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Key Points:

- Fast breakdown of both polarities appears to begin with an around 1 μ s burst of positive-dominated streamer development
- Newly identified mixed fast breakdown exhibits simultaneous upward and downward streamer development
- We conjecture that many fast breakdown events consist of simultaneous positive and negative streamer development

Correspondence to:




S. A. Cummer,
cummer@ee.duke.edu

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

Anjing Huang¹ , Steven A. Cummer¹ , and Yunjiao Pu¹ 

¹Electrical and Computer Engineering Department, Duke University, Durham, NC, USA

Abstract Evidence of positive polarity dominated streamers preceding fast negative breakdown (FNB) and of simultaneous positive and negative polarity streamer development in lightning initiation is reported. Observations of lightning initiation as FNB have remained a puzzle because simulations of lightning initiation have shown that negative streamers are not produced in virgin air without simultaneous positive streamers. Here, the authors observe positive streamer development forms first or at least simultaneously with negative streamers. Further evidence comes from observations of mixed fast breakdown (FB). The overall trajectory of the positive breakdown during such mixed events indicates that the positive streamers continuously propagate during the burst of strong negative breakdown. These observations indicate that even when negative streamers dominate the overall very high frequency (VHF) emissions, both positive and negative streamers are propagating simultaneously from the initiation point. These findings on the structure and dynamics of FB provide key new insight to our understanding of lightning initiation.

Plain Language Summary Lightning initiation remains a complex and poorly-understood process. Recent observations have indicated that lightning initiation can sometimes occur through a burst of negative polarity streamers called FNB. However, our understanding of streamer initiation says that positive polarity streamers should always initiate first. We used high bandwidth and fast time resolution VHF interferometry to examine in greater detail of the development of FB during first several microseconds. We find strong evidence that FNB in fact begins with streamer systems containing positive streamers, and transitions to negative streamer dominance after 1–2 μ s. Further evidence for unseen positive streamer development comes from observations of mixed FB, in which a strong burst of negative streamers masks the development of continuous positive streamers that become visible only after the negative streamer emissions get weakened. These observations show that even when negative streamers dominate the overall VHF emissions in FB, positive and negative streamers are both likely propagating simultaneously from the initiation point. These observations represent a significant addition to our current physical understanding of lightning initiation.

1. Introduction

Understanding how lightning initiates in air remains a challenging one due to the difficulty of direct observations in a thunderstorm (Marshall et al., 2005; Rakov & Uman, 2003; Smith et al., 1999; Willett et al., 1989). Radio imaging of lightning with broadband interferometry is a widely adopted technique that can effectively detect detailed development of the lightning breakdown and has been improved persistently by many studies (Lyu et al., 2019; Rhodes et al., 1994; Rison et al., 2016; Shao et al., 1995, 2018, 2020; Stock et al., 2014, 2017; Sun et al., 2013; Tilles et al., 2019). Rison et al. (2016) observed isolated discharge pulses containing brief and compact very high frequency (VHF) electromagnetic radiation, termed narrow bipolar events (NBEs), as the initiation of some lightning. The measurements in Rison et al. (2016) also indicated that NBEs are generated by fast positive breakdown (FPB) consisting of positive streamers (Lyu et al., 2019; Stock, et al., 2017). This hypothesis was strongly supported by analyzing the radio spectrum of NBEs (Liu, Dwyer, et al., 2019). Lyu et al. (2019) showed that FPB is not the initiation process of many flashes but confirmed that FPB precisely as described by Rison et al. (2016) does initiate some flashes.

Tilles et al. (2019) found that sometimes the VHF emissions in lightning initiation propagate upward while still producing a net downward electric current. This implies upward propagating negative streamers that Tilles et al. (2019) termed fast negative breakdown (FNB). These measurements also suggested that a system

of negative streamers can develop alone under an extremely nonuniform electric field (Tilles et al., 2019). An alternative explanation had been suggested by Rison et al. (2016) in which the upward motion of the VHF source region is generated by retrograde motion of positive streamers.

These two explanations, however, encounter challenges as physical descriptions of FNB initiation. First, negative streamers produced in virgin air without positive counterparts are inconsistent with laboratory experiments (Petersen et al., 2006, 2014) and with simulations of dielectric breakdown (Koile et al., 2020; Liu, Kosar, et al., 2012). As the critical field of stable negative streamer propagation is twice as the threshold for positive streamers (Bazelyan & Raizer, 2000; Griffiths & Phelps, 1976), vigorous positive discharge should be more readily produced if the ambient electric field is intense enough to give rise to any negative streamers (Simpson, 1926). Mazur (1989) suggested that the inception process should start at a sharp point where the positive streamers are produced prior to the negative streamers, which occur in an opposite direction when the field is sufficiently strong. Moreover, the negative streamers are always absent during the streamer initiation in laboratory experiments and in simulations (Liu et al., 2012; Petersen et al., 2014). Second, Rison et al. (2016) suggested that a weak positive breakdown could be initiated at successive higher altitude to produce an apparent upward propagation pattern. Although the upward motion of FNB reported by Tilles et al. (2019) contained significant scatter that could be a signature of this retrograde motion, Tilles et al. (2019) concluded that the similar speeds, power and extents of FPB and FNB could not be described by the forward and retrograde propagation mechanisms involving positive streamers. Thus, the retrograde mechanism was considered implausible for their FNB observations. Therefore, the lack of a viable explanation for the FNB observations has made this phenomenon a real puzzle, and makes clear that the physical mechanism of the general phenomenon of fast breakdown (FB) and its space-time relationship to streamer propagation is not fully understood.

In this paper, we use high bandwidth (>200 MHz) and high time resolution (<0.5 μs) VHF interferometer measurements to examine closely the details of the development of FPB and FNB in the first several microseconds and gain some insights into the physics of FB. With a high sampling rate (500 MS s^{-1}), short-baseline VHF broadband interferometry system (Lyu et al., 2019; Pu and Cummer, 2019), we analyzed 50 days of data in 2019 and one specific day of data in 2020. Of the 7727 flashes examined from March 15 to October 31, 2019, 84 flashes plus two flashes on June 22, 2020 were clearly initiated by positive NBEs. We find that while the VHF radiation of FPB appears to be dominated by positive streamers throughout the entire process, FNB also commences with weakly downward VHF source motion for the first several microseconds, implying VHF emissions from positive streamers. This consistent initiation pattern of all the FNBs in our dataset appears to indicate that positive streamer development precedes the formation of negative breakdown.

Further new insight comes from observations of previously unidentified mixed polarity FB (MFB), which is initiated by positive streamers and is followed by fast upward source motion just like FNB. But after $4\text{--}5$ μs , the VHF source region rapidly shifts downwards and soon becomes dominated by downward motion expected from positive streamers. Critically, the trajectory of this later downward motion is continuous with the initiation, indicating that the positive streamers continue propagating, unseen in VHF, during the burst of strong negative breakdown. These MFB observations suggest that all forms of FB (positive, negative, and mixed) have, physically, the same basic process. All initiate similarly with positive streamers, and all are followed by simultaneous upward negative and downward positive streamer development. The streamer region that dominates will determine whether the event appears as FPB, FNB, or MFB.

2. Data and Methods

2.1. Measurements

Since early 2019, our updated 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 14-bit digitizer (Spectrum Instrumentation M4i.4451-x8) at a sampling rate of 500 MS s^{-1} with a bandwidth above 200 MHz (Lyu et al., 2019; Pu and Cummer, 2019), and consists of three discone VHF antennas creating two orthogonal 52 m baselines (Lyu et al., 2019). The high data sampling rate with 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.

We identified 86 flashes in our raw database that were initiated by a FB event and clearly exhibited the key feature of FB, namely a strong VHF radiation burst persisting for 10–30 μs with no preceding high-current discharge events (Le Vine, 1980; Rison et al., 2016; Smith et al., 1999). We further selected 60 strongest FB events (digital amplitude higher than 500 units with 14-bit depth). These 60 NBEs constitute the dataset analyzed here, and of these we find 48 (80%) of FPB, 8 (13%) of FNB, and 4 (7%) of mixed FB (MFB, which we define below). The large fraction of FPB confirms that positive streamer dominated events are the most common form of FB in lightning initiation, and that it may require special and uncommon electric fields for upward negative streamers to dominate the VHF emissions.

2.2. Algorithms and Metrics

Because we focus on the initiation dynamics during the first several microseconds of FB, we adopt a short time processing window and limited window overlap to minimize any non-physical smoothing. However, signal-noise-ratio (SNR) degrades as the window is shortened. Here, we employ a two-pass, time-difference processing approach (Shao et al., 2018, 2020) that applies cross-correlation interferometric processing (Stock et al., 2014) twice. With our 500 MHz sampling rate and 200 MHz bandwidth, we are able to generate high quality source locations with the following parameters: a 500-sample (1.0 μs) first-pass time window, a 500-sample first-pass sliding step, a 300-sample (0.6 μs) second-pass time window, and a 150-sample (0.3 μs) second-pass sliding step.

The VHF data waveform were filtered in a 100–200 MHz frequency window (Pu and Cummer, 2019), which we have found provides the cleanest images. We apply additional quality-control post-processing by ensuring time-delay closure along the three baselines (Stock et al., 2014) and requiring a normalized cross-correlation ratio of at least 0.6. In addition, we calculated the angular uncertainty of the VHF source (Stock et al., 2014). This lower bound estimator is roughly proportional to SNR, and involves several key factors during signal processing such as elevation and bandwidth, and thus can give a comprehensive estimation of the uncertainties in the mapping results (Stock et al., 2014). All points shown in this paper show the resulting angular uncertainty error bars. The electric current of all the FB events in the dataset is flowing downward, as expected. The corresponding polarity of the FB is determined based on the propagation direction of the VHF sources (Tilles et al., 2019).

3. Measurements and Findings

3.1. Direct Comparison of FPB and FNB

On June 11, 2020, one FNB and one FPB occurred less than one minute apart (22:17:52 and 22:18:35 UTC) and separated by only 740 m (36.1011° N, –79.2810° E and 36.1070° N, –79.2771° E, according to National Lightning Detection Network, NLDN). Since these two FBs were produced in nearly identical ambient circumstances, and the received signals propagated along essentially identical paths, the effect of any noise or system variations on the signals is minimized.

Figure 1 shows that the VHF waveforms of these FNB and FPB events are similar and both are typical FBs. The FNB event is clearly dominated by upward VHF source motion, while the FPB event is dominated by downward VHF source motion. Both events produce radiated low frequency (LF) fields indicating the downward motion of positive charge. These two events fit the templates for FNB and FPB established by Tilles et al. (2019).

However, the first 1.5 μs of the FNB exhibit quantitatively different VHF source motion than the later portion. These first five points exhibit downward motion ($\sim 10^7 \text{ m s}^{-1}$) that is comparable to the nearly constant velocity downward motion of the corresponding FPB event, although the uncertainties for these points, which are relatively high due to the lower SNR, are also consistent with no net vertical motion. The angular uncertainty on these initial FNB points allows significant uncertainty in this initial velocity, but these points are not consistent with upward velocity comparable to the $2 \times 10^7 \text{ m s}^{-1}$ unambiguously present later in the FNB event.

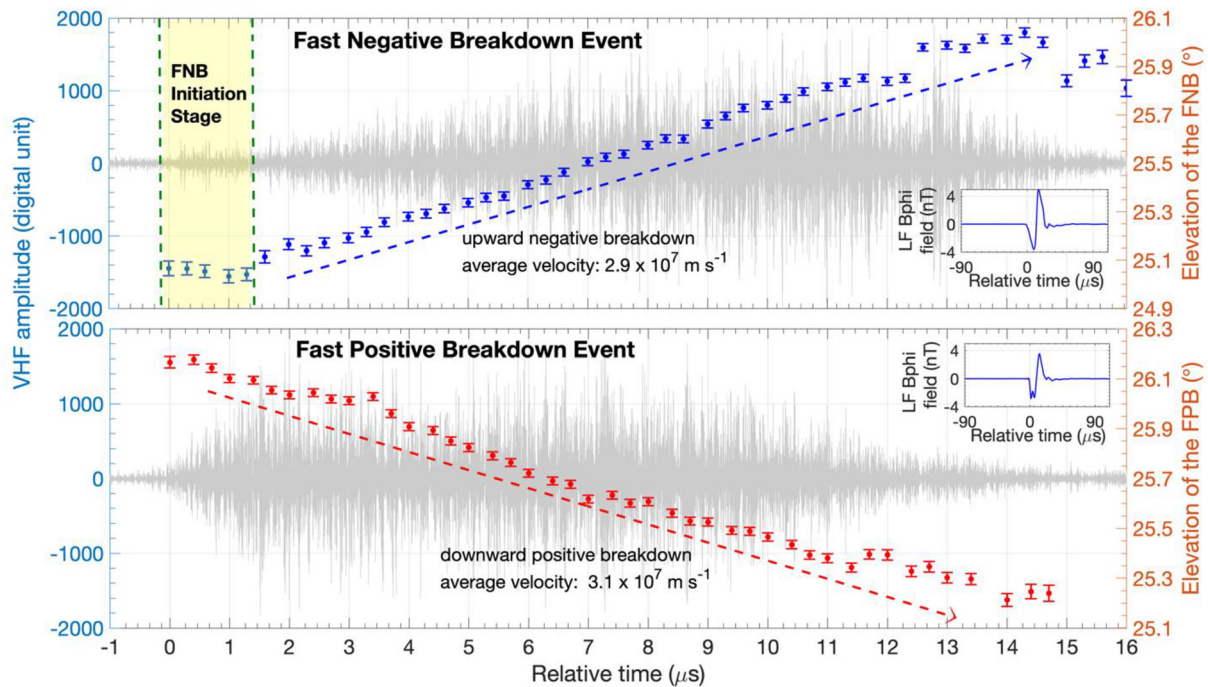


Figure 1. The interferometer data for an FNB (top) and FPB (bottom) that occurred within 43 s on June 11, 2020, at 22:17:52 UTC and 22:18:35 UTC with the corresponding NLDN locations separated by only 740 m. The located VHF points with elevation uncertainties are plotted in elevation versus time and overlaid on the gray VHF waveforms. Inset LF waveforms confirm that both of these events have the same radiated field polarity. The key feature is that the first 1.5 μs of the FNB event exhibits downward motion. This suggests that the initiation stage of FNB involves positive streamers, perhaps in combination with negative streamers, before transitioning to dominant VHF emissions from negative streamers.

These data indicate that this initial FNB window is composed of streamer development that is fundamentally different than the clearly upward and negative polarity streamers occur later in the event. The larger location uncertainties allow for multiple possibilities, but one scenario consistent with the data is that initiation stage is a superposition of simultaneous downward and upward streamers. This finding indicates that both FPB and FNB events could be initiated with either positive streamers or simultaneous positive and negative streamers, before transitioning to dominant positive streamers (for FPB) or negative streamers (for FNB).

This possibility is further supported by observations of additional FPB and FNB events shown in the left panels of Figure 2. The upper left panel shows 2 additional FPB events imaged with our system, both of which exhibit downward motion or, accounting for the uncertainties, no net motion for the first microsecond of the event. Similarly, the 3 additional FNB events in the lower left panel show downward or no vertical motion in 1–3 μs , after which clear upward motion of the VHF sources is seen. Note that the data for FNB3 has a short gap between the initial and subsequent development which is due to a short duration (~ 100 ns) drop in the VHF signal amplitude that resulted in window failing consistency tests during this time, and thus no reliable source location was found. The additional 4 FNBs not shown here exhibit essentially identical features, but they are not as well resolved because they occurred at lower elevation angles.

These observations indicate that FNB events often, and maybe always, originate with streamers that are fundamentally different from the upward propagating, negative polarity streamers that dominate after the initiation stage. Accounting for the location uncertainties in our measurements, the initiation stage of FNB events could be dominated by positive streamers, or composed of a nearly equal-amplitude combination of positive and negative streamers. After a few microseconds, FNB events then transition to dominant VHF emissions from negative streamers. This motivates the question of whether positive streamers continue to propagate downward during the upward negative streamers. A class of FB events described below suggests that the answer is yes.

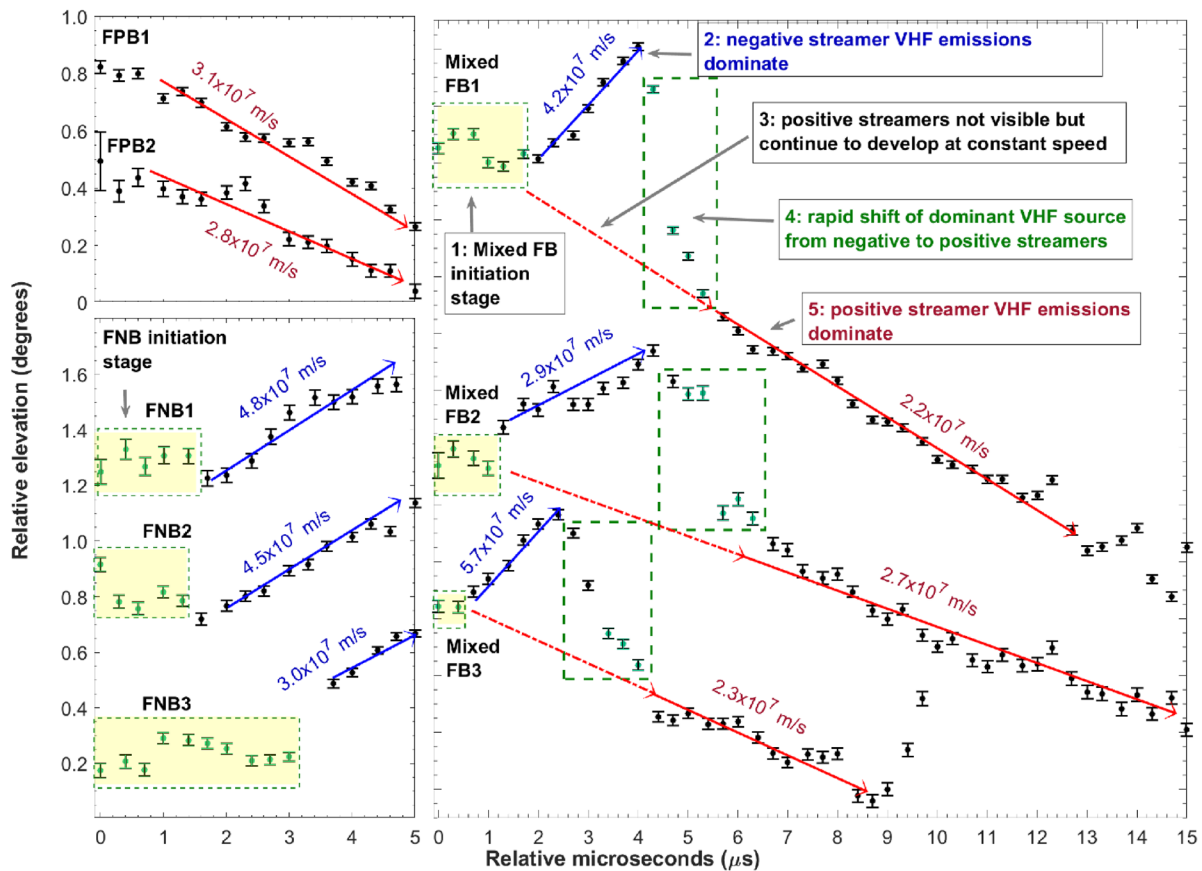


Figure 2. VHF time-elevation plots for 2 FPBs (upper left), 3 FNBs (lower left), and 3 MFBs (right). The elevation uncertainties of the radiation sources are plotted with error bars and overlaid on the radiation sources. The positive polarity streamer dominated propagation is highlighted by red lines and the negative polarity streamer dominated propagation is highlighted by blue lines. The yellow rectangles highlight the initiation stages of FNB and MFB when VHF sources exhibit downward or ambiguous motion. The specific sequence of events in MFB is labeled 1 through 5.

3.2. Further Insight From Mixed Fast Breakdown

Our 60 analyzed FB events contain 4 that do not fit the template of either FPB or FNB, but these 4 events are surprisingly consistent. We call these MFBs because, as shown in the right panel of Figure 2, they contain both upward and downward moving VHF sources. The MFBs start just like FNBs, with a downward propagating initiation stage of several microseconds, followed by a strong burst of upward VHF source motion, presumably associated with negative streamer development.

However, after 2–4 μs of upward source motion, the apparent source location shifts abruptly downward within approximately 1 μs , after which the source motion becomes downward and thus driven by positive streamers, like in FPBs. Remarkably, if we connect the trajectory from initiation to the downward portion of MFB (as the red dashed lines in Figure 2), the resulting time-elevation line is essentially a continuous descent. This feature strongly suggests that positive streamers propagated continuously downward throughout the entire MFB, even during the time window when they were not imaged at VHF due to the simultaneous upward-moving negative streamers that, for whatever reason, emitted more strongly at VHF.

This picture is further supported by the details of the abrupt transition from upward to downward sources. This shift exhibits an apparent velocity that is too fast ($>10^8$ ms^{-1}) for FB propagation (Stock et al., 2017). We thus interpret this fast shift as an artifact of the change from negative dominant to positive dominant VHF emissions. During the transition, the VHF processing identifies weighted source locations between the true source locations of the upward and downward streamers (Shao et al., 2020).

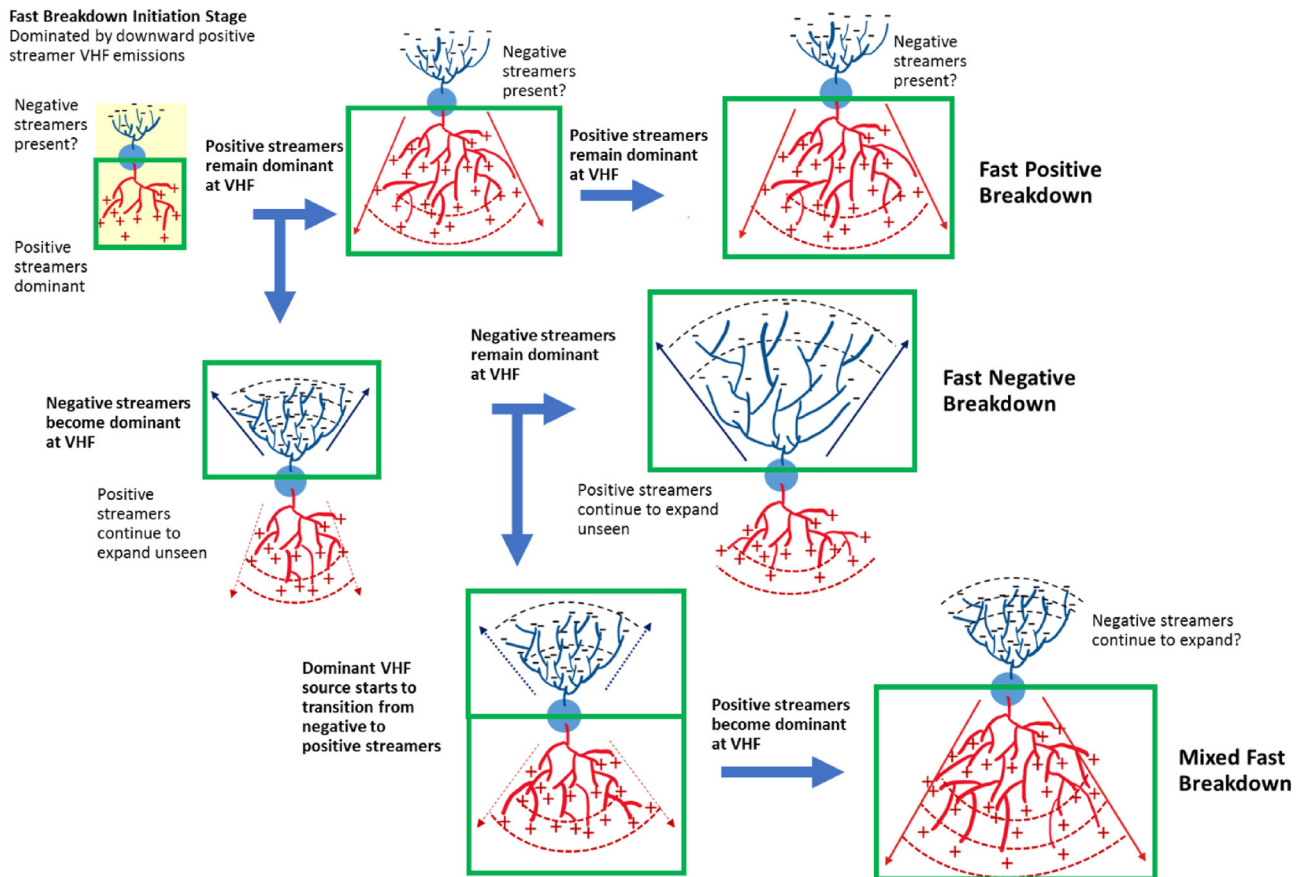


Figure 3. Illustration of the sequence of events of the development of FPB, FNB, and MFB synthesized from the observations shown. We suggest that all three types of FB begin as the same positive streamer-dominated initiation stage. Subsequent development into FPB, FNB, or MFB depends on whether the dominant VHF source switches to negative streamers (FNB and MFB) and then switches back to positive streamers (MFB).

These MFB events are strong evidences, which prove that simultaneous and continuous downward positive and upward negative streamer development occurs in FB. Even when the streamers of one polarity dominate the overall VHF emissions, the streamers of the other polarity continue to propagate. The nature of correlation-based VHF interferometric mapping only allows whichever streamers are instantaneously stronger at VHF to be seen.

Moreover, these different types of FB events may be more similar than they appear at first. MFB and FNB events, in particular, appear to be, physically, the same process. Both initiate with positive or mixed streamer polarity, and quickly transition to upward negative streamers that dominate the VHF emissions. In MFBs, we have shown that positive streamers continuously propagate downward throughout the event, but they become the dominant VHF source only after the negative streamers weaken. In FNBs, it seems likely that positive streamers also continuously propagate downward throughout the event, but never become the dominant VHF source and are thus never explicitly imaged. In FPBs, positive downward streamers dominate throughout, but there also could be weaker simultaneous upward negative streamers that are not imaged at VHF.

4. Synthesis and Discussion

Figure 3 illustrates a physical picture based on our overall observations that indicate that FPB, FNB, and MFB are more closely related than previously observed.

FNB and MFB share the 1–3 μ s duration positive streamer-dominated initiation stage before switching to VHF emissions dominated by upward negative streamers. At this stage, FNB and MFB appear essentially

identical. MFB then rapidly switches back to VHF emissions dominated by downward positive streamers, presumably due to a rapid weakening of VHF from the upward negative streamers. In FNB, in contrast, the upward negative streamers never weaken and always dominate after the initiation stage. The only significant difference between FNB and MFB seems to be whether the upward negative streamers weaken or not during the overall development.

The role of positive streamers after the initiation stage of FNB and MFB is also interesting. As seen clearly in Figure 2, the later downward positive streamer trajectory in MFB events indicates continuous, constant velocity downward motion after initiation, even though the positive streamers are not detected during the time when the upward negative streamers dominate the VHF emissions. Physically, this is not a surprise, as simulations (Koile et al., 2020), lab measurements (Petersen et al., 2008), and indirect measurements of the background electric field in lightning initiation regions (Cummer, 2020) all indicate that negative streamers are accompanied by positive streamers. This also strongly suggests that unseen positive streamers are continuously developing during FNB, but that they are never detected directly because the negative streamers always dominate the VHF emissions.

In FPB, only positive streamers are mapped throughout. It is possible that FPB also fits the FNB/MFB template described above, with a similar initiation stage dominated by VHF from positive streamers, followed by a development stage that remains dominated by positive streamers but is accompanied by weaker upward negative streamer development. FPB is the most commonly observed FB scenario, which suggests that it is something unusual (perhaps related to the local electric field distribution) that enables negative streamers to dominate the VHF emissions for a portion of MFB or the entire FNB development stage. It remains an open question whether weakly emitting upward negative streamers develop unseen during FPB.

The observations of a positive streamer dominated initiation stage for FNB and MFB appear to solve the puzzle identified in previous FNB observations (Tilles et al., 2019). In a wide range of previous work, the positive corona streamer development is identified as the initial process in lightning development (Griffiths & Phelps, 1976; Koile et al., 2020; Lyu et al., 2019; Petersen et al., 2008). Yet previously reported FNB measurements gave no clear indication of activity other than upward negative streamers. As shown in Figures 1 and 2, with higher time resolution and higher VHF bandwidth, one can see that there is a short-time window at the beginning of FNB and MFB events in which the streamers move downward or ambiguously before transitioning to clear upward motion. This is the initiation stage shown at the top of Figure 3, which typically lasts for 1–3 μs and during which the streamers exhibit a high average velocity ($\sim 10^7 \text{ ms}^{-1}$).

As has been noted by previous authors, simultaneous development of negative and positive streamers is consistent with our understanding of the underlying physics. The lightning initiation model of Griffiths and Phelps (1976) described how a succession of overlapped positive streamers would deliver negative charge back to the streamer initiation point and significantly boost the local electric field to help initiate negative streamer breakdown from the same point (Attanasio et al., 2019). Once that occurs, the positive space charge produced from negative breakdown could also feed into the initiation point to reinforce the development of positive breakdown in return. Our observations of MFB indicate that this simultaneous development of streamers of both polarities does occur at least few times. Whether FNB and FPB events also contain both streamer polarities while only one is mapped by VHF interferometry merits further investigation.

5. Conclusions

In conclusion, we have probed the development of FB in lightning flash initiation with high spatial and temporal resolution. We find significant evidence that all types of FB initiate as either positive polarity or mixed polarity streamers, including the FB events that become FNB. Our observations appear to solve the inconsistency of previous FNB observations (Tilles et al., 2019) containing only upward negative streamer propagation with recent simulation results (Koile et al., 2020) indicating that FNB cannot be initiated only by negative streamers without positive counterparts. This FB initiation stage typically lasts for 1–3 μs , after which upward negative streamers dominate in FNB events.

Additionally, we identify an uncommon (<10%) new type of FB event that we call MFB which provides additional new insight into the FB process. MFB begins with an initiation stage followed by upward negative

streamers, like FNB, but then quickly transitions to downward positive streamers. Importantly, the later positive streamer development follows almost exactly a trajectory that points back to the initial source and location. This strongly suggests that positive streamers continuously propagate downward during MFB events, but they are simply not visible during the stronger VHF emissions of the upward negative streamers. This further indicates that unseen downward positive streamers may propagate throughout FNB events as well, and perhaps even that unseen upward negative streamers may propagate throughout FPB events. FPB, FNB, and MFB events may be the manifestations of the same physical processes, but with apparent observational differences due to different relative strengths of the VHF emissions from the positive and negative streamers.

These observations represent a significant addition to our current physical understanding of lightning initiation and the electrode-less initiation of dielectric discharge in general. Further measurements with even higher time resolution and the ability to image simultaneous VHF source locations could provide important confirmation of the findings presented here.

Data Availability Statement

This work complies with the AGU data policy. The NLDN data are available at <https://www.vaisala.com/en/products/data-subscriptions-and-reports/data-sets/nldn> website. The lightning data are available at the data repository link: <https://doi.org/10.7924/r44m97j8v>.

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