Chapters 9.4 - 9.7 of Rakov and Uman, 2003 (Some details about in-cloud lightning processes)

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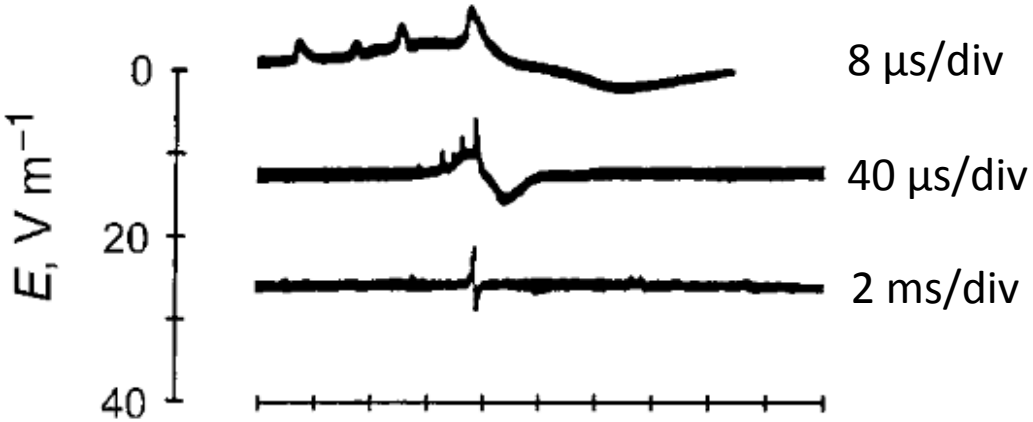
9.4 Early (active) stage of cloud discharges

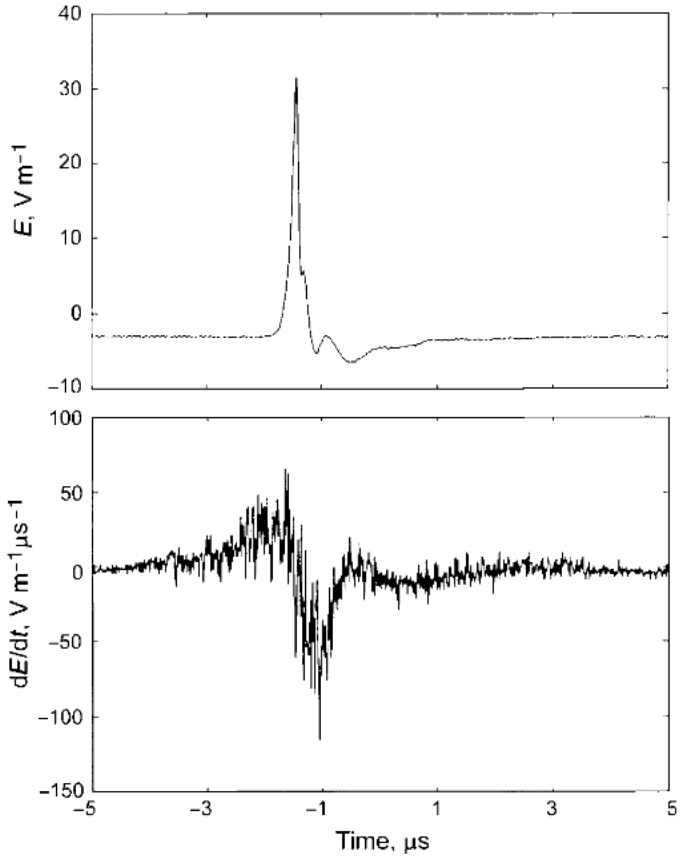
→ 10s-100 ms beginning of flash.

→ Large EM pulses near beginning of cloud flash:

→ Initial breakdown pulses (IBPs).

→ Narrow bipolar events (NBEs).





9.4 Early (active) stage of cloud discharges

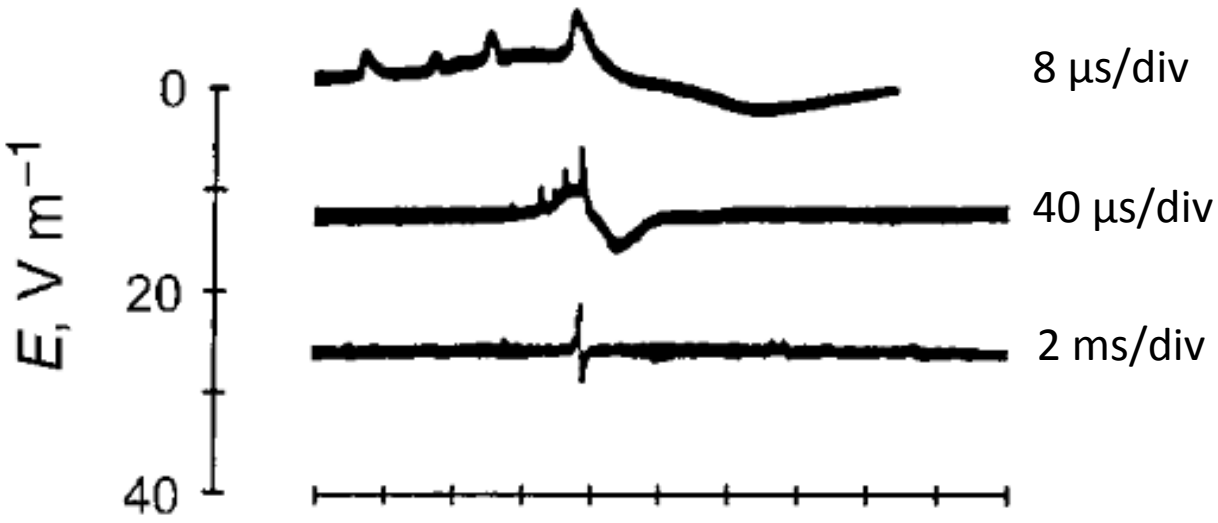
Initial breakdown pulses (IBPs)

→ “Wide” bipolar waveform, smaller pulses superimposed.

→ 50 to 80 μs duration (~2x longer than CG IBPs).

→ Pulses separated by 0.1 to 10 ms (up to 100x longer than CG IBPs).

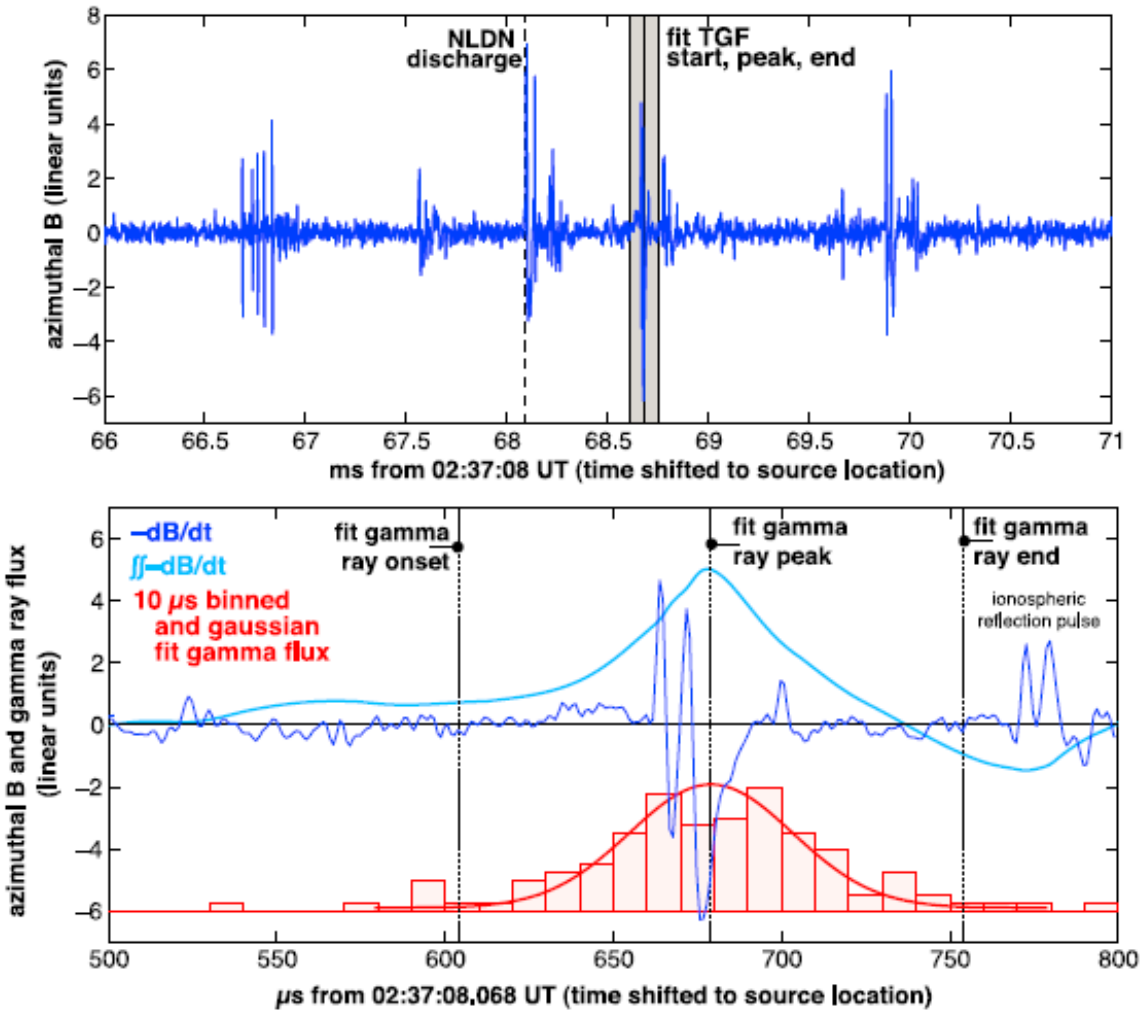
→ HF/VHF peaks during initial half cycle.



9.4 Early (active) stage of cloud discharges

Initial breakdown pulses (IBPs)

→ Possibly related to TGF production.



Cummer et al., 2011

9.4 Early (active) stage of cloud discharges

Initial breakdown pulses (IBPs)
→ Possibly related to TGF production.

Initial breakdown pulses in intracloud lightning flashes and their relation to terrestrial gamma ray flashes

Thomas Marshall,[1] Maribeth Stolzenburg,[1] Sumedhe Karunarathne,[1] Steve Cummer,[2] Gaopeng Lu,[2] Hans-Dieter Betz,[3,4] Michael Briggs,[5,6] Valerie Connaughton,[5,6] and Shaolin Xiong[5]

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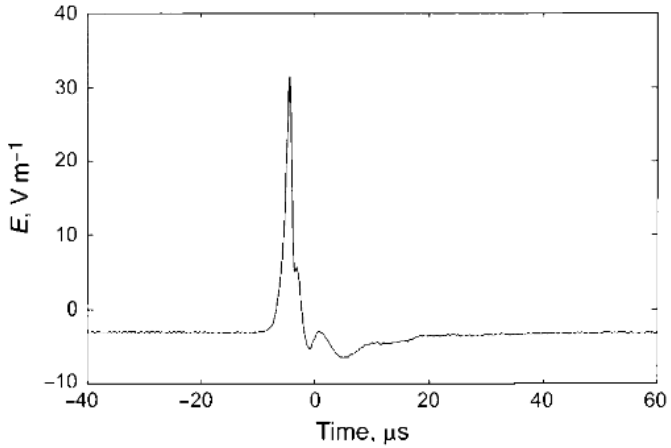
9.4 Early (active) stage of cloud discharges

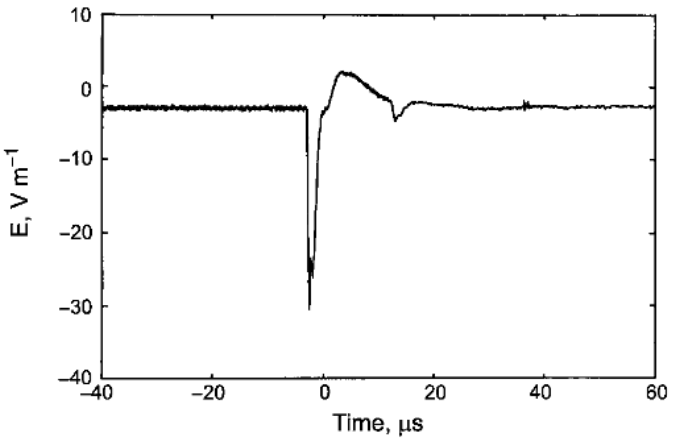
Narrow bipolar events (NBEs)

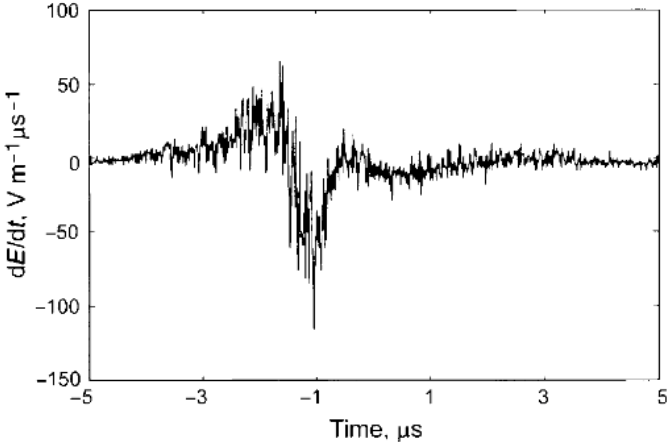
→ Fast rising (10-90% in ~2 μs) bipolar waveform, relatively smooth.

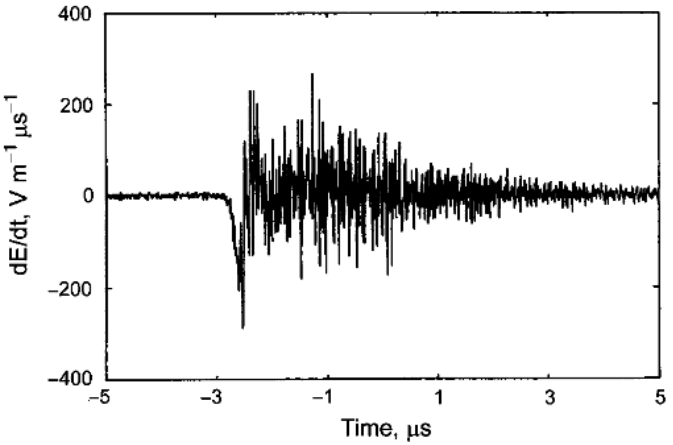
→ ~25 μs duration, i.e., “narrow”.

→ Accompanied by large HF/VHF (10s of MHz) emissions.









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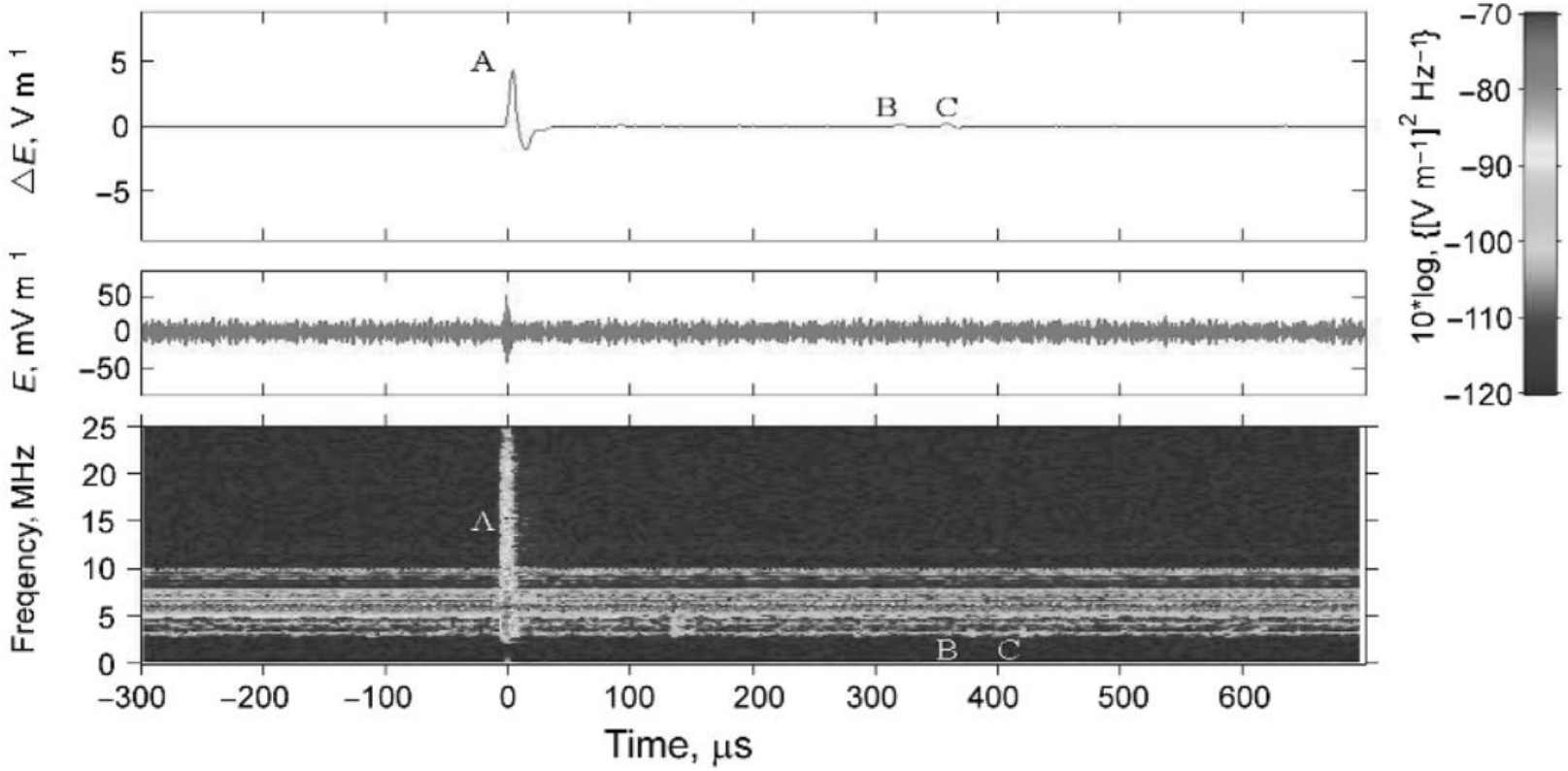

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Example: >100 kW in 60-66 MHz

Example: at 18 MHz, $ESD_{NBE} \approx 40\ ESD_{RS1}$

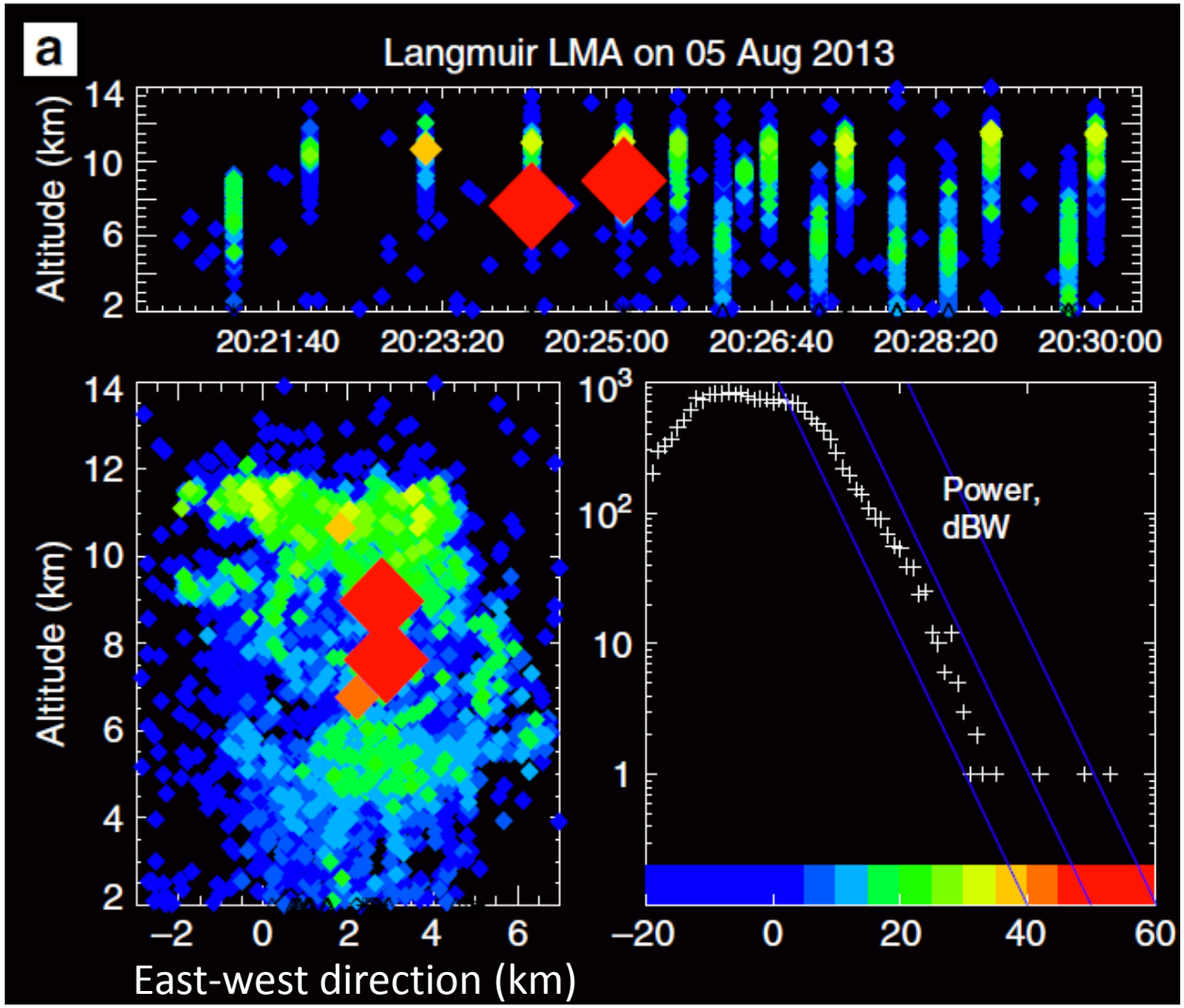
→ Initial event in cloud discharges / can occur in isolation.

→ Compact intracloud discharge (CID), 0.5 to 1 km vertical extent.

9.4 Early (active) stage of cloud discharges

Narrow bipolar events (NBEs)

→ Lightning mapping array (LMA) data (3D 60-66 MHz) of NBEs.

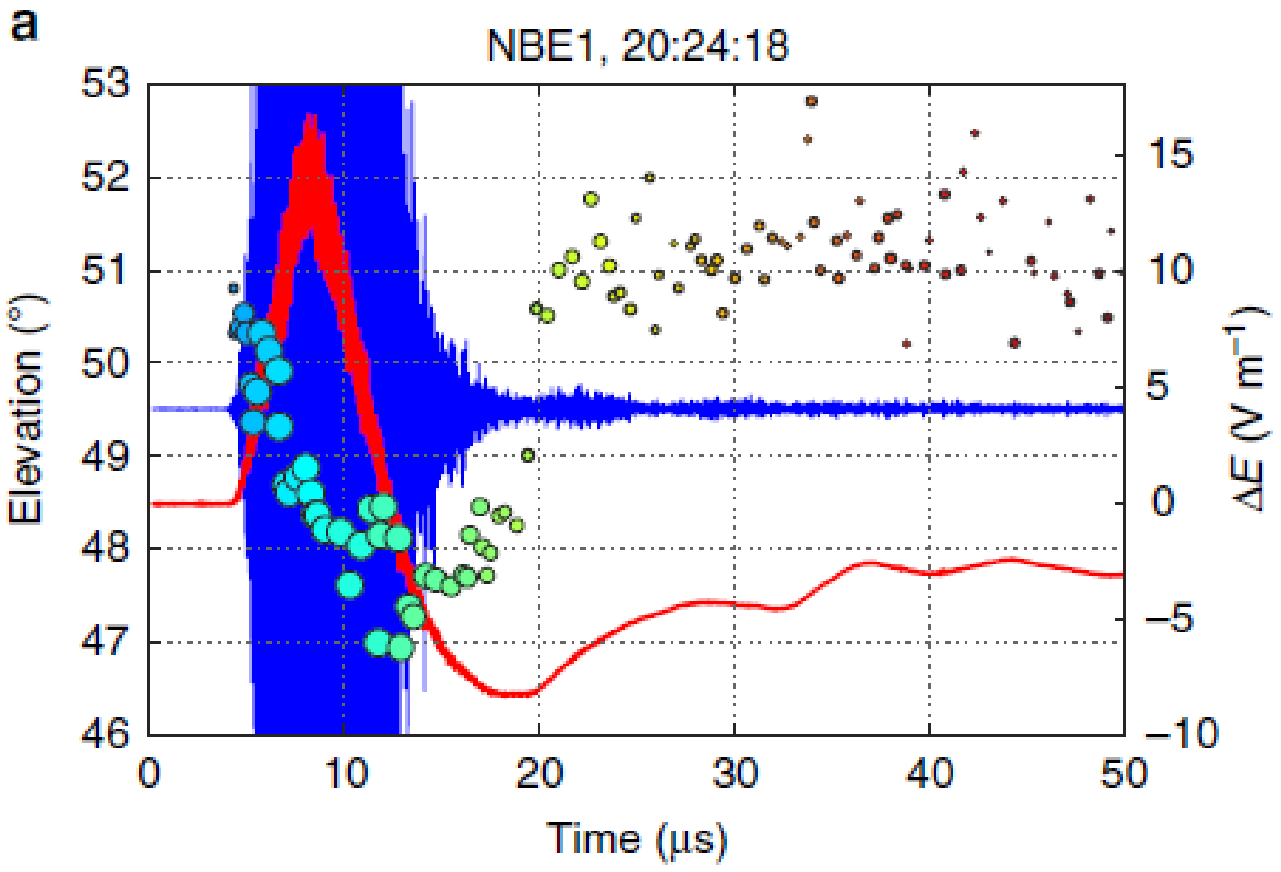


Rison et al., 2016

9.4 Early (active) stage of cloud discharges

Narrow bipolar events (NBEs)

→ Broadband (20-80 MHz) 2D interferometer data.



Rison et al., 2016

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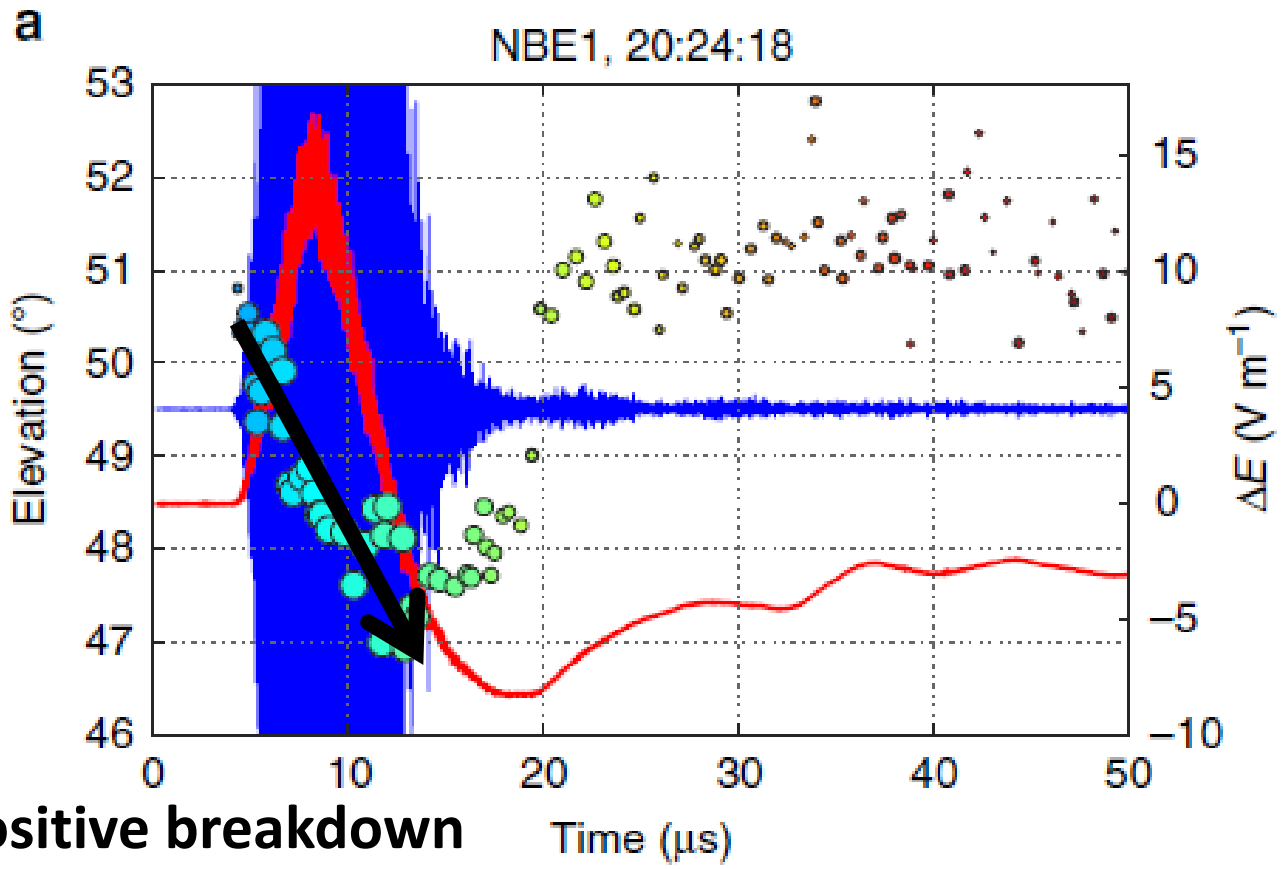


Fast positive breakdown

(system of ~10^7 m/s positive streamers)

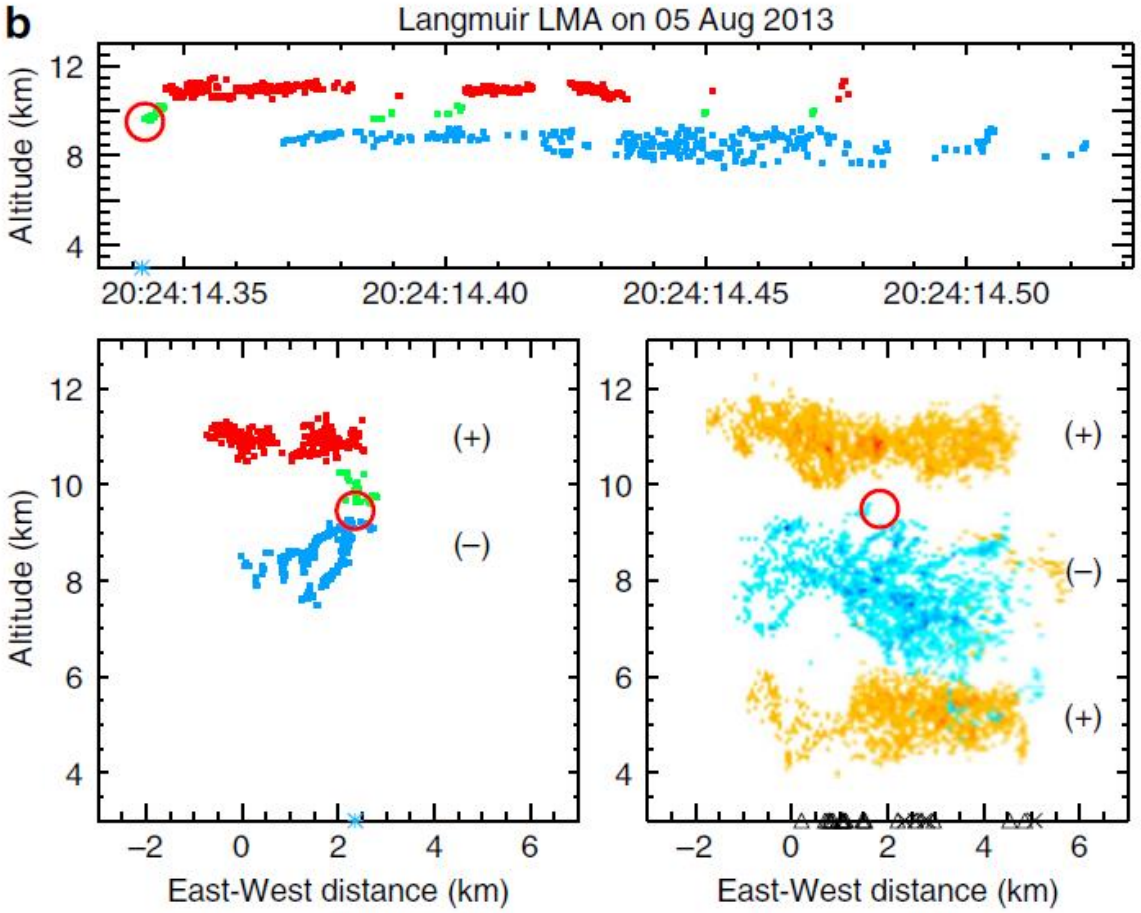
Rison et al., 2016

9.4 Early (active) stage of cloud discharges

→ Leader forms at some point after streamers, likely during IBPs.

→ Leader speeds of 10^4 to 10^5 m/s, typical currents of 0.1 to 1 kA, line charge density of about 0.5 to 1 C/km.

→ Vertical extent reached in first 10s of milliseconds of flash.



Rison et al., 2016

9.5 Late (final) stage of cloud discharges

→ The final 50-200 ms of IC flash.

→ Similar to inter-stroke intervals of CG/ after last stroke of CG.

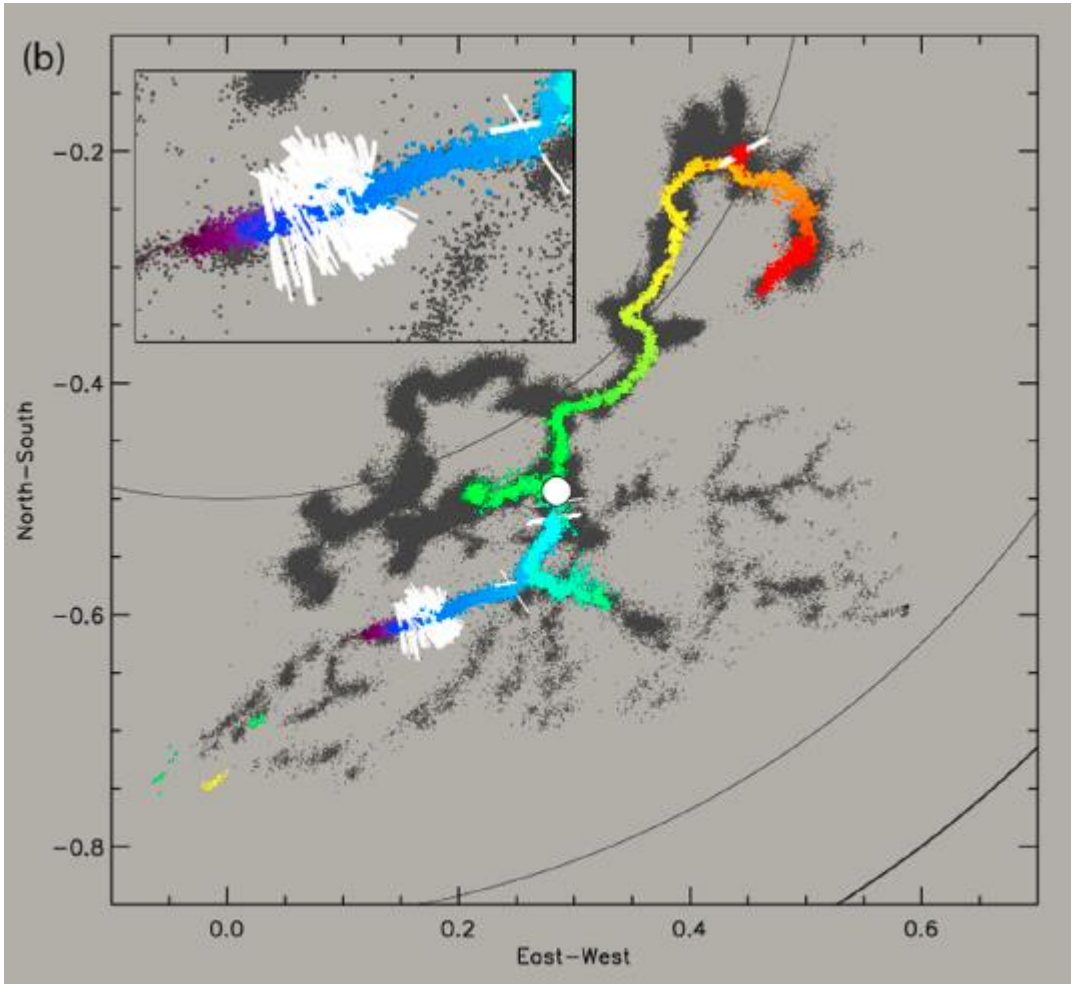
→ J- (~10^4 m/s positive leader) and K-changes (~10^7 negative recoil leader) taking place, and regular pulse bursts.

9.5 Late (final) stage of cloud discharges

K-change (negative recoil leader)

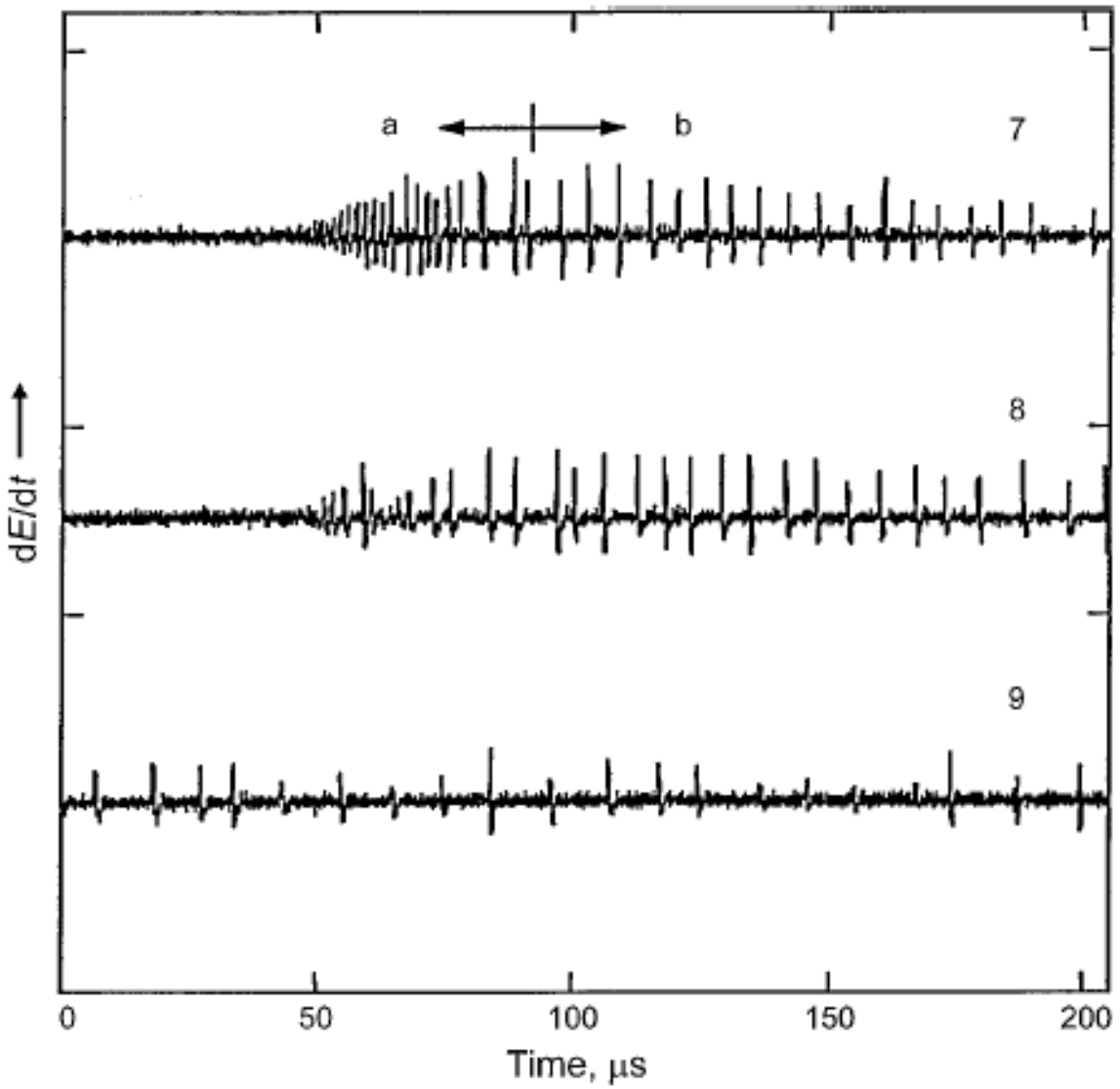
→ ~1.4 C transferred.

→ ~1.4 A.



9.5 Late (final) stage of cloud discharges

Regular pulse burst
→ ~20 pulses/ burst.
→ ~5 μs inter-pulse.
→ ~100 μs long.



9.5 Late (final) stage of cloud discharges

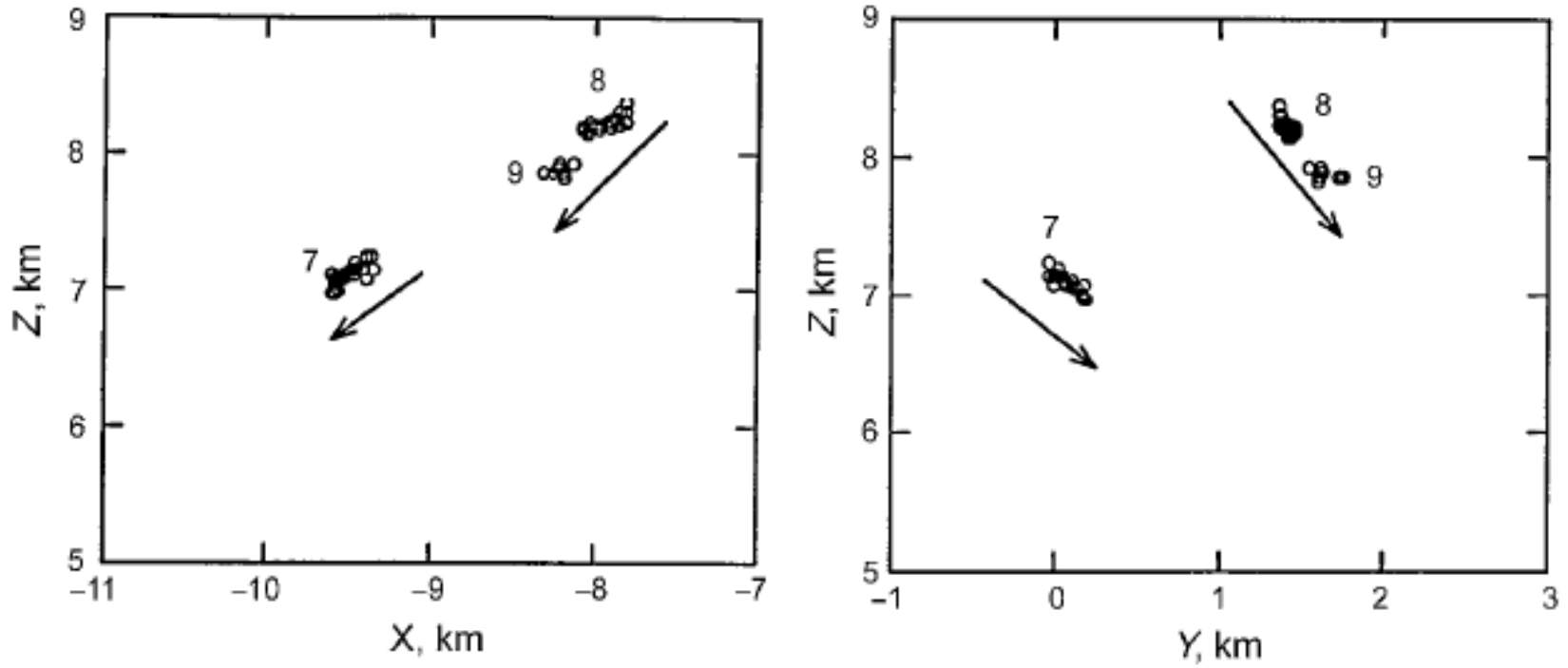
Regular pulse burst

→ ~20 pulses/ burst.

→ ~5 μs inter-pulse.

→ ~100 μs long.

→ Similar to dart-stepped leader, with ~10^6 m/s.

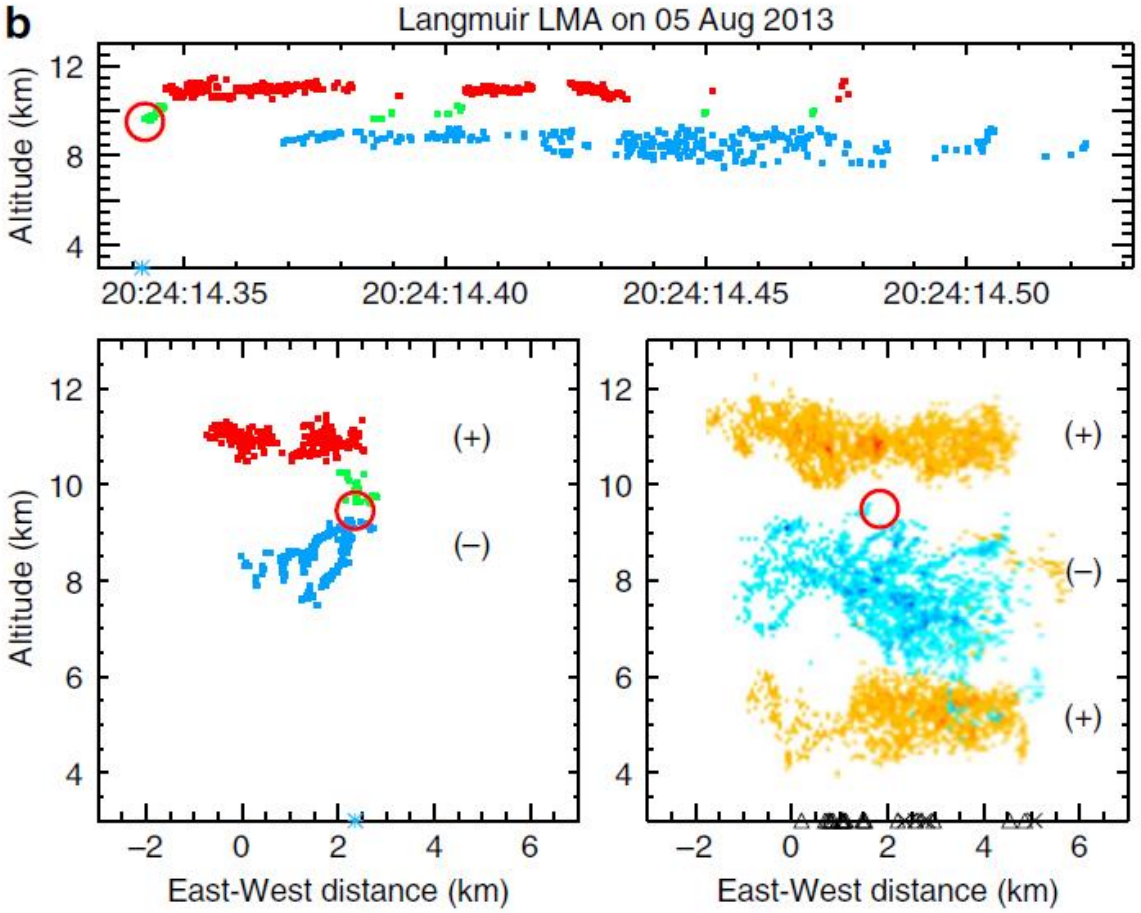


9.6 Comparison of cloud and ground discharges

→ 10s-100s kA stepped leader.

→ IBP E-field polarity opposite for IC and CG discharges.

→ ~10x longer inter-pulse interval for IC IBPs than CG IBPs → IBPs may just be negative stepped leader.



9.6 Comparison of cloud and ground discharges

→ 10s-100s kA stepped leader.
→ IBP E-field polarity opposite for IC and CG discharges.
→ ~10x longer inter-pulse interval for IC IBPs than CG IBPs → IBPs may just be negative stepped leader.
→ ~10^5 m/s initial leader propagation speed.
→ Regular pulse burst (i.e., maybe dart-stepped leader?) similar for both IC and CG discharges.

9.7 Summary of cloud discharges

→ IC initial stage: NBEs and IBPs.
→ IC final stage: recoil leaders and dart-stepped leaders.
→ IC discharge initiated between main negative charge and upper positive charge in cloud.
→ NBEs are likely a streamer process involved in lightning initiation.
→ IBPs involved in initial leader development, probably.
→ Final stage occurs when disconnection of lightning channels in the two charge regions of cloud.
→ K- and J-process transfer negative charge toward lightning origin.
→ K- and J-process similar in ICs and CGs.
→ Regular pulse bursts similar in ICs and CGs.