Downward negative lightning discharges to the ground (“Lightning physics and effects” ch. 4.1 – 4.4.6)

Paweł Jujeczko

General picture

- Cloud to ground negative lightning (CG-)
- a) still camera; b) moving (streak) camera
- Time interval at b) – tens of ms (“flickering” effect)
- How do we know it is CG-?
  - Downward directed branches (downward movement)
  - Multiple strokes (CG+ is usually 1 stroke)

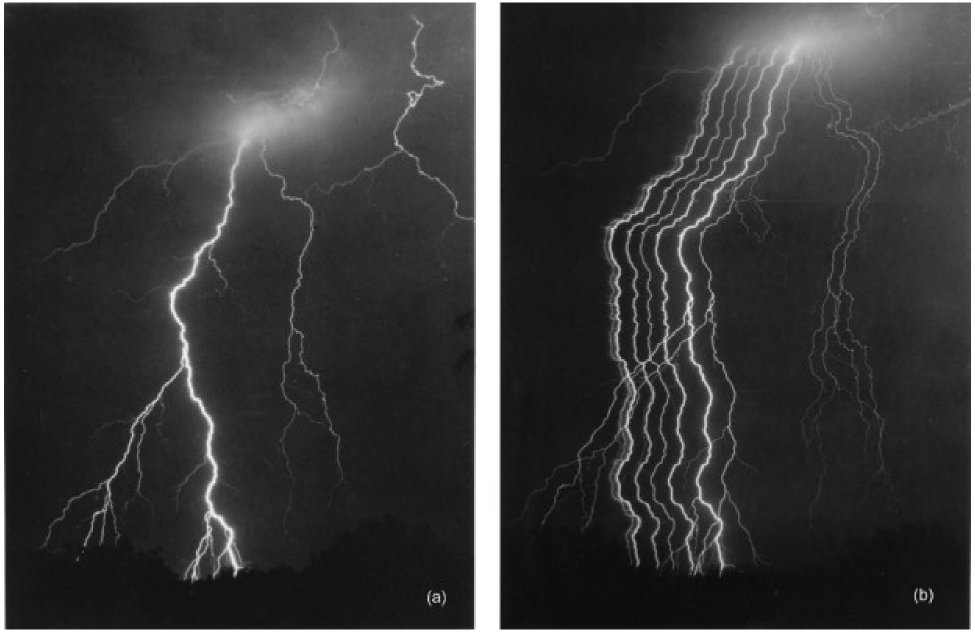
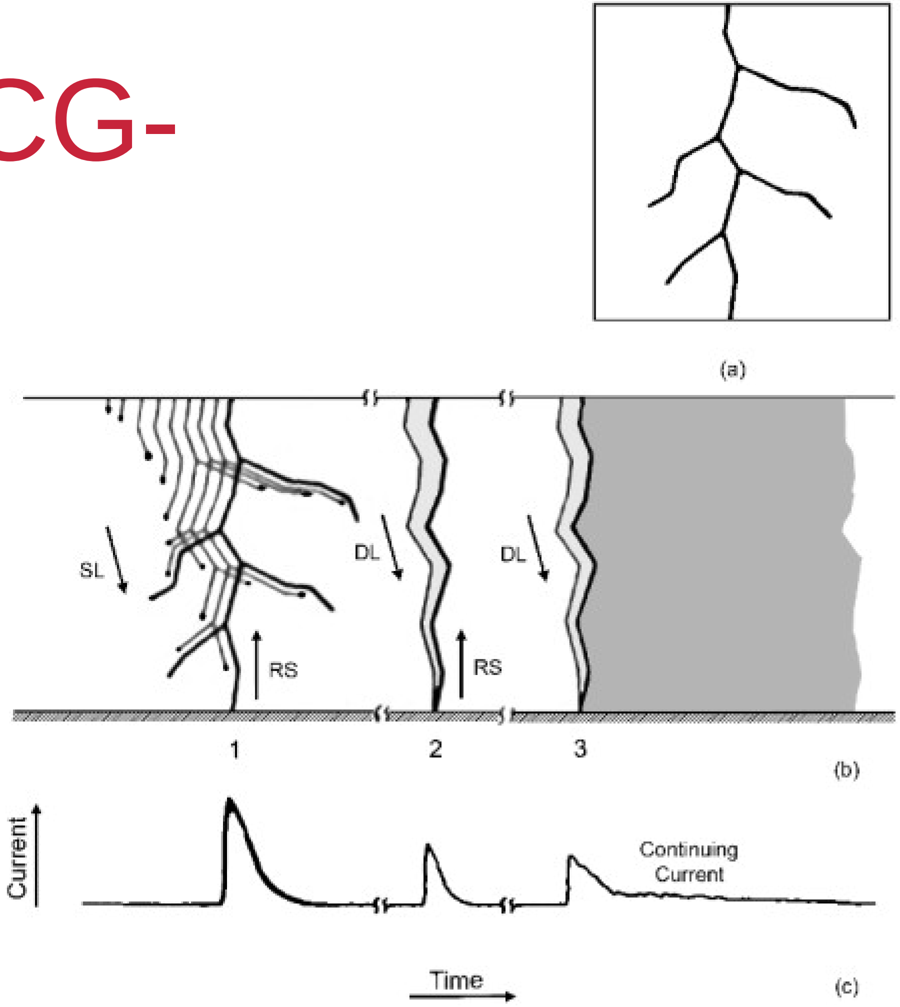


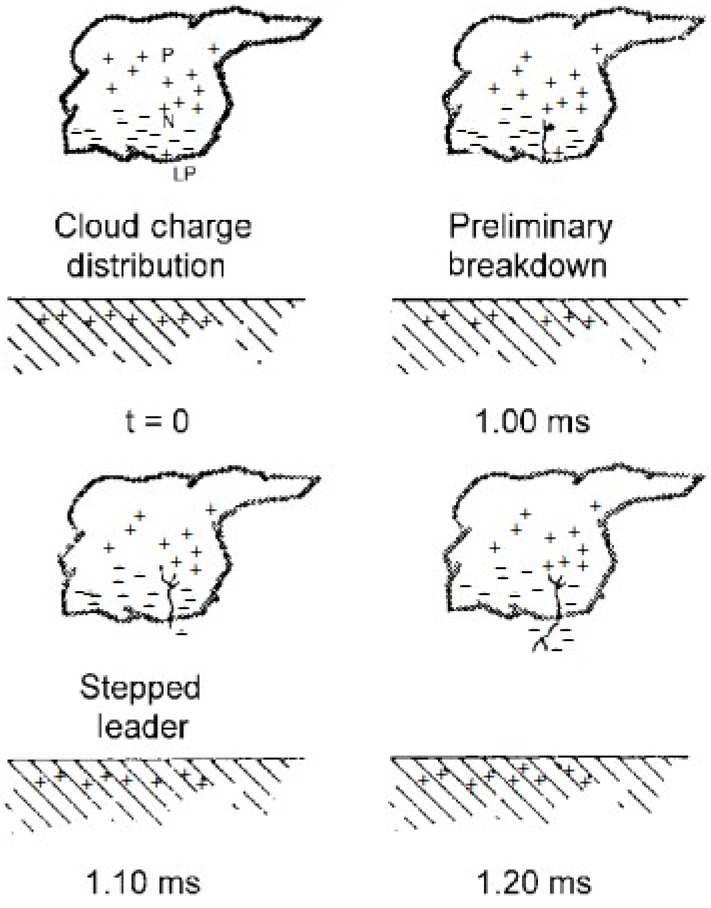
Diagram of 3-stroke CG-

- Analogous to previous photography
- 1st stroke (at virgin air):
  - stepped leader (SL) – downward, branching conducting path between the cloud and the earth with negative charge distributed along the way
  - Return stroke (RS) – removes accumulated charge to the ground (current flows upward)
- Subsequent strokes:
  - Dart leader (DL) – in air pre-conditioned by 1st stroke, there are mostly no branches and no steps
  - RS – usually weaker than 1st RS



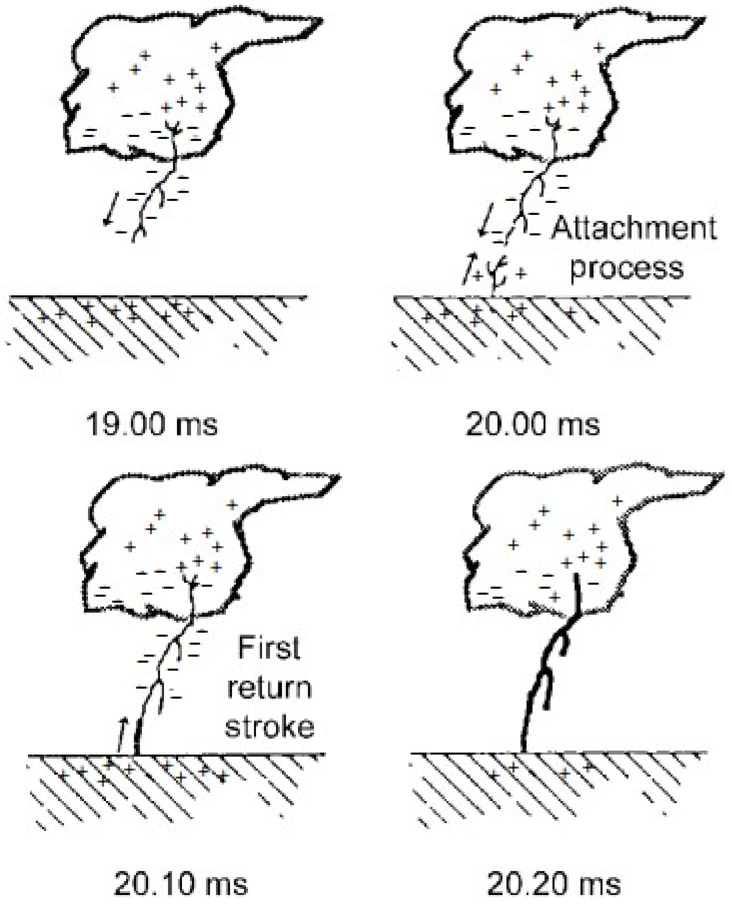
Development of CG-

- Basic picture of chapter 4
- Tripole structure (**P**ositive, **N**egative, **L**ower **P**ositive)
- Preliminary (initial) breakdown – few to tens of ms – it may be a discharge bridging N and LP regions, but there is no consensus. It develops conditions for SL to occur.
- SL – negative charge accumulates along the channel



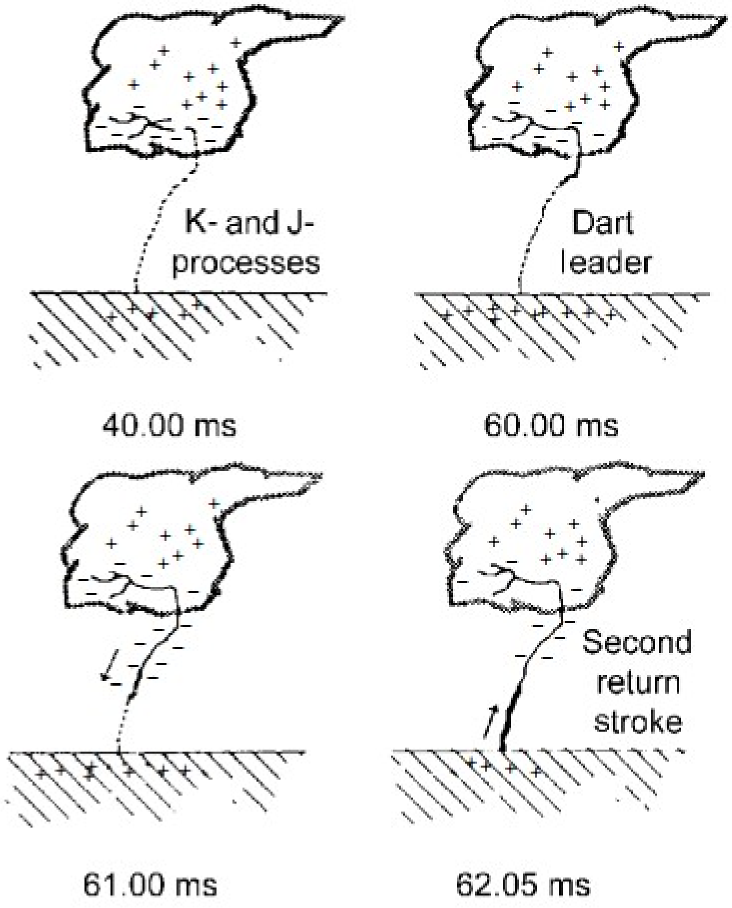
Development of CG-

- SL approaches the earth and E field on earth and sharp objects rises, upward-moving positive leader starts attachment (tens of meters above ground or sharp object)
- First RS – transport of negative charge from the channel to the ground
- Current heats the air to 30,000 K, p = 10 atm – thunder
- Process may end here, but mostly subsequent strokes appear



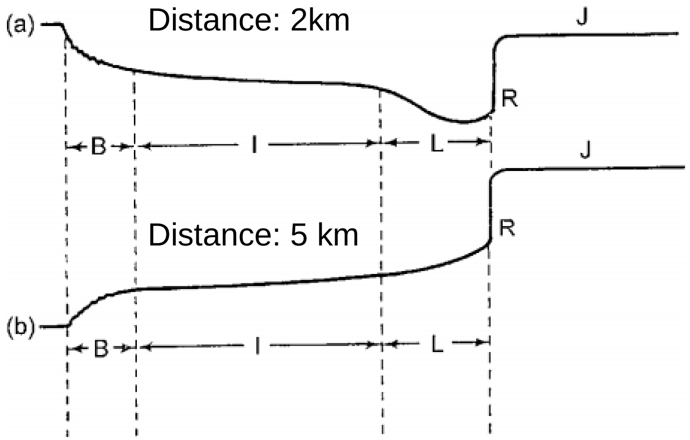
Development of CG-

- Initiation of DL: J- (*junction*) and K- processes act to extend the RS into the cloud by redistributing the charge inside the cloud (if they do not produce subsequent stroke they are called final (F-) processes
- Dart leader
- In 70% of cases 1st RS is stronger than subsequent ones
- For CG- there are 3-5 strokes per flash in most cases



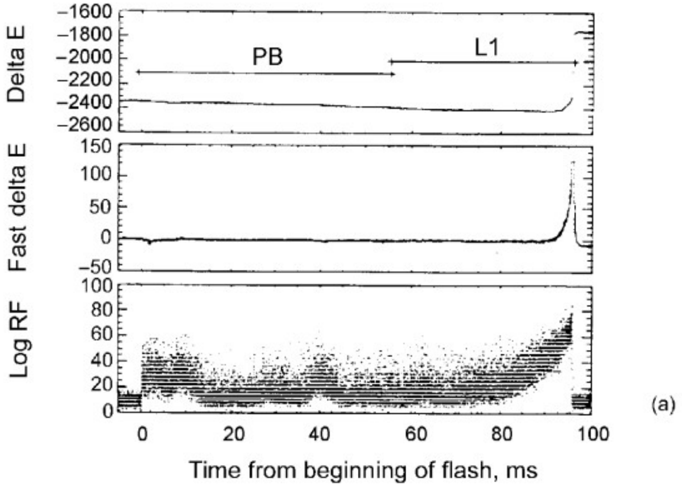
Initial breakdown

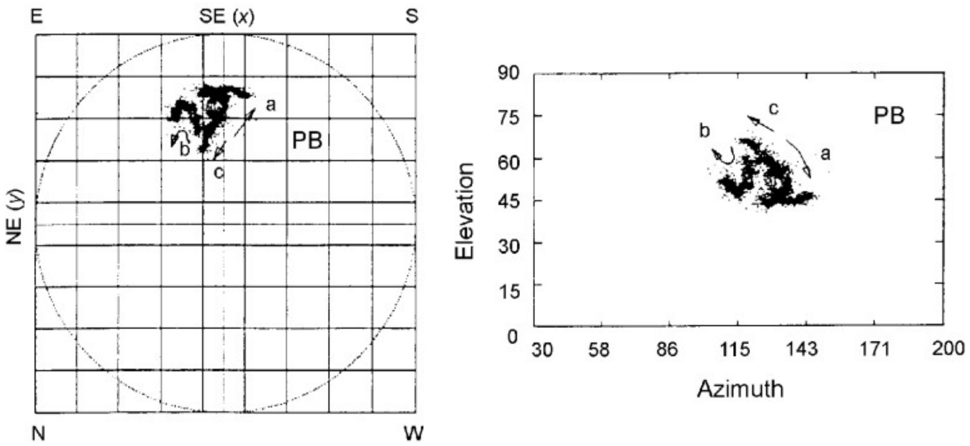
- B-I-L structure (according to Clarence and Malan):
- **B** (breakdown phase) – vertical discharge between N and LP regions can produce such inverted outcome
- **I** (intermediate phase) – negative charging of breakdown channel (0-400 ms)
- **L** - leader



Initial breakdown

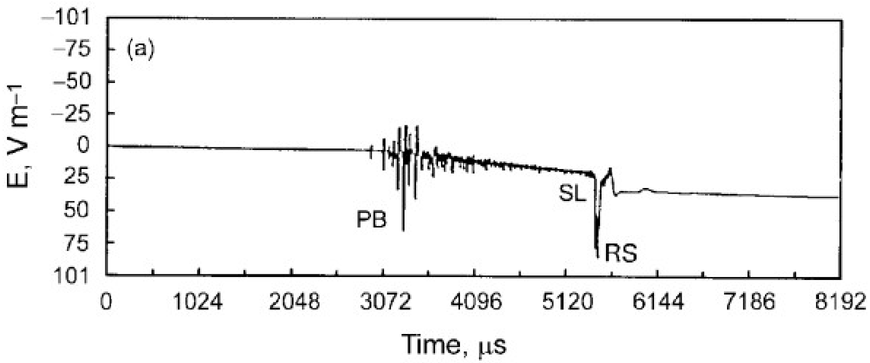
- 274 MHz (VHF) interferometric picture
- 3 branches originating from volume that seems to be the source of the SL
- Recent VHF-UHF channel imagining suggest, that IB is sequence of random channels from charge volume that is an origin of the SL





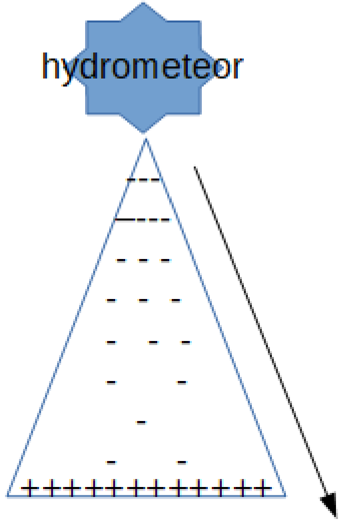
Initial breakdown pulses

- us-scale, bipolar pulses with variable amplitude (may be as high as RS)
- Form “diamond” shape
- Associated with β-type leaders (larger amplitude, fast)
- Different from SL pulses produced near ground

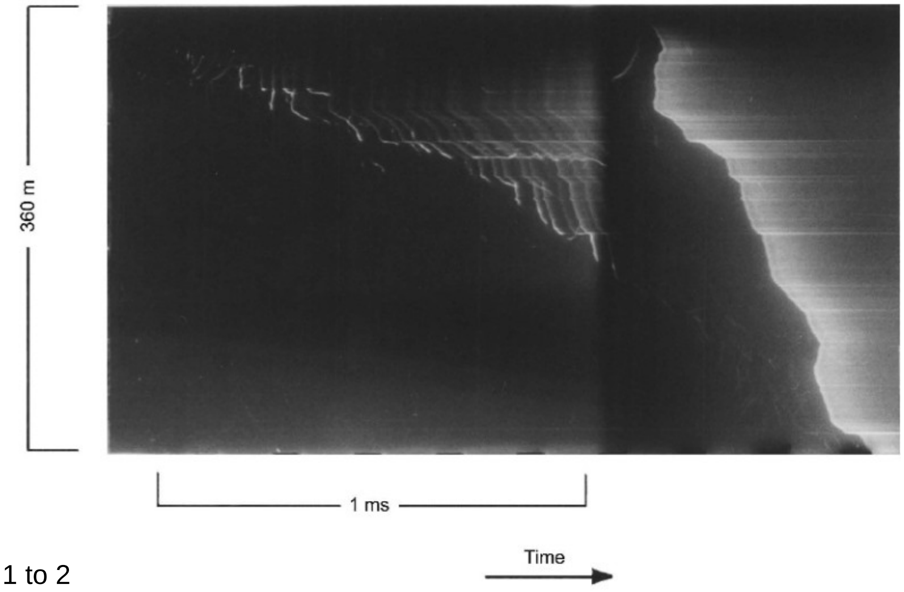


Lightning initiation in thunderclouds

- E field inside thunderstorm is insufficient for production of a lightning (E_{th}=2.6x10^6 V/m)
- Griffiths and Phelps's proposed *hypothesis*: cone-shaped positive corona streamers are emanating from hydrometeors if E > E_0 (corona onset, 1.5x10^5 V/m at 6.5 km, 2.5x10^5 V/m at 3.5 km). Propagation of positive base of the cone leads to deposition of equal negative charge in cone's volume, leading to E enhancement in the apex.
- After several streamer passes into the debris of previous ones the enhancement can reach 1.5x10^6 V/m over few meters and lead to formation of the SL
- Other approaches:
  - Nguyen and Michnowski: +/- streamers
  - Gurevich: runaway electrons that gain more energy from E field than they lose in collisions, energy range 150 eV – 1.4 MeV, breakdown occurs at 10x lower E field than conventional breakdown



Stepped leader



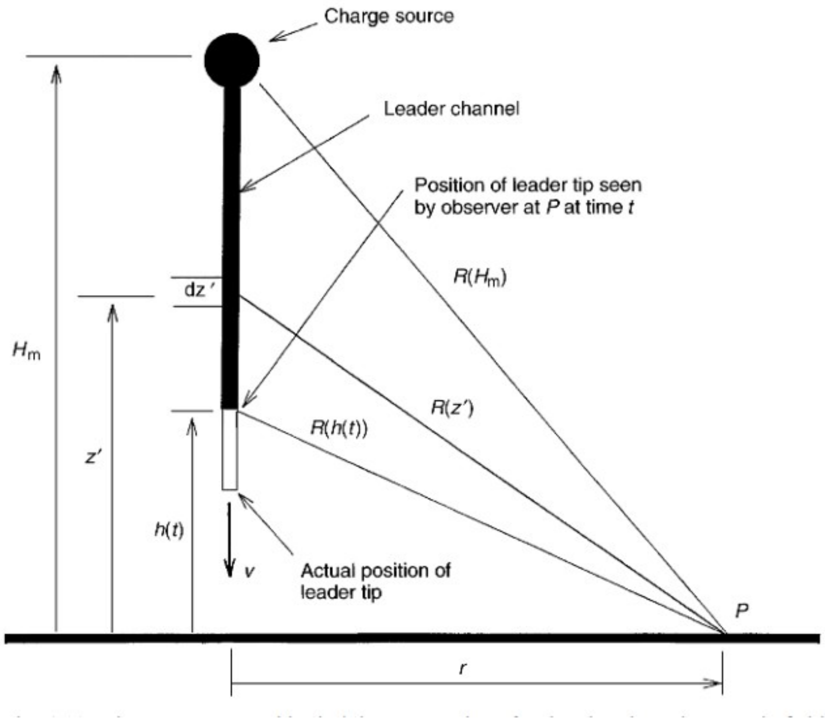
- Early classification of stepped leaders (Schonland 1938):
  - α-type (55-70%) - v~10^5 m/s
  - β-type - 2 stages:
    - Upper: long, bright steps and high velocity ~10^6 m/s
    - Lower: resembles α-type (shorter, less bright steps)
    - Extensive branching near cloud base
  - Possibly α-type may have upper stage hidden in the clouds and be β-type too
  - β_2-type leaders produce luminous waves in ~10ms intervals at turning from stage 1 to 2
- V_{avg} = 1~2x10^5 m/s, faster close to the ground
- Mean duration: tens of ms (8-46 ms)
- Accumulated charge ~5C
- Lower boundary of N region voltage is 50~500 MV, Marshall&Stolzenburg soundings: -102~+94 MV in the whole cloud.
- Current: e.g. 5 C lowered in 35 ms gives **I**=143 A; 50-63 A (Brook); 100 A – 5 kA, I_{avg} = **1.3** kA, ρ_L = 3.4x10^{-3} C/m (Thomson, 62 SLs); 200 A – 3.8 kA, I_{avg} = **1.3** kA (Krehbiel)

Electrostatic model

- (4.1) first term: change of E due to expanding of the charge with the leader; second term: change due to draining this charge from the cloud
- Net charge remains constant
- (4.4) v,ρ_L = const, propagation to observer neglectable

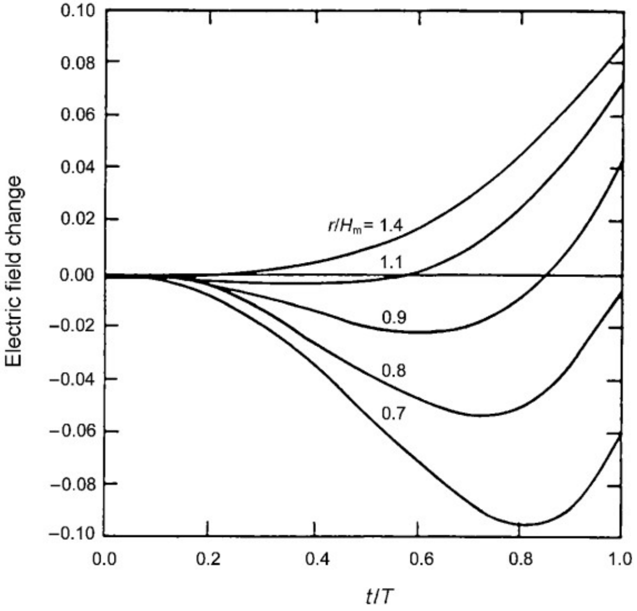
$$E_z(r,t) = \frac{1}{2\pi\varepsilon_0}\int_{h(t)}^{H_m} \frac{z'}{R^3(z')}\rho_L\left(z', t - \frac{R(z')}{c}\right)dz' - \frac{1}{2\pi\varepsilon_0}\frac{H_m}{R^3(H_m)}\int_{h(t)}^{H_m}\rho_L\left(z', t-\frac{R(z')}{c}\right)dz' \quad (4.1)$$

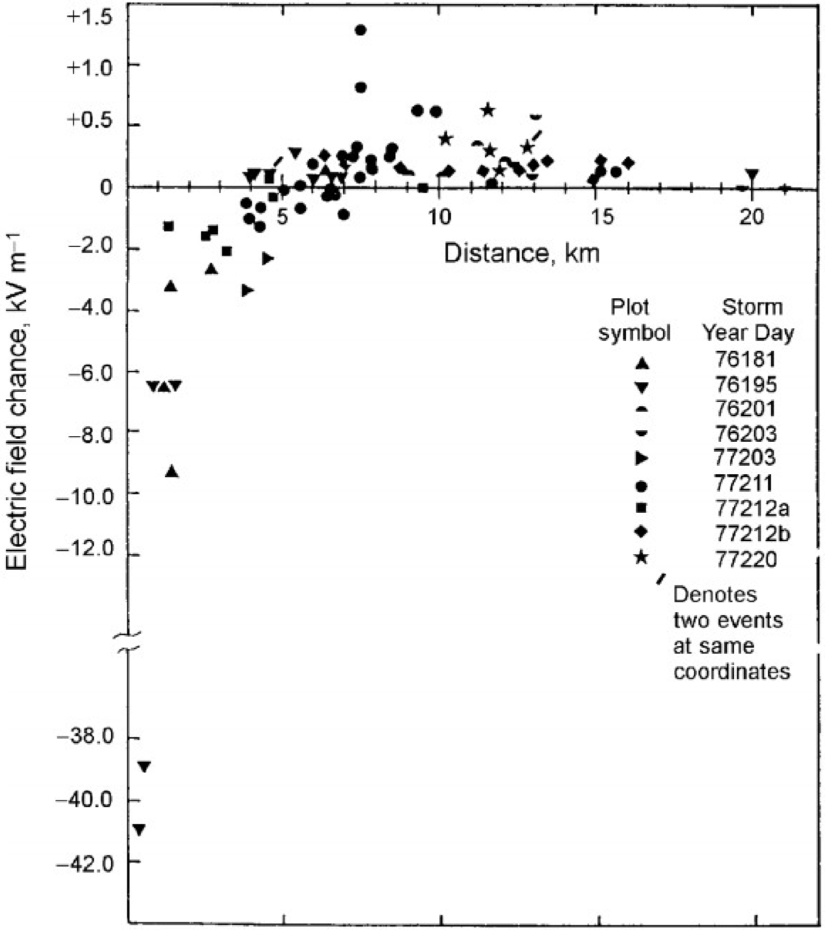
$$E_z(r,t) = \frac{\rho_L}{2\pi\varepsilon_0 r}\left[\frac{1}{(1+z_t^2/r^2)^{1/2}} - \frac{1}{(1+H_m^2/r^2)^{1/2}} - \frac{(H_m - z_t)H_m}{r^2(1+H_m^2/r^2)^{3/2}}\right] \quad (4.4)$$



Electrostatic model

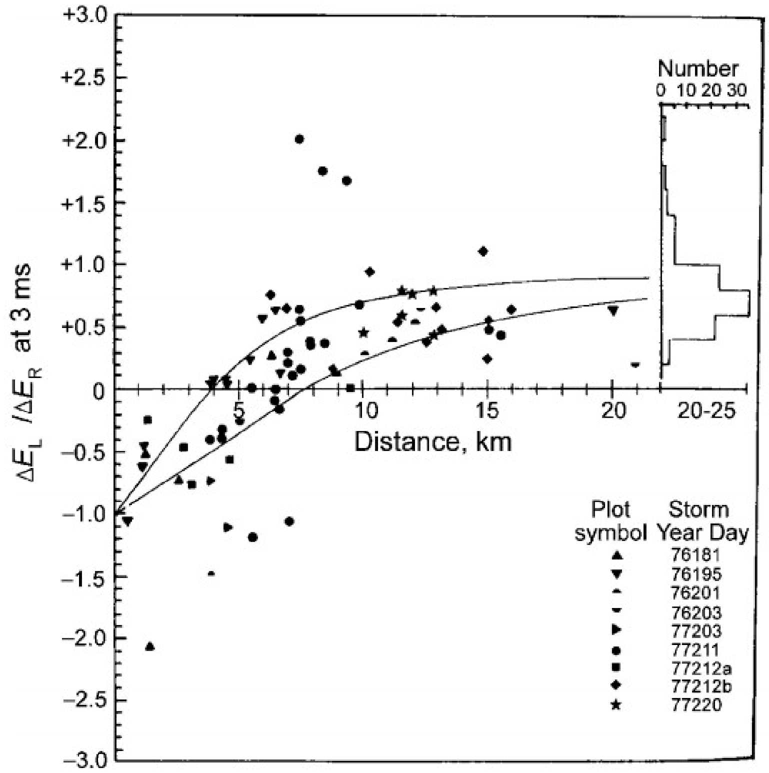
- The SL E field change can be bipolar depending on the distance from the leader to the observer (r/H_m>1.27 is close measurement)



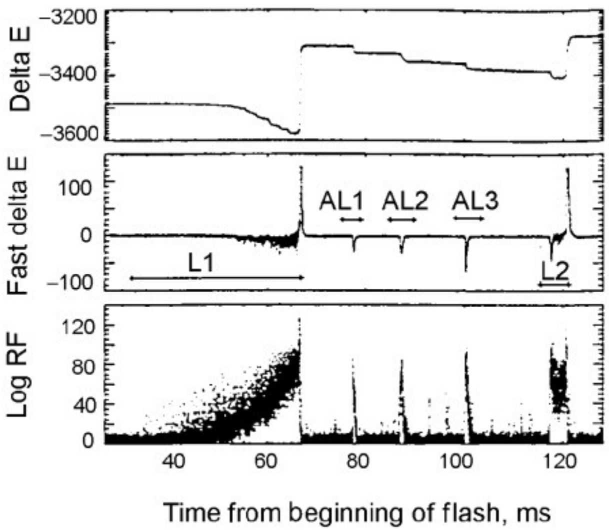


Leader/RS ratio

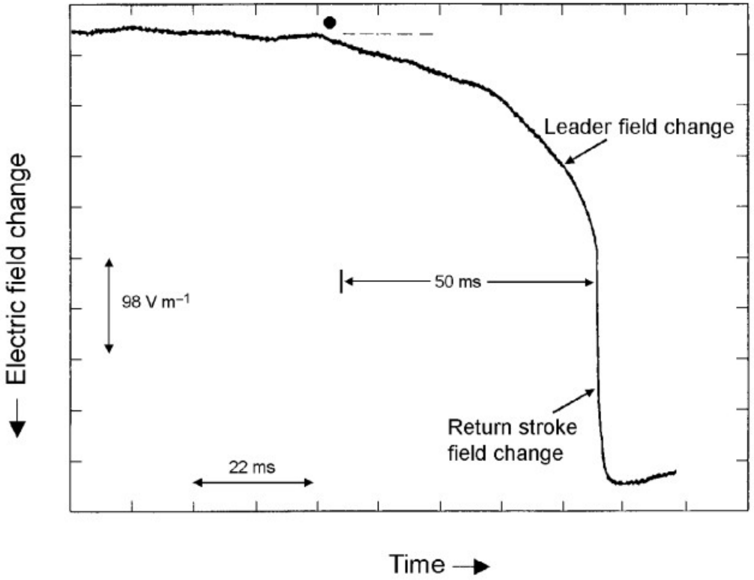
- At small distances ($H_m/r > 1.27$) polarisation of L and RS electric fields are opposite (modeled lines: upper: $H_m = 5$ km, lower $H_m = 10$ km) (eq. 4.1, 4.4)



EM fields



Delta E
−3200
−3400
−3600
Fast delta E
100
0
−100
AL1 AL2 AL3
L1
L2
Log RF
120
80
40
0
40 60 80 100 120
Time from beginning of flash, ms



Electric field change
Leader field change
50 ms
98 V m−1
Return stroke field change
22 ms
Time

Leader steps

- Size: 3-200 m; diameter: ~0.5m; inter-step interval: $t_{int.step}$=5-100 us
- E field pulses (leader steps), width $w_{1/2}$=0.4~0.5 us, many of them produce light, unipolar (unlike IB pulses)
- I_{peak} = 2-8 kA/step
- T = 30,000 K, chilling to 15,000 K
- C = 1-4x10^{-3} C/step
- Average speed v_{SL}= 2x10^5 m/s
- Baum assumed SL extending only during pulses, thus ratio of $t_{int.step}$=20us and $w_{1/2}$=0.4 us is 50.

  v_{step}=50 * v_{SL}= 50 * 2x10^5 m/s = 1x10^7 m/s