

Lightning Initiation from Fast Negative Breakdown is Led by Positive Polarity Dominated Streamers

Anjing Huang¹, Steven Cummer¹, and Yunjiao Pu¹

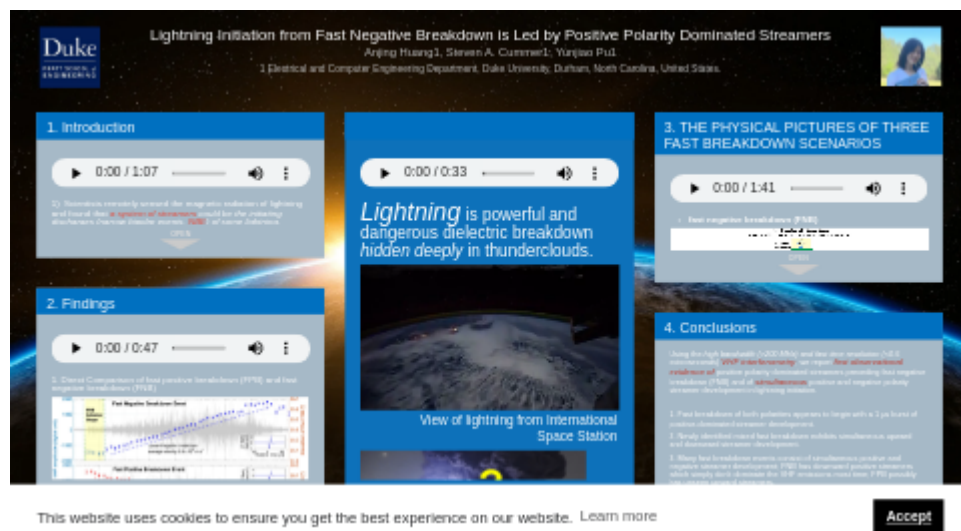
¹Duke University

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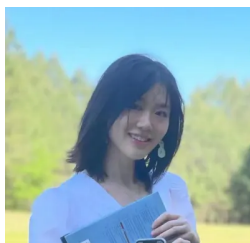
Abstract

Lightning is a magnificent natural experiment of dielectric breakdown on a vast scale, providing us rare opportunities to explore this powerful and dangerous phenomenon hidden deeply in the thunderclouds. Specifically, how lightning is initiated in the insulating air is still poorly understood. Using the radio-imaging technique, scientists remotely sensed the very-high frequency (VHF) radiation of lightning and found that a system of positive polarity streamers, named fast positive breakdown (FPB), could be the initiating discharges of some lightning. Streamers are potential plasma waves composed of ionized air molecules, which can gradually transition the insulating air into hot, high conductivity lightning plasma channels. Recently, lightning has also been reported to be initiated by a burst of negative polarity streamers, called fast negative breakdown (FNB). However, the laboratory experiments and simulations of dielectric breakdown suggest that FPB should be more readily produced compared with FNB. Here, we use our high bandwidth (>200 MHz) and fast time resolution (<0.5 microseconds) VHF radio-imaging system, reporting the first observational evidence of FPB preceding FNB and of simultaneous development of positive and negative polarity streamers in lightning initiation. These observations represent a significant addition to our current physical understanding of natural dielectric breakdown in thunderstorms.

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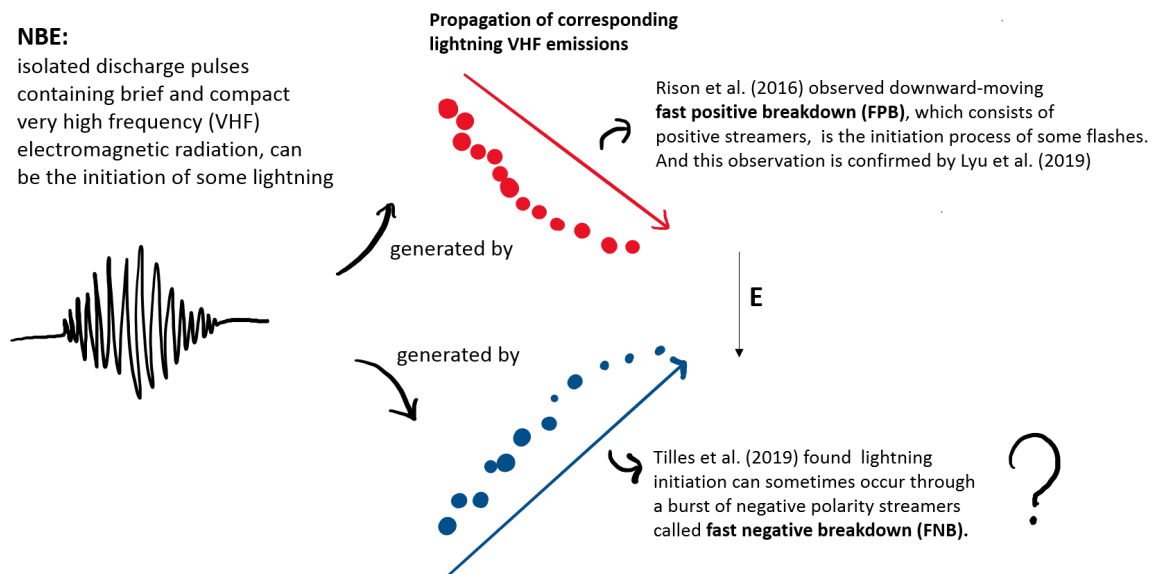


1. INTRODUCTION

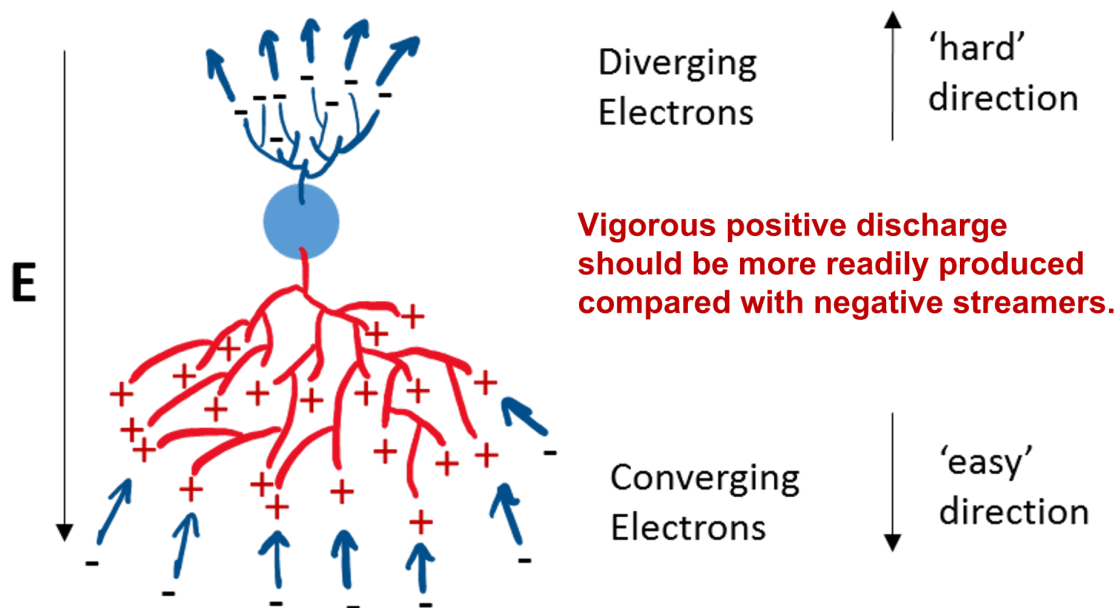
1) Scientists remotely sensed the magnetic radiation of lightning and found that *a system of streamers could be the initiating discharges (narrow bipolar events, NBE) of some lightning.*

NBE:

isolated discharge pulses containing brief and compact very high frequency (VHF) electromagnetic radiation, can be the initiation of some lightning



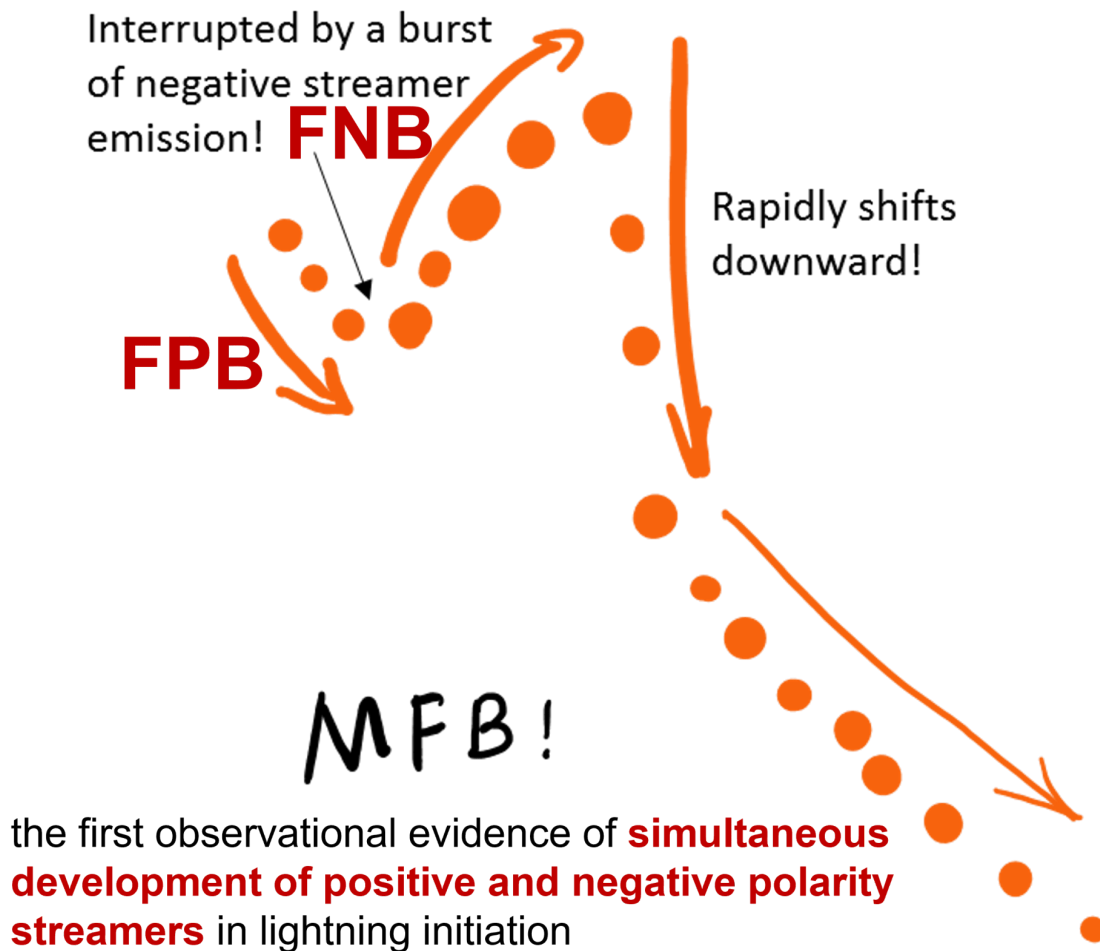
2) However, lightning initiated by negative streamers alone (**FNB**) is inconsistent with laboratory experiments.



(depicted according to Figure 7 from Williams et al. (2006). The red branches represent the development of positive streamers, FPB; The blue branches represent the development of negative streamers, FNB; The plus and minus signs are positive and negative charges, respectively)

The lack of a viable explanation for the FNB observation has made this phenomenon a real puzzle!

3) We also provide further new insight from observations of previously unidentified *mixed fast breakdown* (*MFB*)!



2. FINDINGS

1. Direct Comparison of fast positive breakdown (FPB) and fast negative breakdown (FNB)

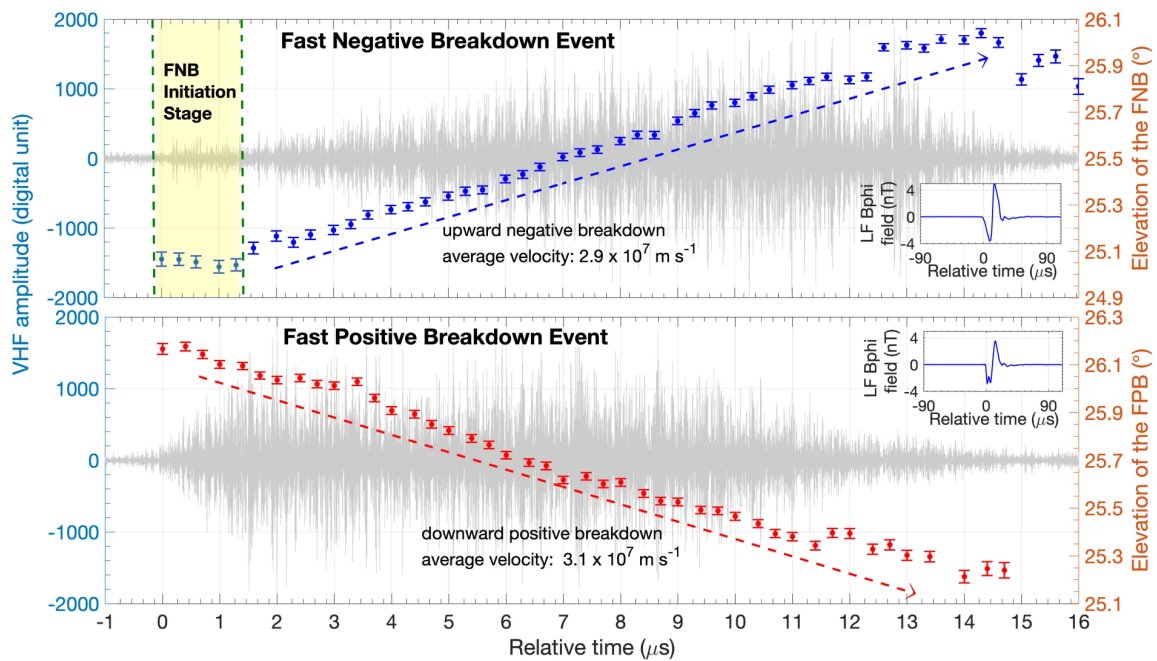


Figure 1. The interferometer data for an FNB (top) and FPB (bottom).

- 1) These two fast breakdowns occurred within 43 seconds on 11 June 2020, at 22:17:52 UTC and 22:18:35 UTC with the corresponding NLDN locations separated by only 740 meters
- 2) The key feature is that the first 1.5 μs of the FNB event exhibits downward motion
- 3) This suggests that the initiation stage of FNB involves positive streamers before transitioning to dominant VHF emissions from negative streamers

2. Further Insight from Mixed Fast Breakdown (MFB)

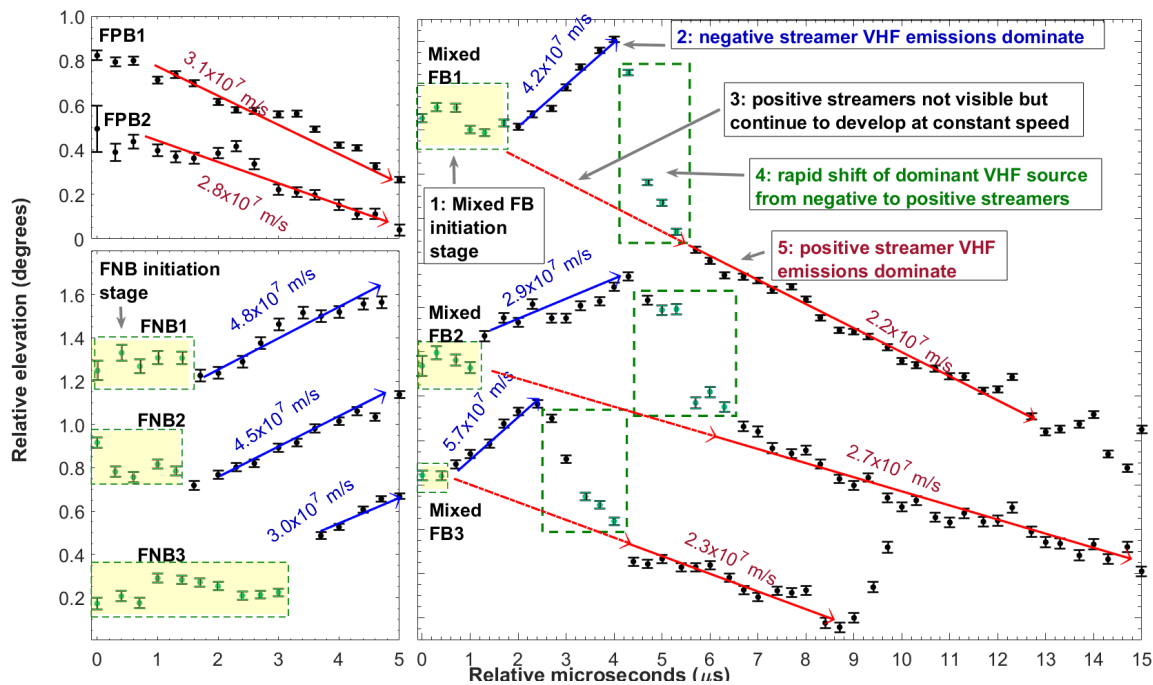


Figure 2. VHF time-elevation plots for 2 fast positive breakdowns, 3 fast negative breakdowns, and 3 mixed polarity breakdowns. All the narrow bipolar events discussed in this iposter are positive. The red dashed line and blue dashed line respectively mark the propagation dominated by positive and negative polarity streamers. The yellow rectangles highlight the initiation stages of FNB and MFB when streamers exhibit downward or ambiguous motion.

1) If we connect the trajectory from initiation to the downward portion of MFB (as the red dashed lines in the figure), the resulting time-elevation line is essentially a continuous descent → **Positive streamers propagated continuously downward throughout the entire MFB**

2) The abrupt transition from upward to downward sources exhibits an apparent velocity that is too fast (>10 ms) for fast breakdown propagation → **This fast shift is an artifact of the change from negative dominant to positive dominant VHF emissions**

Lightning is powerful and dangerous dielectric breakdown *hidden deeply* in thunderclouds.

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638762710/agu-fm2021/2B-16-B1-D2-81-5F-8D-B3-2A-8A-A4-30-9D-D7-C7-97/Video/Global_view_of_lightning_short_rmcaji.mp4

View of lightning from International Space Station



Thunderclouds provide environments for magnificent natural experiments of dielectric breakdowns on vast scales.

How lightning is initiated in the thunderclouds is not well understood.

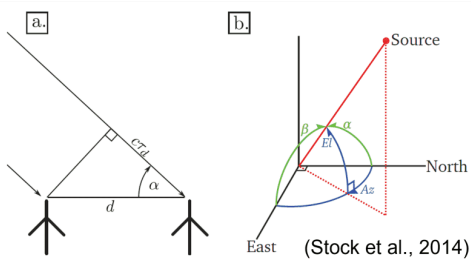
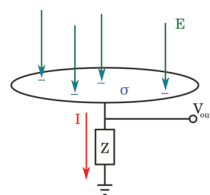
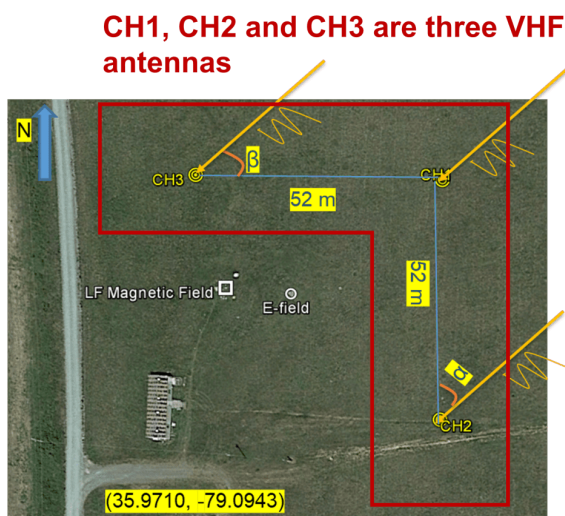


Could lightning also be produced by gaining powers through exposure to heavy water like the Flash?

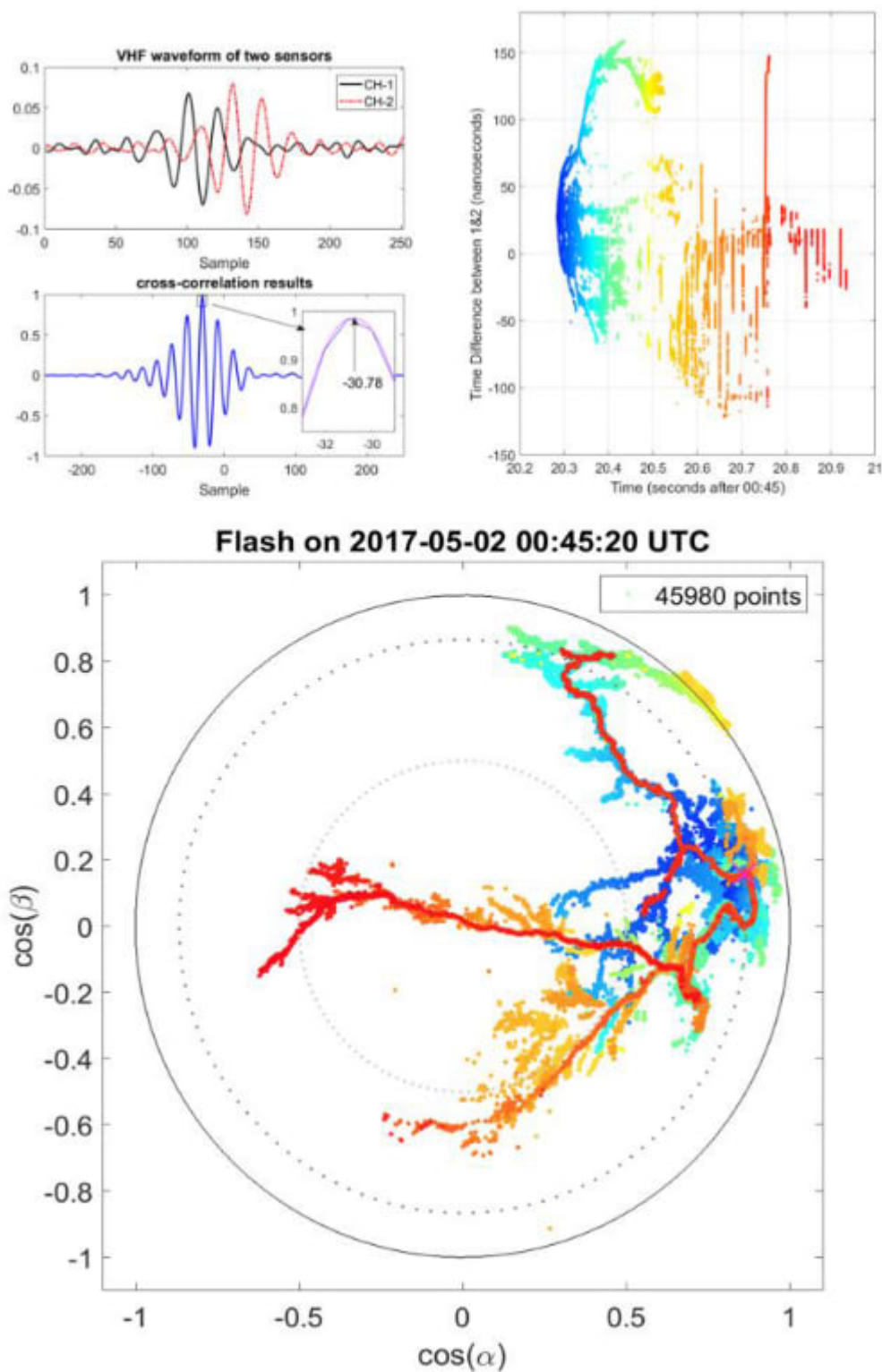
So, how do we deliver details of lightning initiation with high-level resolution?

Since early 2019, our updated very-high frequency (VHF) interferometer system installed near Duke University (35.9710 °N, -79.0943 °E) has captured and imaged the VHF radiation from nearby lightning flashes. The system features a 500 MS s⁻¹ sampling rate and a 200 MHz bandwidth (*Pu et al.* 2019) and consists of three discone VHF antennas creating two orthogonal 52 m baselines (*Lyu et al.* 2019). The high

data-sampling-rate corresponding bandwidth provides the ability to process data with sub-microsecond time resolution. As a result, we can spatially resolve the streamer motion at the very beginning of lightning initiation.



Using the time differences between the arrival time of lightning VHF radiation at different antennas, we can obtain the location of lightning radiation sources



Cummer and Lyu (2017)

(Top left: Sample short windows of data from two VHF sensors, showing how the time difference between the two signals can be measured from signal cross-correlation. Top right: The whole flash yield a nearly continuous distribution of signal time differences. Bottom: The time differences from orthogonal baselines map to azimuth and elevation, which yield a detailed view of the spatial and temporal development of the flash.)

3. THE PHYSICAL PICTURES OF THREE FAST BREAKDOWN SCENARIOS

- **fast negative breakdown (FNB)**

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639031634/agu-fm2021/5C-8F-C5-51-40-04-FE-E8-F5-CB-75-0D-9E-28-32-4A/Video/movie2_m9clq7.mp4

1. FNB has a 1-3 μ s duration positive streamer-dominated initiation stage
2. In FNB, the upward negative streamers never weaken and always dominate after the initiation stage
3. Unseen positive streamers may continuously develop during FNB (but remain undetected due to the dominant VHF emissions from negative streamers)

- **fast positive breakdown (FPB)**

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639031675/agu-fm2021/5C-8F-C5-51-40-04-FE-E8-F5-CB-75-0D-9E-28-32-4A/Video/movie1_cotn9s.mp4

1. In FPB, only positive streamers are seen throughout
2. FPB is the most commonly observed FB scenario
3. It remains an open question whether weakly-emitting upward negative streamers develop unseen during FPB

- **mixed fast breakdown (MFB)**

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1639031693/agu-fm2021/5C-8F-C5-51-40-04-FE-E8-F5-CB-75-0D-9E-28-32-4A/Video/movie3_wlrugh.mp4

1. MFB also has a 1-3 μ s duration positive streamer-dominated initiation stage, identical to FNB
2. Negative streamers weaken soon; MFB then rapidly switches back to VHF emissions dominated downward positive streamers
3. The positive streamer in MFB events continuously propagate with constant velocity downward motion after initiation (even being unseen when negative streamers dominate)

We suggest that:

- 1) All three types of FB begin as the same positive streamer-dominated initiation stage;
- 2) Subsequent development into FPB, FNB, or MFB depends on whether the dominant VHF source switches to negative streamers (FNB and MFB) and then switches back to positive streamers (MFB).

4. CONCLUSIONS

Using the *high bandwidth* (>200 MHz) and *fast time resolution* (<0.5 microseconds) *VHF interferometry*, we report *first observational evidence of* positive polarity dominated streamers preceding fast negative breakdown (FNB) and of *simultaneous* positive and negative polarity streamer development in lightning initiation.

1. Fast breakdown of both polarities appears to begin with a 1 μ s burst of positive-dominated streamer development.
2. Newly identified mixed fast breakdown exhibits simultaneous upward and downward streamer development.
3. Many fast breakdown events consist of simultaneous positive and negative streamer development; FNB has downward positive streamers which simply don't dominate the VHF emissions most time; FPB possibly has unseen upward streamers.

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ABSTRACT

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