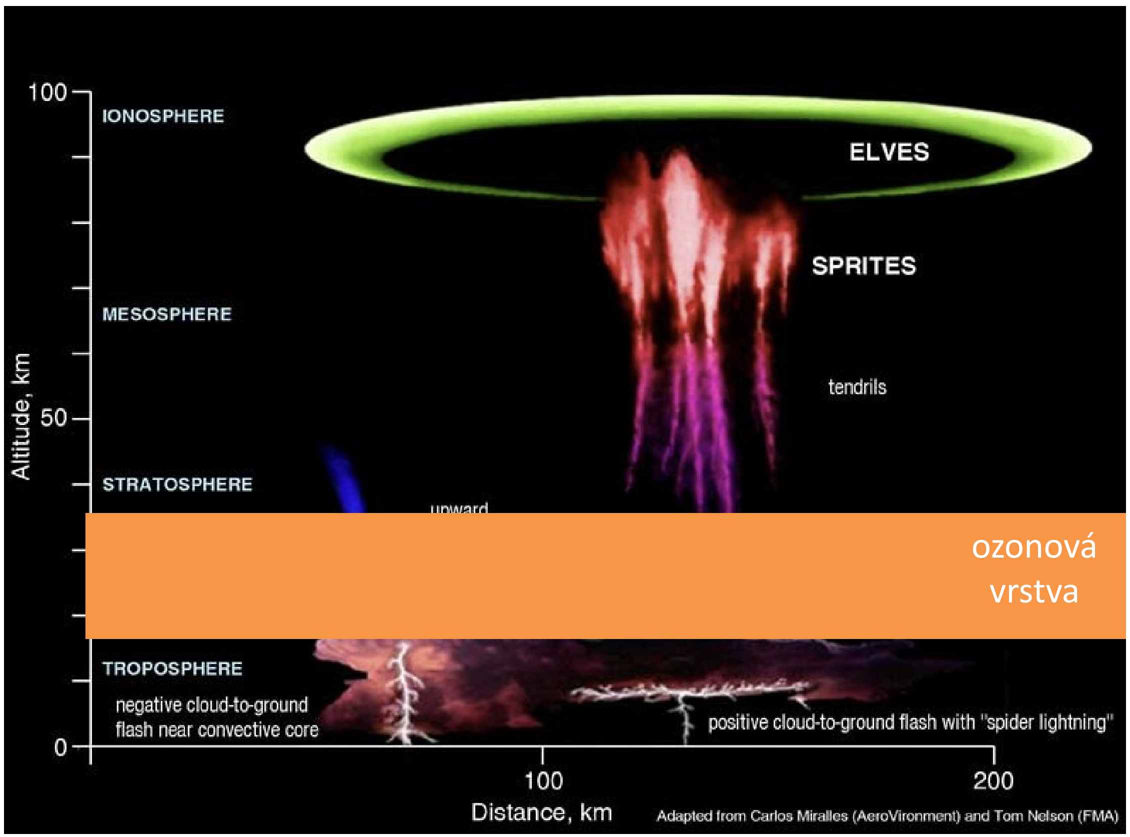
- Atmospheric electrical activity is not limited solely to classic lightning.
- Other components include: continuous picoampere current, TLE or transient luminous events, current caused by cosmic radiation, solar proton showers, relativistic electrons, gamma-ray bursts, terrestrial radioactivity and probably other, yet undocumented, phenomena

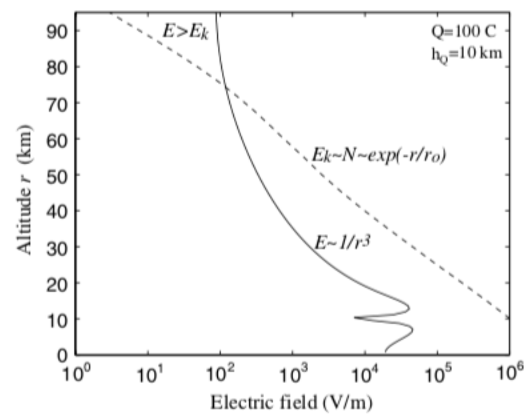




TLE – transient luminous events

- This refers to **lightning activity above the clouds**, that is**, from the cloud to the ionosphere**.
- In the case of a discharge from a portion of a large thundercloud towards the ground, part of the cloud remains undischarged and thus reorganizes the electric field direction towards the ionosphere. Under various pressure, thermal, and ionization conditions, this then leads to above-cloud lightning.
- These are known as: **elves, sprites, blue jets, tendrils, halos**...





TLE – transient luminous events

- This refers to **lightning activity above the clouds**, that is**, from the cloud to the ionosphere**.
- In the case of a discharge from a portion of a large thundercloud towards the ground, part of the cloud remains undischarged and thus reorganizes the electric field direction towards the ionosphere. Under various pressure, thermal, and ionization conditions, this then leads to above-cloud lightning.
- These are known as: **elves, sprites, blue jets, tendrils, halos**...

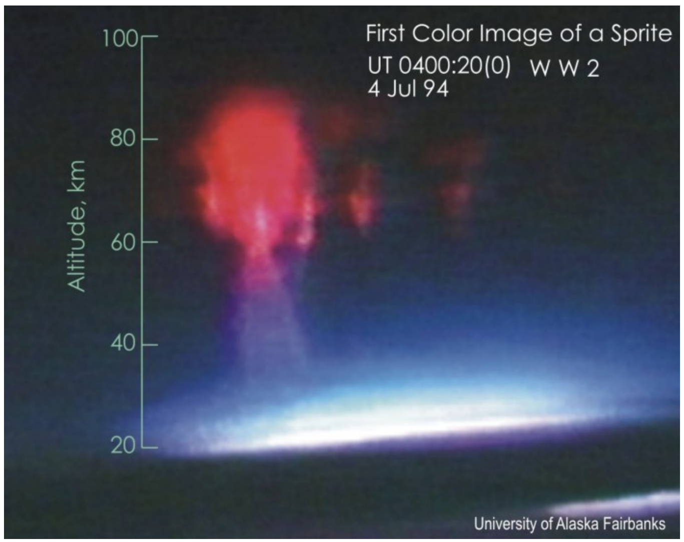
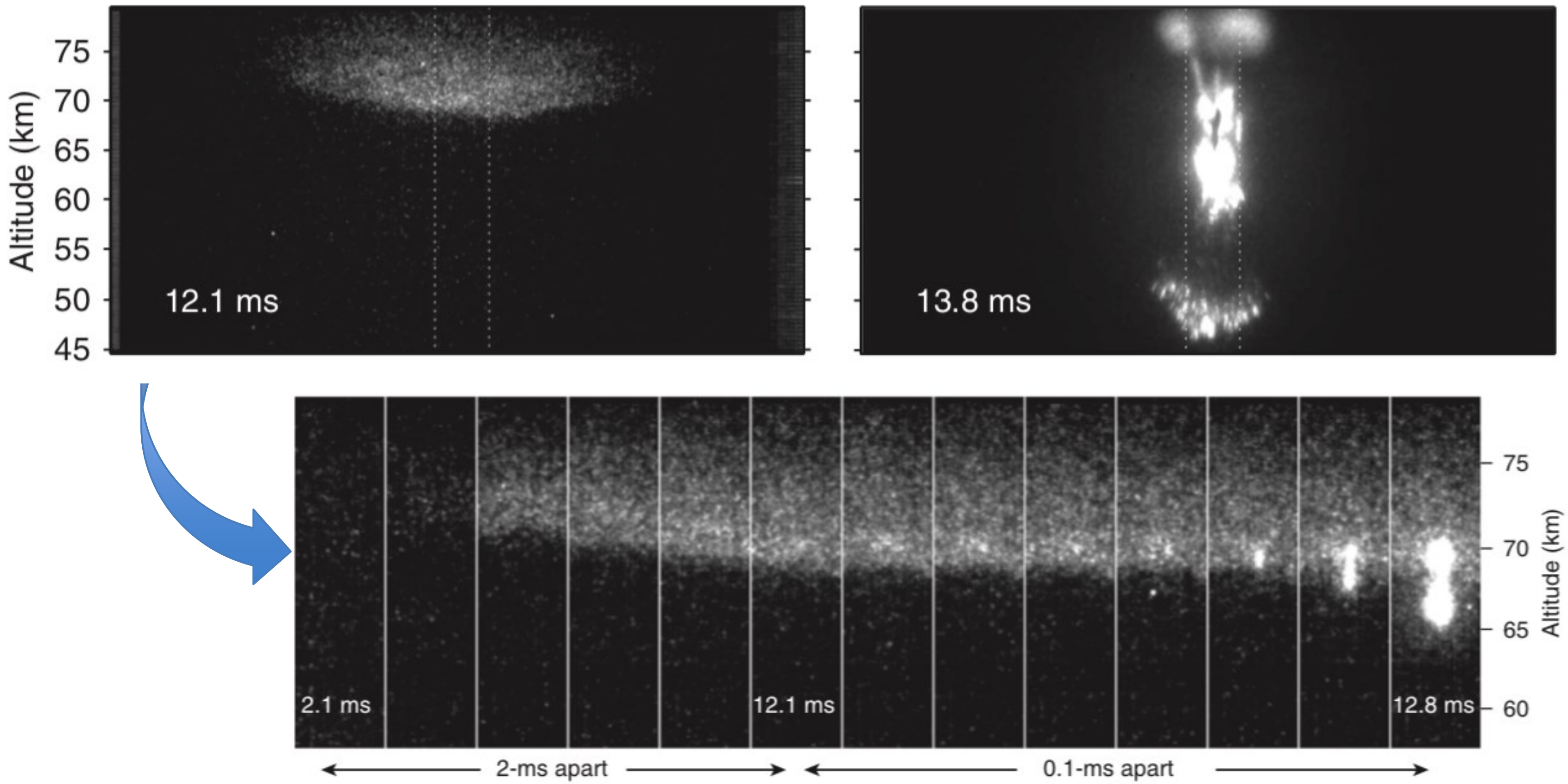


Table 1. Summary of emissions from sprites [62].

Emission band system	Transition	Excitation energy threshold (eV)	Lifetime at 70 km Alt.	Quenching Alt. (km)
$1PN_2$	$N_2(B\,^3\Pi_g)\rightarrow N_2(A\,^3\Sigma_u^+)$	~7.35	5.4 μs	~53
$2PN_2$	$N_2(C\,^3\Pi_u)\rightarrow N_2(B\,^3\Pi_g)$	~ 11	50 ns	~30
LBH N_2	$N_2(a\,^1\Pi_g)\rightarrow N_2(X\,^1\Sigma_g^+)$	~8.55	14 μs	~77
$1NN_2^+$	$N_2^+(B\,^2\Sigma_u^+)\rightarrow N_2^+(X\,^2\Sigma_g^+)$	~18.8	69 ns	~48

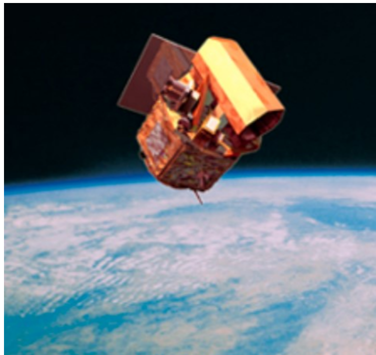
Origin of a sprite from a halo

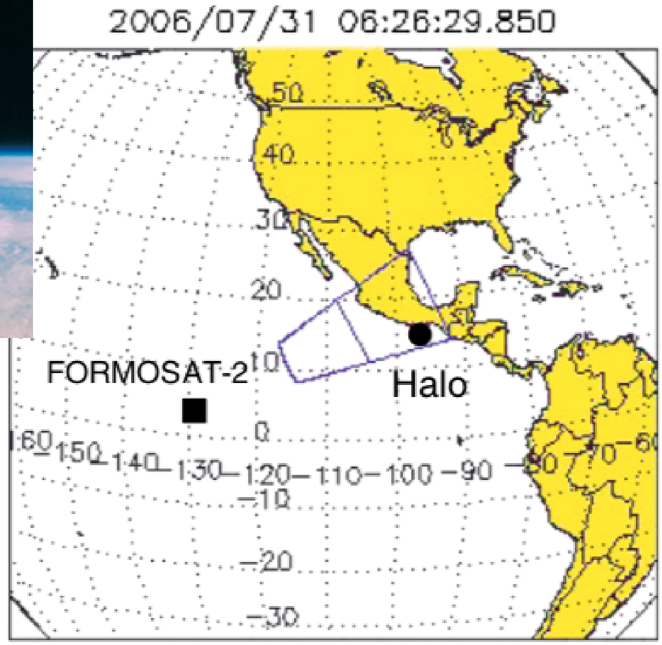


The record of the birth of a Sprite from Halo on July 6, 2011, at 73 km.
The transition hypothesis is a perturbation in the surrounding electron density in the upper mesosphere.

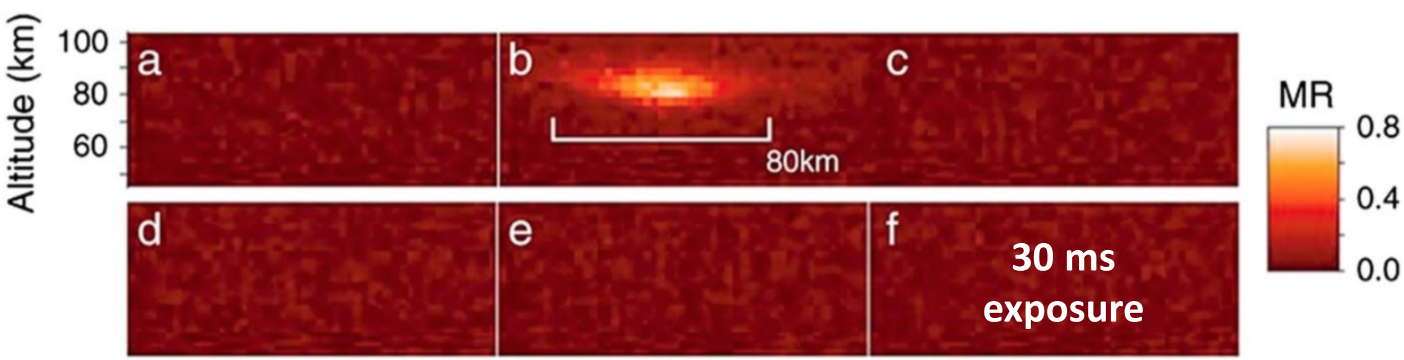
Liu et al. 2014 Nature Com.

Other observations





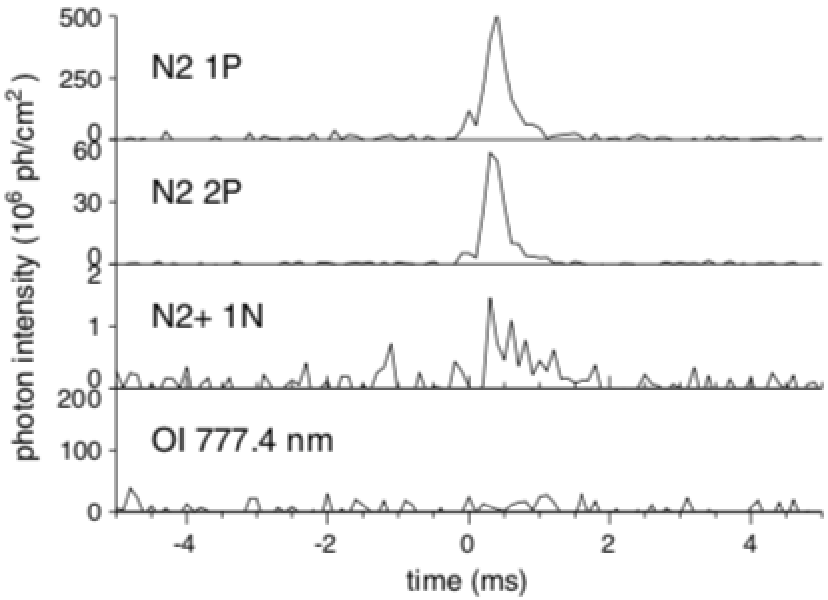
- Observation of Halo on July 31, 2006, above Mexico.
- Record from the ISUAL module of the FORMOSAT-2 satellite of the Taiwan Space Agency.

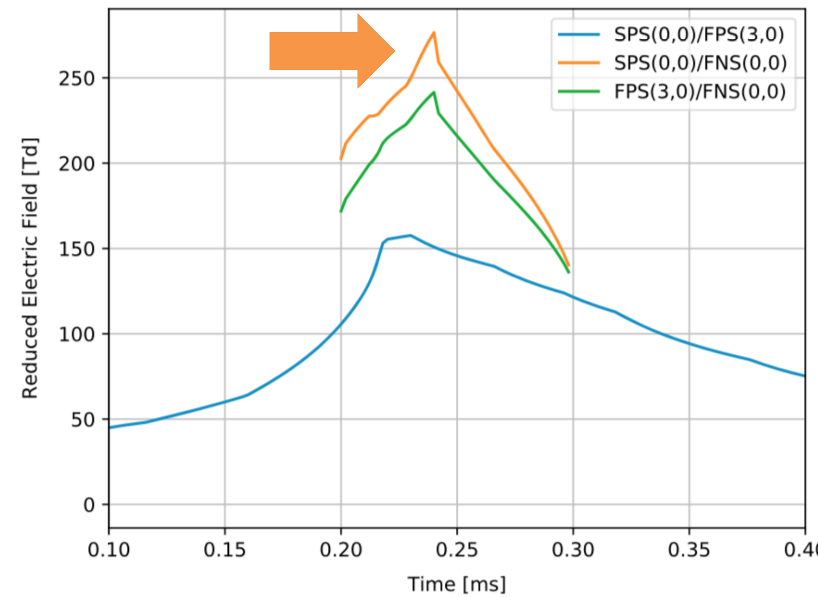


Kuo et al. 2013 JGR

[redacted]

Plasma diagnostics from a satellite





- Measuring electric field based on a spectrometer mounted on a satellite

Pérez-Invernón et al. 2018 JGR

Take aways

- Understand the difference between streamer and leader, positive and negative.
- Be able to qualitatively describe lightning formation – from the cloud formation all the way to discharge
- Be aware of the main plasma properties of lightning plasmas (current, temperature, pressure, propagation speeds etc.)
- Know of the existence of TLE and their characteristic dimensions.