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Key Points:
• Relativistic runaway electrons from extensive air showers start electron avalanches in many small volumes with electric field >3 MV/(m·atm)
• Lightning initiation occurs when many ordinary positive streamers, with speeds of 0.1–1×10⁶ m/s, develop from these electron avalanches
• Mechanism accounts for variety in observed characteristics of initiating event, initial electric field change, and initial breakdown pulses

Supporting Information:
• Supporting Information S1

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Abstract Based on experimental results of recent years, this article presents a qualitative description of a possible mechanism (termed the Mechanism) covering the main stages of lightning initiation, starting before and including the initiating event, followed by the initial electric field change (IEC), followed by the first few initial breakdown pulses (IBPs). The Mechanism assumes initiation occurs in a region of ~1 km³ with average electric field $E > 0.3$ MV/(m·atm), which contains, because of turbulence, numerous small “$E_{th}$ volumes” of ~$10^{-4}$–$10^{-3}$ m³ with $E \geq 3$ MV/(m·atm). The Mechanism allows for lightning initiation by either of two observed types of events: a high-power, very high frequency (VHF) event such as a Narrow Bipolar Event or a weak VHF event. According to the Mechanism, both types of initiating events are caused by a group of relativistic runaway electron avalanche particles (where the initial electrons are secondary particles of an extensive air shower) passing through many $E_{th}$ volumes, thereby causing the nearly simultaneous launching of many positive streamer flashes. Due to ionization-heating instability, unusual plasma formations (UPFs) appear along the streamers’ trajectories. These UPFs combine into three-dimensional (3-D) networks of hot plasma channels during the IEC, resulting in its observed weak current flow. The subsequent development and combination of two (or more) of these 3-D networks of hot plasma channels then causes the first IBP. Each subsequent IBP is caused when another 3-D network of hot plasma channels combines with the chain of networks caused by earlier IBPs.

1. Introduction
Despite great efforts by the scientific community, there is still no generally accepted, qualitatively consistent mechanism of lightning initiation from the initiating event (IE) through the subsequent development to the beginning of a stepped leader (e.g., Dwyer & Uman, 2014; Gurevich & Zybin, 2001; Rakov & Uman, 2003). This situation is partly due to the exceptional complexity of the lightning phenomenon, which requires both experimental and theoretical knowledge about lightning itself, along with information from high-energy atmospheric physics, radio physics of atmospheric discharges, physics of turbulent multiphase charged aerosols, gas discharge physics at high pressure, and physics of long sparks. This list could easily be extended. However, after recent significant progress in experimental and theoretical work, there is now an acute need for at least a qualitative construction of a single mechanism describing in space and time the origin and development of lightning.

As far as we know, only Petersen et al. (2008) have attempted to describe the initiation of lightning from the first streamer to the appearance of a negative stepped leader. Prior to Petersen et al. (2008), the problem of lightning initiation was primarily concerned with the appearance of the first avalanche or the first streamer. Based on measurements with a very high frequency (VHF) interferometer operating at 20–80 MHz, Rison et al. (2016) “tentatively” concluded that the initiating event of all lightning flashes is a narrow bipolar event (NBE) caused by “fast positive breakdown” (FPB). The NBEs investigated had apparent speeds of 4–10×10⁶ m/s. Attanasio et al. (2019) recently proposed a FPB propagation mechanism, based on a modernization of the Griffiths and Phelps model (Griffiths & Phelps, 1976) describing initiation of lightning due to a powerful streamer flash from hydrometeors. Using an electric field change sensor (called a “fast antenna” or “FA” with a typical bandwidth of 0.1–2,500 kHz), typical isolated NBEs have a characteristic bipolar waveform with a duration of 10–30 µs and large pulse amplitudes (e.g., Karunarathne et al., 2015; Nag et al., 2010; Willett et al., 1989). Typical NBEs also have large power in the HF/VHF frequency band of 3–300 MHz...
(Le Vine, 1980). For 10 positive NBEs initiating intracloud (IC) flashes, Rison et al. (2016) found peak powers in the VHF band (30–300 MHz) ranging from 1–274,000 W, while for five negative NBEs initiating cloud-to-ground (CG) flashes, they found NBE peak powers ranging from 1–600 W. Tilles et al. (2019) further reported that some positive NBEs are caused by “fast negative breakdown” (FNB) with apparent propagation speeds of $4 \times 10^7$ m/s.

Recent findings suggest that most lightning flashes are not initiated by NBEs; rather, most flashes are initiated by much shorter and much weaker events. Marshall et al. (2019) reported the first examples of flashes with much weaker initiating events. Two IC flashes were initiated by VHF events with durations of 1 $\mu$s and peak VHF powers of 0.09 and 0.54 W; there was no coincident pulse in the FA data of these two flashes. Note that the FA data are primarily measuring charge motions with length scale $>50$ m while the VHF data are primarily measuring charge motions of length $<5$ m, so the lack of an FA pulse with the IE suggests charges moved a distance of order 5 m, but not 50 m. Two CG flashes studied by Marshall et al. (2019) were initiated by VHF events with durations of 1 and 2 $\mu$s and VHF powers of 0.14 and 0.64 W; there was a weak, short duration FA pulse coincident with one of the CG VHF initiating events. Lyu et al. (2019) studied 26 IC flashes that occurred within 10 km of their VHF interferometer and found that NBEs initiated only 3 of the 26 flashes; the other 23 flashes were initiated by weak VHF events with durations of less than 0.5 $\mu$s. Bandara et al. (2019) investigated 868 negative CG flashes at ranges of 17–125 km and found that only 33 (4%) were initiated by negative NBEs; these relatively weak negative NBEs had VHF powers in the range 1–1,300 W.

In this article, we describe, as a first step, the main stages of a possible Mechanism for the initiation and development of lightning from the IE through the first several classic initial breakdown pulses (IBPs). We recognize from the outset the riskiness of such an endeavor, since many processes and phenomena that form the basis of the Mechanism herein proposed by us have not been studied sufficiently or have not yet been considered in such close relationship with each other. This position of limited knowledge gives considerable space for theoretical speculation. But, in our opinion, the construction of a unified Mechanism composed of a consistent sequence of events also has advantages, as it allows future research to focus on quantitative analysis and improvement of (or substantial changes to) each step of the sequence. Thus, our intent is to improve the understanding not only of separate aspects of lightning development but also of the whole process that combines these key aspects.

For reference, we provide a partial list of terms and abbreviations used in this article:

1. The initiating event (IE) of a lightning flash is the first electromagnetic manifestation of initiation and can be of the weak sort described by Marshall, Stolzenburg, et al. (2014); Marshall et al. (2019); and Lyu et al. (2019) or of the stronger NBE sort as described by Rison et al. (2016) and Lyu et al. (2019). As introduced above, weak IEs have VHF powers $<1$ W and durations $\leq 1$ $\mu$s, while NBEs have orders of magnitude stronger VHF powers and durations of 10–30 $\mu$s.

2. A narrow bipolar event (NBE) is a particular type of electrical event that occurs in or near thunderstorms (Le Vine, 1980). (Note that synonyms for “NBE” include “CID” or Compact Intracloud Discharge and “NBP” or Narrow Bipolar Pulse.) An NBE in FA data has a bipolar waveform with a duration of 10–30 $\mu$s; in the VHF band of 60–66 MHz NBEs have a large power (30,000–300,000 W or 45–55 dBW) (Rison et al., 2016). The FA data for weak NBEs have smaller amplitudes than NBEs and can have either bipolar or “mostly monopolar” waveforms; weak NBEs also have smaller VHF powers of 3–300 W or 5–25 dBW (Rison et al., 2016).

3. An initial electric field change (IEC), as described by Marshall, Stolzenburg, et al. (2014) and Chapman et al. (2017), is a relatively long period (40–9,800 $\mu$s) that begins with the IE and ends with the first classic initial breakdown pulse. Marshall et al. (2019) showed that during the IEC, there are many VHF pulses with durations of 1–7 $\mu$s and that some coincident pairs of FA pulses and VHF pulses seem to increase the IEC (as “enhancing events”).

4. An initial breakdown pulse (IB pulse or IBP) is a bipolar electrical pulse occurring in the first few ms of a flash, typically detected with a FA (e.g., Nag et al., 2009; Weidman & Krider, 1979). The largest IBPs are called “classic IBPs” and are systematically accompanied by VHF pulses in CG flashes (Kolmasova et al., 2019). By our definition classic IBPs have durations $\geq 10$ $\mu$s and amplitudes $\geq 25\%$ of the largest IBP and often have subpulses. Essentially all lightning flashes have a series of IBPs (Marshall, Schulz,
et al., 2014) that occur for a few ms after the IEC; we call the period during which IBPs occur the “IB stage” of the flash. During the IB stage, bipolar pulses smaller in amplitude or shorter in duration than classic IBPs are also IBPs; classic and smaller IBPs may be caused by different processes.

t5. A streamer is a cold plasma, as described, for example, by Raizer (1991). In this article the term streamer means only “ordinary” streamers, which have been observed for many decades in gas discharges and long sparks at pressures of 1–0.3 atm and have a length from centimeters to several meters (Raizer, 1991, pp. 326–338).

t6. An unusual plasma formation (UPF) is a short hot plasma channel as described by Kostinskiy et al. (2015a, 2015b). UPFs often appear as a network of hot plasma channels that are tens of centimeters long.

t7. A positive leader is a hot plasma channel that meets certain conditions of length and ambient electric field such that the leader will be self-propagating as described by Bazelyan, Raizer, and Aleksandrov (2007). Note that with a sufficient electric field of 0.45–0.50 MV/(m-atm) (depending on humidity), a hot plasma channel of any length will be self-propagating.

t8. EE volume, $E_{str}$ volume, $E_{th}$ volume: An EE volume ($0.1–1$ km$^3$) is a region in the thundercloud with average electric field magnitude $E > 0.28–0.35$ MV/(m-atm) and with a large number of charged hydrometeors of different sizes. Hydrometeors can be liquid or solid state, large or small in size, as long as they are plentiful and carry significant electrical charges such that turbulent motions can result in small-scale regions of the EE volume with substantially larger electric fields. An $E_{str}$ volume is a region in the thundercloud with $E \geq 0.45–0.5$ MV/(m-atm); $E$ magnitudes this large are sufficient for the movement of positive streamers in air (Bazelyan & Raizer, 1998). An $E_{th}$ volume (or “air electrode”) is a region in the thundercloud with $E > 3$ MV/(m-atm); $E$ magnitudes this large are sufficient to produce “classic” electron avalanches, which, when fulfilling the Meek’s criterion (Raizer, 1991), can transform into classical gas-discharge streamers. The EE volume can have strongly inhomogeneous electric fields (on a scale of hundreds of meters) and consist of many closely spaced turbulent regions that can be formed by similarly or oppositely charged countercurrent air flows (e.g., Karunarathna et al., 2015; Yuter & Houze, 1995).

t9. An EAS-RREA (extensive air shower—relativistic runaway electron avalanche) (e.g., Dwyer, 2003; Gurevich & Zybin, 2001) occurs when a flow of secondary charged particles of the EAS enters a region hundreds of meters on a side with electric field $E > 280$ kV/(m-atm). For the problem of lightning initiation, EASs with primary particle energies $E_0 \geq 10^{15}$ eV are important (as described later).

2. Experimental and Theoretical Basis of the Mechanism

The Mechanism proposed herein, despite its complexity, is determined and regulated by reliably established experimental and theoretical work. In this section we list (i1, i2, ...) the main observations and theoretical ideas that are considered in the development of our Mechanism.

i1. As introduced above, Rison et al. (2016) used an interferometer to detect VHF radiation during lightning initiation, and they located sources at a rate of roughly one per μs. Three positive NBEs that were IEs of three IC flashes had durations of 10–20 μs and very short, exponentially growing fronts of increasing VHF activity with durations of 1–3 μs. The NBE radiation sources advanced downward with apparent speeds of $4–10 \times 10^7$ m/s over distances of 500–600 m. Bandara et al. (2019) found 33 of 868 CG flashes were initiated by weak negative NBEs, with VHF powers of 1–1,300 W or 0–31 dBW.

i2. Also, as introduced above, Marshall et al. (2019) showed that the IEs of two negative CG flashes and two IC flashes were associated with a weak VHF pulse, not an NBE, having a duration of about 1 μs and a VHF power <1 W. Lyu et al. (2019) showed that 23 IC flashes had an IE that was associated with a weak VHF pulse, not an NBE, with a duration ≤0.5 μs.

i3. Marshall, Schulz, et al. (2014) studied the initiation of 18 CG flashes and 18 IC flashes and showed that for each of the 36 IEs, there was no significant electrical activity for 100–300 ms before each flash. After the IE an IEC occurred in each flash. Chapman et al. (2017) found IEC durations averaged 230 μs for 17 CG flashes (range 80–540 μs) and 2,700 μs for 55 normal IC flashes (range 40–9,800 μs) and some flashes had multiple IECs. The physical process causing an IEC is unknown, but apparently, the effect is to separate and accumulate enough charge to cause the first classic IBP.
i4. Classic IBPs have range-normalized (to 100 km) amplitudes averaging about 1 V/m (Smith et al., 2018) and estimated peak currents of 1–165 kA (Betz et al., 2008; Karunarathne et al., 2014, 2020). High-speed video cameras reveal that there is a bright burst of light with each classic IBP (Campos & Saba, 2013; Stolzenburg et al., 2013, 2014). Stolzenburg et al. (2013) showed and described the light coincident with several series of IBPs in CG flashes as follows: “linear segments visibly advance away from the first light burst for 55–200 μs, then the entire length dims, then the luminosity sequence repeats along the same path” with total lengths of 300–1,500 m during the IB stage. These bursts of light indicate the rapid appearance (in less than 20 μs, the frame rate of the camera) of hot, highly conductive channels which mostly vanish in 40–100 μs; after 2–5 ms the IBPs transition to a negative stepped leader with much weaker luminosity (Stolzenburg et al., 2013).

i5. Gurevitch et al. (1992) and Gurevitch and Zybin (2001) theoretically predicted an important role for cosmic rays in the initiation of lightning. They suggested that in an electric field $E > 218$ kV/(m·atm), cosmic rays can cause avalanches of runaway electrons. Allowance for elastic scattering refined the threshold field of runaway electrons $E > 284$ kV/(m·atm) (Babich et al., 2004; Dwyer, 2003; Lehtinen & Østgaard, 2018). Gurevitch et al. (1999) were the first to suggest that the combined action of EAS and runaway electrons can play a significant role in initiating the first streamer in a thundercloud. Dwyer (2003, 2007) presented a different mechanism for the generation of runaway electrons. For this latter mechanism, positrons and energetic photons produce a positive feedback effect that exponentially increases the number of runaway electron avalanches (Dwyer, 2003, 2007). The Dwyer (2003, 2007) mechanism requires much higher mean electric fields than the Gurevitch et al. (1992, 1999).

i6. Using a balloon-borne electric field meter inside an active thunderstorm, Marshall et al. (2005) estimated that the region where three CG flashes initiated had an average electric field $E > 284–350$ kV/(m·atm) and occupied a volume of 1–4 km$^3$ with vertical and horizontal extents of 300–1,000 m. This volume is an experimental example of an $EE$ volume, as defined above. Based on the first detected VHF source of each flash, the three initiations occurred within 1.1 km of the balloon. Marshall et al. (2005) found that the in-cloud $E$ exceeded the relativistic runaway electron avalanche threshold of 284 kV/(m·atm) for about 100 s before one of the lightning flashes.

i7. Bazelyan and Raizer (1998, 2000); Bazelyan, Raizer, et al. (2007); and Popov (2009) theoretically showed the key role of the “ionization-heating instability” in transforming the cold plasma of positive streamers into a hot plasma channel of a long spark leader (i.e., the streamer-leader transition); this transformation (depending on the current strength) occurs in less than ~0.2–0.5 μs, at a pressure of one atmosphere (da Silva & Pasko, 2013; Popov, 2009). If the concentration of neutral molecules in the atmosphere $n$ decreases with height, then, according to recent theoretical calculations, the development time of ionization-heating instability varies in proportion to $n^{-\alpha}$, where $\alpha$ is in the range from 1 to 2 (Bazelyan, Aleksandrov, et al., 2007; da Silva & Pasko, 2012, 2013; Riousset et al., 2010). We will use the value $\alpha \approx 1$ (Raizer, 1991; Velikhov et al., 1977, pp. 223–227; Riousset et al., 2010) in our estimates, since there is no experimental confirmation of such high values as $\alpha \approx 2$. Herein, we will use the term “ionization-heating instability,” although this concept is called different terms in different scientific fields, including “thermal instability” (Nighan, 1977; Raizer, 1991), “ionization-overheating instability” (Panchenko et al., 2006), and “thermal ionizational instability” (da Silva & Pasko, 2012).

i8. Kostinskiiy et al. (2015a, 2015b) experimentally showed that in electric fields of 500–1,000 kV/(m·atm) within artificially charged aerosol clouds, UPFs are actively initiated, along with bidirectional leaders of 1–3 m length. It was also experimentally shown that in electric fields of 500–1,000 kV/(m·atm), UPFs are generated from the plasma of positive streamer flashes via the ionization-heating instability (Kostinskiiy et al., 2019).

i9. Colgate (1967) suggested that turbulence in a thundercloud can significantly enhance the local $E$ on scales of about 100 m. Trakhtengerts with coauthors theoretically showed that, due to hydrodynamic instabilities, $E$ in a thunderstorm can fluctuate over about 100 m (Iudin et al., 2003; Mareev et al., 1999; Trakhtengerts, 1989; Trakhtengertz et al., 1997). Trakhtengerts and Iudin (2005), Iudin (2017), and Iudin et al. (2019) theoretically estimated that more significant amplifications of $E$ on a smaller scale (10–100 cm) are possible due to the statistical movement of hydrometeors of different sizes and charges in a cloud. Many studies have connected lightning initiation with turbulent air motions in thunderstorms. For example, Dye et al. (1986) studied a small, single-cell thunderstorm with a single main
updraft and adjacent downdrafts. Dye et al. (1986) found that thunderstorm charge generation occurred primarily at the updraft-downdraft interface in the storm. Yuter and Houze (1995) found that multicellular thunderstorms had “a three-dimensional multicellular radar reflectivity pattern that contained a rapidly evolving, complex jumble of updrafts and downdrafts.” Karunarathna et al. (2015) studied the locations of positive NBEs in thunderstorms and found that many positive NBEs occurred in storm regions where the expected large-scale electric field, $E$, was upward pointing (physics convention) while the positive NBEs required a downward pointing field. Karunarathna et al. (2015) inferred that these NBEs probably occurred “in highly dynamic regions (such as contiguous updrafts and downdrafts in and beside the overshooting cloud top) where turbulent motions can stir, fold, and invert oppositely charged regions, thereby leading to a strong negative $E$ (needed for positive NBE initiation) over a very limited distance.” Bruning and MacGorman (2013) studied lightning flash characteristics based on LMA (Lightning Mapping Array) data from two supercell thunderstorms and found that the “shape of lightning flash energy spectrum is similar to that expected of turbulent kinetic energy spectra in thunderstorms,” which suggested that “advection of charge-bearing precipitation by the storm’s flow, including in turbulent eddies, couples the electrical and kinematic properties of a thunderstorm.” Brothers et al. (2018) modeled electrification of a multicellular thunderstorm and a supercell thunderstorm using a large-eddy-resolving model (125 m grid); for both storms they found that large-eddy turbulence caused more regions where breakdown could occur due more closely spaced small pockets of opposite charges.

3. Conditions and Phenomena Which the Mechanism Should Satisfy and Explain

Based on the above experimental and theoretical results, the Mechanism must satisfy the following conditions (c1, c2, ...) and consistently explain the following phenomena:

- **c1.** Overall, The Mechanism should explain how lightning initiation works. The development of the lightning flash should begin immediately after the appearance of the IE. In particular, the Mechanism should explain the series of lightning initiation stages: the IE, the IEC, and the first few classic IBPs in the IB stage. These three initial stages of a flash are followed by the well-understood negative stepped leader stage.

- **c2.** The optical radiation of IEs seems to be quite weak (Stolzenburg et al., 2014, 2020). Thus, the Mechanism should not contain an initial powerful flash of light like the powerful burst of light that occurs during an IBP.

- **c3.** For both types of IEs (NBE or Weak), during the IEC, the Mechanism should develop conducting paths of several kilometers so that significant charge can be stored in corona sheaths and so that charge can flow, thereby producing the IEC.

- **c4.** For IEs that are NBEs (e.g., Rison et al., 2016), the Mechanism should explain the production of the NBE itself, including a short, powerful flash of positive streamers with an exponentially increasing radiation risetime of a few microseconds, a total duration of 10–30 μs, and a very strong VHF signal.

- **c5.** For IEs that are NBEs, before and during the powerful VHF radiation that NBEs produce, the Mechanism must not produce a strongly emitting long hot conductive plasma channel (Rison et al., 2016).

- **c6.** For IEs that are NBEs, the Mechanism should contain a physical process that moves at a speed close to the speed of light to match the experimental data (Rison et al., 2016) while also providing a short duration narrow bipolar pulse in FA data.

- **c7.** The Mechanism should not contradict the well-known and well-tested data on gas discharge physics and the physics of a long spark: for example, propagation speed of positive streamers depending on the electric field; avalanche-streamer transition; streamer-leader transition; and fast attachment of electrons to oxygen molecules. In particular, laboratory measurements show that the speed of positive streamers is usually 1–10 × 10^4 m/s with a maximum of 5 × 10^6 m/s for $E$ of 3–4 MV/(m-atm) (Les Renardieres Group, 1977).

- **c8.** The Mechanism should explain how the first classic IBP (with a current $\geq$10 kA and a bright light burst) is produced so soon after the IE.
4. Some Main Components of the Mechanism

4.1. The IE, EAS-REA, and Avalanche-Streamer Transition

The Mechanism assumes that the IE consists of a three-dimensional (3-D) group of classic electron avalanches rather than a single avalanche. A “classic” electron avalanche develops in an electric field $E \geq 3$ MV/(m-atm). The Mechanism further assumes that most of the classic electron avalanches in the group are started by an electron (or several electrons) freed from atoms by a relativistic electron, relativistic positron, or high energy photon of a relativistic runaway avalanche (Dwyer, 2003; Gurevich & Zybin, 2001), which occurs when a EAS ($E_0 > 10^{15}$ eV) occurs in the region of a strong electric field $E > 0.4$ MV/(m-atm). Text S0 in the supporting information discusses necessary and sufficient conditions needed for classic electron avalanches.

In order for an avalanche to transform into a positive streamer (i.e., undergo avalanche-streamer transition), the avalanche must produce about $10^8 – 10^9$ electrons in a volume of about 0.3–0.5 mm$^{-3}$. This is Meek’s criterion (Raizer, 1991). When this electron density is reached ($2–3 \times 10^8–10^9 \text{ mm}^{-3}$), a strong $E$, created by the polarization of the avalanche head by the cloud $E$, starts a self-sustaining ionization in front of the head. Accordingly, the $E$ of the streamer head begins to exceed several times 3 MV/(m-atm). After that, the streamer begins to move independently. This process is indicated by a rough estimate of the electric field of a sphere of such dimensions. $E = \frac{1}{4\pi \varepsilon_0} \frac{Q}{R^2}$, $E \approx 9 \times 10^9 \cdot (1.6 \times 10^{-19}) \cdot 10^9 / (0.4–0.2 \times 10^{-3})^2 \approx 9–36$ MV/m. But in order for the streamer to be fully formed from one or several initial electrons, $E > 3$ (MV/(m-atm)) is necessary over the entire length of the avalanche growth. This length is determined by Meek’s criterion $\alpha_{eff} \cdot d \approx 20$, where $\alpha_{eff}$ is the Townsend coefficient, which is 10–12 cm$^{-1}$ for air at 1 atm pressure and with $E$ of ~3.0–3.2 MV/(m-atm) (Raizer, 1991). This means that the length of the avalanche when it transforms into a streamer will be about 2 cm at atmospheric pressure (Raizer, 1991) and this length will increase exponentially with height. See Supporting Information S1 for more discussion of the avalanche-positive streamer transition.

4.2. Positive Streamer Flashes

Positive streamer flashes are composed of a large number of positive streamers; positive streamer flashes that start from metal electrodes have been well studied. The task of determining the parameters of a streamer flash in a thundercloud at the time of lightning initiation limits the relevant experimental data to the following parameters: voltage and $E$ risetimes (or fronts) must be >100 $\mu$s, and the size of the “air electrodes” in the cloud must be ≥2–5 cm. We give a detailed explanation of these restrictions in the next section.

4.2.1. The Front and Duration of a Typical Individual Positive Streamer Flash

Figure 1a shows a typical current oscillogram of a streamer flash on the electrodes with a diameter of ~5–25 cm in discharge gaps of ~20 m (Bazelyan & Raizer, 1998; Les Renardieres Group, 1977). Figure 1b shows the corresponding image-converter picture of the positive streamer flashes emitted from the electrode. The voltage pulse causing the positive streamer flashes had a rather slow front of ~200–500 $\mu$s and a pulse duration of 2.5–10 ms.

In such streamer flashes from the electrode (Figure 1), the leading front of current growth is ~25–40 ns, and it grows until the first branching of streamers (1). At time (2), the second branching of streamers begins (for the second streamer flash) with a front of ~30–60 ns (3). The whole streamer flash lasts about 300–500 ns. The voltage at which the streamer flash is initiated depends strongly on the electrode dimensions and its capacity. For example, for a rod electrode with a hemisphere cap 100 mm in diameter, the initiation voltage of the streamers is ~509 kV (and $E$ on the electrode surface reaches ~6 MV/m), but for a sphere with 1 m diameter, the voltage reaches ~1,855 kV (and $E$ on the electrode surface is ~3.2 MV/m; Les Renardieres Group, 1977). Also, the size of the electrode significantly affects the total charge of the streamer flash: For a hemisphere with a diameter of 100 mm, total charge is 6.8 ± 3.4 $\mu$C, while for a sphere of 1 m diameter,
total charge is $62 \pm 1 \mu C$. In clouds, due to the relatively long lifetime of the electric fields, the generation of streamers will most likely take place in $E$ close to the breakdown field of $3 \text{ MV/(m-atm)}$, without a large overvoltage and with a very slow voltage rise compared to discharges on electrodes. Kostinskiy et al. (2015a, 2015b) studied positive streamer flashes in a charged aerosol cloud, and these experiments are useful for our understanding of positive streamer flashes in a thundercloud. When generating a charged aerosol cloud, the rise of the voltage front on a grounded sphere with a diameter of 5 cm was 300–500 ms, and the duration of the applied voltage was several tens of minutes, which is closer to the actual conditions in a thundercloud.

Therefore, we describe the positive streamer flashes in the $E$ of an aerosol cloud in detail and show their development in Figure 2 (Kostinskiy et al., 2019), since understanding their development is useful in constructing the Mechanism. It is important that even in the conditions of a very slowly varying $E$ (e.g., over 300–500 ms) created by a charged aerosol cloud, the current fronts (risetimes) of streamer flashes also had a duration of about 30 ns as in the experiment described above and shown in Figure 1. The first streamer flash of Figure 2a (1) had a current peak of 1.1 A, the current front was $30 \pm 5$ ns, the half-width of the peak at half-height was $90 \pm 10$ ns, and the falltime was $147 \pm 10$ ns. A picture of this streamer flash is shown in Figure 2b.I(1). The total duration of the flash current was about 200 ns. Streamers continued to exist and move even after the current on the electrode dropped to zero, since $E$ in the entire region from sphere (2) to cloud (3) exceeded the threshold required for movement of positive streamers in air of $E_{\text{tr}} \geq 0.45–0.5 \text{ MV/(m-atm)}$ (Bazelyan & Raizer, 1998). Streamers flew to the center of the cloud in 1.7 $\mu s$. Therefore, the duration of the streamer flash current measured at the electrode ($\approx 200$ ns) is determined by the time of loss of the galvanic (current) connection of the streamers with the metal sphere. The streamers themselves moved and existed for at least 1.7 $\mu s$. The flash had a length of at least 1.2 m, and the streamers moved from the sphere, Figure 2b.I(2), to the area labeled 5, Figure 2a 2b.I, where they were detected by a microwave diagnostic beam. Since the streamers were moving and did not transition to positive leaders, we know that the $E$ values in their path were 0.5 MV/m $\leq E \leq 1 \text{ MV/m}$. (The upper $E$ value $<1 \text{ MV/m}$ was deduced as follows: The artificial aerosol cloud in these experiments—Kostinskiy et al., 2015a, 2015b—was negatively charged. If the electric field in the interval from the cloud to the grounded plane exceeded $\sim 1 \text{ MV/m}$ the threshold for maintaining the movement of negative streamers—then negative streamers would have moved from the negative cloud to the grounded plane. Since Kostinskiy et al., 2015a, 2015b, did not observe negative streamers at the edge of an artificial negative cloud but did observe that positive streamers crossed the entire gap from the grounded surface to the middle of the artificial cloud, we assume that the electric field $E$ is in the range 0.5 MV/m $\leq E \leq 1 \text{ MV/m}$. The average speed of the positive streamers of the first flash in the image plane was found to be $7 \times 10^{5} \text{ m/s}$. The small maxima and minima of the current on the oscillogram of the first streamer flash Figure 2a (6), as well as on the entire oscillogram of the current, are artifacts of the measuring circuit and should be ignored. The two other current maxima, which correspond to the second and third streamer flashes of Figure 2a (2 and 3), had similar current risetimes ($\approx 30$ ns) as the first streamer flash, despite having much higher currents (3.14 A and 5.8 A). Thus, the risetime of a streamer flash in such $E$ values does not change and characterizes the physical parameters of individual streamers. The total current of an individual streamer flash from a large-diameter electrode can reach 100–200 A, but the
The size of image pixel in the object plane is 3.1 × 3.1 mm². The ambient temperature was 11°C, and the humidity was 81% (adapted from Kostinskiy et al., 2018).

4.3. Corona From Hydrometeors Producing the Group of Positive Streamer Flashes

One possibility for lightning initiation may be that positive streamers are emitted from one or more hydrometeors (e.g., Dawson & Duff, 1970; Griffiths & Latham, 1974; Griffiths & Phelps, 1976; Petersen et al., 2015; Phelps, 1974). For example, a system of hydrometeors distributed in a volume can generate a system of positive streamers distributed in space and time, with the minimum system being a single positive streamer.

4.3.1. Corona From Hydrometeors Producing the Group of Positive Streamer Flashes

In the previous section, we described individual streamer flashes that occur on a metal electrode, but (in nearly all cases) there are no metal electrodes in a thunderstorm cloud. In a thundercloud there are various hydrometeors that are statistically distributed within the cloud and carry different charges. We assume that the lightning IE produces a system of positive streamers distributed in space and time, with the minimum system being a single positive streamer.

4.2.2. Length and Conductivity of Long Streamers

For long streamers the movement of the streamer head is supported by its own strong E, which ionizes the air in front of the head. This E considerably exceeds $E_{th}$ required for different estimates of the E in front of the streamer head are in the range 10–30 MV/(m·atm) (Bazelyan & Raizer, 1998, 2000). When the head crosses this point of its trajectory (i.e., the location with E of 10–30 MV/(m·atm)), then $E$ immediately drops to a value close to the ambient $E$. In this case, the ionization frequency very rapidly decreases, while the frequency of electron attachment to oxygen molecules begins to play the main role (Bazelyan & Raizer, 1998, p.25). At $E < 0.5$ MV/(m·atm), there is a strong loss of plasma conductivity behind the streamer head in only 100–200 ns at a pressure of 0.3–1 atm. In typical $E$ values of a thundercloud, the main loss mechanism is the three-particle attachment of electrons to oxygen molecules (Bazelyan & Raizer, 2000; Kossyi et al., 1992):

$$e + O_2 + M = O_2^- + M, \quad M = (N_2, O_2, Ar),$$

with the attachment rate falling in proportion to the square of pressure. Thus, if the propagation velocity of streamers is 2–5 × 10⁷ cm/s and the characteristic time of attachment is 1–2 × 10⁻⁷ s, then the length of the streamer conductive channel at atmospheric pressure will be 2–10 cm. The concentration of electrons in the streamer head reaches 1–3 × 10¹⁴ cm⁻³, and behind the streamer head the plasma concentration decreases exponentially with the length (Bazelyan & Raizer, 1998, 2000). The near-real length of streamers at atmospheric pressure is visible in Figure 3 (Kostinskiy et al., 2018) and is 10–20 cm. The physical nature of electron attachment to oxygen does not change for positive and negative streamers. At an altitude of 6 km above the Earth, where the pressure has decreased by a factor of 2, the length of the conductive channel of the streamers will increase four times and reach a length of 8–40 cm (depending on $E$), and at an altitude of 9–10 km, the length of the streamers will be 18–90 cm with the same exponential decrease in conductivity behind the streamer head.

4.3. The IE as a Nearly Simultaneous Initiation of a Group of Positive Streamer Flashes in a Thundercloud

In the previous section, we described individual streamer flashes that occur on a metal electrode, but (in nearly all cases) there are no metal electrodes in a thunderstorm cloud. In a thundercloud there are various hydrometeors that are statistically distributed within the cloud and carry different charges. We assume that the lightning IE produces a system of positive streamers distributed in space and time, with the minimum system being a single positive streamer.

4.3.1. Corona From Hydrometeors Producing the Group of Positive Streamer Flashes

One possibility for lightning initiation may be that positive streamers are emitted from one or more hydrometeors (e.g., Dawson & Duff, 1970; Griffiths & Latham, 1974; Griffiths & Phelps, 1976; Petersen et al., 2015; Phelps, 1974). For example, a system of hydrometeors distributed in a volume can generate a system of...
positive streamer flashes distributed in the volume. Thus, if the IE is an NBE, a large total streamer flash may consist of a set of individual flashes initiated by hydrometeors and distributed in a volume; each of these flashes may be similar to the streamer flashes from metal electrodes described above. If the IE is a weak event (e.g., Marshall et al., 2019), it may also be a 3-D set of positive streamer flashes but with fewer individual streamers. Electromagnetic radiation from the volumetrically and temporally distributed positive streamers, as detected by instruments at the ground, may appear as point sources developing in 3-D space and in time. Thus, the combined event consisting of a set of individual streamer flashes should generate the commonly observed, single VHF pulse of the IE.

For NBEs Rison et al. (2016) stated, “the breakdown appears to be produced by a spatially and temporally distributed system of positive streamers, in which the total current is spread over some cross-sectional area as a volume current density.” Rison et al. (2016) estimated a spatial scale of ~500 m for NBEs and suggested that the positive “streamers would be initiated by corona from ice crystals or liquid hydrometeors.” However, each streamer initiation also requires a thermal free electron (energy <100 eV) near the initiating hydrometeor to start the electron avalanche that develops into the streamer flash (Dubinova et al., 2015; Rutjes et al., 2019). Dubinova et al. (2015) argued that thermal free electrons in thunderclouds have a very low density due to the three-particle attachment of electrons to oxygen and water molecules, so the lack of a free electron may prohibit hydrometeor initiation of streamers. In addition, some studies have inferred that the initiating-hydrometeor size must be larger than believable, 6–20 cm (e.g., Babich et al., 2016; Dubinova et al., 2015). These problems with the hydrometeor-corona IE process encouraged us to consider an alternative IE process, as described in the next paragraph.

### 4.3.2. Hydrodynamic and Statistical Processes for Enhancing the Electric Fields of a Thundercloud and Thereby Producing the Group of Positive Streamer Flashes

Another possibility for the IE of a lightning flash (as well as for an isolated NBE) is that hydrodynamic and statistical processes (driven by turbulence) could enhance $E$ in many small regions of the cloud to allow individual free electrons to produce a 3-D set of positive streamer flashes; this set would then radiate in the VHF band, as discussed in the previous section. Thus, this alternative way of producing a group of positive streamer flashes would account for the measurements of lightning initiation and development. The small-scale $E$ enhancements probably require a relatively large region of relatively strong $E$, which seems to exist in thunderclouds, as discussed next.

Based on balloon soundings through active thunderclouds, the typical large-scale charge distribution has 4–8 horizontally extensive charge layers distributed vertically with typical maximum measured vertical $E$ of ±350 kV/(m-atm) (Marshall & Rust, 1991; Stolzenburg & Marshall, 2009). Local maximum $E$ magnitudes typically occur between opposite polarity charge regions, so these maxima are distributed vertically through the cloud. Less is known about the volume of the large $E$ regions, but Marshall et al. (2005) used balloon $E$ measurements and found volumes of 1–4 km$^3$ with vertical and horizontal extents of at least 300–1,000 m associated with three lightning flash initiations. Note that the balloon studies mentioned above ignored small-scale $E$ variations for cloud depths <100 m and short duration $E$ variations for times <10 s. However, Stolzenburg et al. (2007) studied nine balloon flights in which the balloon and/or instruments were struck by lightning and found maximum $E$ magnitudes just before seven lightning strikes of 309–626 kV/(m-atm) and inferred magnitudes of 833 and 929 kV/(m-atm) before the other two strikes. Another finding in Stolzenburg et al. (2007) supports the turbulence-driven, small-scale enhancement of thundercloud $E$ underlying our Mechanism, especially since the typical duration of a CG lightning flash is 200–300 ms (Table 1.1, Rakov & Uman, 2003): Stolzenburg et al. (2007) reported that for seven of the nine lightning strikes, $|\Delta E|$, increased rapidly for 2–5 s before the lightning strike with $dE/dt$ magnitudes of 11–100 kV/m/s. A few seconds before one of the flashes, there was a step increase (in <1 s) in measured $E$ of 380 kV/(m-atm) that lasted for only 1 s, and before another flash, there was a step increase of 505 kV/(m-atm) that lasted 13 s, and then $E$ declined by 15% for the last 2 s before the flash occurred. Thus, the $E$ data in Stolzenburg and Marshall (2009), Marshall et al. (2005), and Stolzenburg et al. (2007) support the existence of $E$ volumes within thunderclouds. These works are also consistent with the idea of smaller-scale regions occurring for short times with much larger $E$ values caused by the hydrodynamic, turbulent, and statistical nature of the charge distribution in a thundercloud.
Following the hypotheses of Trakhtengerts (1989), Trakhtengertz et al. (1997, 2002), and Trakhtengerts and Iudin (2005), we assume that discharges in a thundercloud are fundamentally different from the laboratory discharges from metal electrodes precisely because the \( E \) is created by statistically located charges in the cloud, which create small-scale variations in \( E \). These small-scale variations of the field do not exist in the physics of a classical electrode gas discharge. For several decades, an approach has been developed for the possible local enhancement of \( E \) in a thunderstorm on scales from tens of centimeters to hundreds of meters. As introduced above (19), fluctuations of \( E \) over about 100 m can occur due to hydrodynamic instabilities (Colgate, 1967; Iudin et al., 2003; Mareev et al., 1999; Trakhtengerts, 1989; Trakhtengertz et al., 1997). In an \( EE \) volume these hydrodynamic instabilities create periodic increases and decreases in the magnitude of the electric field; we refer to volumes of these periodic increases and decreases as “cells.” There is a spatial network of cells within an \( EE \) volume. The electric field enhancements found in these cells have a scale of tens of meters. Some cells are \( E_{\text{avr}} \) volumes, capable of supporting the movement of positive streamers (as defined in t8). Furthermore, Trakhtengerts and Iudin (2005), Iudin (2017), and Iudin et al. (2019) have shown that additional \( E \) enhancements at even smaller scales may be possible due to the random statistical motion of a multitude of charged particles of different sizes in the cloud, and it is inside these very small volumes that breakdown electric fields can occur. Unfortunately, these approaches rely on theoretical work, and it is difficult to verify them experimentally. The calculations so far have not incorporated the full structure of real turbulence in the cloud and the full dynamics of real hydrometeors due to the very large computational complexities. Brothers et al. (2018) examine this topic using a large-eddy-resolving model (125 m grid). Their numerical simulations for two storms showed “tremendous amounts of texture” or small-scale spatial variations and inhomogeneities, in the charge density due to charge advection in large-eddy turbulence. Although they do not show the small-scale \( E \), Brothers et al. (2018) mention that there should be “more favorable locations for breakdown to occur” due to there being more neighboring small pockets of opposite charges. It seems a reasonable conjecture that higher spatial resolution modeling of this sort, to include smaller turbulent eddies along with meter-scale hydrodynamic instability effects, will yield even smaller scale \( E \) enhancements.

This hypothesis of small-scale variations in \( E \) seems promising to us for two main reasons. First, we have not found any contradictions between this hypothesis and measurements of lightning or \( E \) in real thunderstorms. Second, the development of a lightning flash from the IE through the IB pulses is quite varied from flash to flash with a wide range of IEC durations and amplitudes (e.g., Marshall, Schulz, et al., 2014), a wide range of IB pulse durations, inter-IB pulse times, IB pulse amplitudes, and a wide range in the number of subpulses (0–5) on the classic IBPs (e.g., Marshall et al., 2013; Smith et al., 2018; Stolzenburg et al., 2014). Of special note in the flash development is the seemingly random order of the classic IBPs: In roughly 1/3 of flashes, the first classic IBP has the largest amplitude followed by classic IBPs with varying amplitudes, while in many flashes the largest classic IBP is third, fourth, or fifth with a median time after the first IB pulse of 1.4 ms for IC flashes and 0.25 ms for CG flashes (Smith et al., 2018). These variations in flash development from IE through the IB stage are easier to understand in the context of a statistical distribution of small-scale regions of large magnitude \( E \), rather than with a single, smooth region of large \( E \).

### 4.3.3. Advantages of the Process of Hydrodynamic and Statistical Enhancement of \( E \)

First, it is important to note that this process for increasing \( E \) does not depend on the phase state of the hydrometeors, and therefore, it fits with the fact that lightning initiation occurs over the altitude range of 3–15 km (or greater). In this process hydrometeors of any size (i.e., cloud particles or precipitation particles) can be liquid and highly conductive or completely frozen with poor conductivity. The main requirement is that hydrometeors carry charge and move in turbulent flows, such that hydrodynamic instabilities in a turbulent cloud will lead to charge density variations and thus to increases and decreases in \( E \) on scales of tens of meters or smaller. That is, within an \( EE \) volume of 1,000 × 1,000 × 1,000 m or 500 × 500 × 500 m and large-scale \( E \geq 284–350 \text{ kV/(m·atm)} \), there are fluctuations of \( E \) with scales of tens of centimeters to tens of meters and \( E \) amplitude variations on the order of 10–100 \text{ kV/(m·atm)} or more, as we discuss in more detail next.

In the \( EE \) volumes, charged hydrometeors are separated by distances of several millimeters to tens of centimeters and moving randomly. In Brownian motion, a multitude of 0.03 \( \mu \text{m} \) molecules can simultaneously strike a large particle 3 \( \mu \text{m} \) in size on one side, while a smaller number of molecules hit it on the other side, thereby causing the large particle to make a big jump. One molecule cannot affect a larger particle that is a...
Figure 4. Possible variations of the electric field in turbulent streams (jets) of a thundercloud.

million times heavier, but in an ensemble there are always fluctuations proportional to $\sqrt{n}$ molecules to produce Brownian motion in a larger particle. Similar processes should also occur in the cloud during random motion among differently charged hydrometeors (Iudin, 2017; Iudin et al., 2019). This movement of hydrometeors leads to a broad spectrum of amplitude oscillations in $E$. Rare, small-volume, large-amplitude oscillations of $E$ should be added to larger scale oscillations of hydrodynamic changes in $E$. These statistical waves of oscillations of $E$ are estimated to have a scale of 1–30 cm (Iudin, 2017; Iudin et al., 2019; Trakhtengerts & Iudin, 2005). Ordinary metal electrodes have a similar scale (1–30 cm) during high-voltage discharges. Hypothetically, these increases and decreases in $E$ can add up with each other and lead, on a small scale, to a spectrum of $E$ values up to the breakdown value of 3 MV/(m·atm). The volumes with scales of 1–30 cm and $E \approx 3$ MV/(m·atm) would be the “air electrodes” mentioned earlier. Of course, such large fluctuations in the thunderstorm should occur very rarely (no more than one small region with $E \approx 3$ MV/(m·atm) per 3–100 m$^3$), but unlike high-voltage electrodes, the thundercloud has dimensions in cubic kilometers, and the lifetime of a strong average $E$ may be tens of minutes. It is important that the probability of waiting for such strong amplitude oscillations of $E$, as in other similar statistical processes, is proportional to $\sim \sqrt{n}$. The cloud is able to “wait patiently” and probably “manages to witness” such strong local oscillations of $E$ in conditions of strong turbulence. The characteristic lifetime of a small-scale field gain should be from tens to hundreds of milliseconds (Iudin, 2017; Iudin et al., 2019). Moreover, in the typical large field of an EE volume there should be a multitude of small $E$ increases, creating a network of “mountain ranges” of $E$ with peaks and valleys (depicted in Figure 4). In our Mechanism it is the network of “tops” of the electric field mountain range, exceeding in some places $E_{th}$ of 3 MV/(m·atm) and separated by centimeters to meters to tens of meters, that can initiate positive streamers. In our Mechanism these large $E$ locations (“tops” or $E_{th}$ volumes or “air electrodes”) replace the large hydrometeors proposed by others to enhance $E$ at the tips of hydrometeors and thereby start positive streamers (e.g., Dawson & Duff, 1970; Griffiths & Phelps, 1976; Phelps, 1974; Rison et al., 2016). In other words, our Mechanism focuses on the $E$ “landscape” rather than on the hydrometeor distribution.

The second advantage of this hydrodynamic and statistical approach is that the dimensions of volumes where $E$ exceeds $E_{th} > 3$ MV/(m·atm) are in the range 2–5 of centimeters (see Kostinskiy et al., 2020), and these dimensions at lightning initiation altitudes of 3 to 15 km will be sufficient for the transition from avalanche to streamer.

If the initial streamer flashes are completely formed in a small number of areas with very strong $E$, then positive streamers will be able to advance providing the average $E$ exceeds the minimum required of $E_{arr} + > 0.45–0.5$ MV/(m·atm). Transition of streamer flashes into a hot conductive channel will occur when the streamers reach an $E \approx 0.5–1.0$ MV/(m·atm). After traveling a distance of several meters, these streamers will, with a high probability, transition into short (1–30 cm), hot, conductive plasma formations similar to UPFs (Kostinskiy et al., 2015a, 2015b). Statistically, the areas with $E > 500–1,000$ kV/(m·atm) should be larger than areas with a very high $E > 3$ MV/(m·atm).

5. The Mechanism

In this section we describe our Mechanism for lightning initiation from the IE to the negative stepped leader. Our Mechanism is only slightly different for the two cases of (1) the IE is a NBE (either strong or weak) as in Rison et al. (2016) and (2) the IE is a much weaker event as in Marshall et al. (2019). We describe the NBE case first.

5.1. The Mechanism for Lightning Initiation by NBEs or the NBE-IE Mechanism

An important condition for this case of the Mechanism is Condition c6: A short and powerful phenomenon that initiates NBEs should move at a speed close to the speed of light (Rison et al., 2016). For such rapid propagation, ordinary streamers are not suitable. Even in relatively large $E$, positive streamers will travel only 500 m in 500 $\mu$s ($v_{str} \approx 10^6$ m/s) because for motion over such large distances, only the average $E$ is important, so statistical field enhancements and attenuations are averaged. To propagate with a speed close to the speed
of light, an electromagnetic pulse seems to require a hot, well-conducting plasma channel, as found for a return stroke or after the end-to-end meeting of two bidirectional leaders (Jerauld et al., 2007; Rakov & Uman, 2003). Even dart leaders moving in previous return stroke channels only attain speeds of one tenth of the speed of light. Thus, for NBEs to actually move at a speed close to the speed of light, it seems that hot channels are needed; this implication directly contradicts the experimental data of Conditions c5 (before and during the NBE, a long, hot conductive plasma channel must not be produced) and c2 (during the IE, there should not be a powerful flash of light). Of all the physical processes known to us, the only process moving at a speed close to the speed of light without the assistance of a highly conductive hot plasma channel is the movement of relativistic particles (Dwyer, 2003; Gurevich & Zybin, 2001), so we employ relativistic particles in our Mechanism (see also Kostinskiy et al., 2020).

The steps in the NBE-IE Mechanism for flash initiation by an NBE are detailed in the following subsections.

5.1. Necessary Conditions
The NBE IE will occur in an EE volume of the thundercloud as defined earlier: a volume of about 0.1–1 km$^3$ with a high average $E > 0.28$–0.35 MV/(m·atm) and a large number of charged hydrometeors of different sizes. Hydrometeors can be liquid or solid, large or small, and a substantial number of them must carry a significant electrical charge. As described earlier (Idea i6), Marshall et al. (2005) measured $E$ of this magnitude in volumes this large and larger.

5.1.2. Large Electric Fields Develop Because of Turbulent Motions
In the EE volume, clouds develop hydrodynamic instabilities and turbulence, which lead to strong local statistical fluctuations of $E$ of different scales and sizes around the background of the average large $E$: See Figure 5, I. Due to the spectrum of oscillations of $E$, we assume that the $E_{\text{th}}$ volumes (“air electrodes”) are relatively small (3–60 cm$^3$) and exist for at least a few tens of milliseconds (Kostinskiy et al., 2020); recall that in $E_{\text{th}}$ volumes the local $E$ exceeds the conventional breakdown threshold $E_{\text{th}} \geq 3$ MV/(m·atm) necessary to start streamers. The small $E_{\text{th}}$ volumes are marked with “1” in Figure 5 (I) and with “6” in Figures 5 (II) to 5 (IV). A simple estimate given in the next paragraph shows that in order to provide NBEs with sufficient streamers to explain the total charge moved in an NBE, one $E_{\text{th}}$ volume should, on average, be found in each volume of approximately 5 m $\times$ 5 m $\times$ 5 m. Larger volumes are also formed with an average electric field strength greater than the threshold for propagation of positive streamers $E_{\text{air+}} \geq 0.45$–0.5 MV/(m·atm); see Figure 5, I (3); these regions are the $E_{\text{str}}$ volumes defined earlier (t8). Of course, many regions in the EE volumes will have smaller $E$ than the average $E$ (Figure 5, I (2)).

We now give a simple estimate of the number of $E_{\text{th}}$ volumes needed for a strong NBE. We assume that each $E_{\text{th}}$ volume may act as an “air electrode.” Let the charge carried by the NBE be about 1 C, since estimated charges of the three NBEs in Rison et al. (2016) were 0.5, 0.7, and 1.0 C. The charge of a small streamer flash from an “air electrode” of about (10 cm)$^3$ (= $10^{-3}$–$10^{-4}$ m$^3$ = 0.1–1 L), where $E_{\text{th}} \geq 3$ MV/(m·atm), Figures 5, III (6), and 5, IV (6), should be similar to a positive streamer discharge in Figure 2, I (1), with a charge of about $10^{-7}$ C. (The minimum charge of an individual streamer flash is determined by the charge of one streamer. According to Bazelyan & Raizer, 1998, pp. 174–175, the measured charge of one positive streamer for a pressure of 0.33 atm (~9 km altitude) is $10^{-8}$ C. Therefore, the charge of a streamer flash consisting of 10 streamers ($10^{-7}$ C) seems reasonable.) Thus, about $10^7$ of $E_{\text{th}}$ volumes are required to provide a 1 C charge. We can divide an EE volume of $1,000 \times 1,000 \times 1,000$ m$^3$ into $10^7$ equal volumes that are 100 m$^3$ ($\approx 4.6 \times 4.6 \times 4.6$ m). It seems reasonable to imagine that each one of the 100 m$^3$ volumes might contain one region of $10^{-3}$–$10^{-4}$ m$^3$ with a large statistical enhancement to $E \geq 3$ MV/(m·atm), since there are very many particles in 100 m$^3$ (e.g., in a thunderstorm anvil, Dye et al., 2007, found concentrations of $10^4$–$5 \times 10^5$ per m$^3$ for particles with diameters of 30 μm to 2 mm) and measurements suggest that in a thunderstorm many of the cloud particles and precipitation particles are charged (e.g., Marshall & Stolzenburg, 1998). As we show in the next section, an NBE begins with a superposition of a large number of positive streamer flashes that occur in most of the $E_{\text{th}}$ volumes.

Figure 5 (I) A sketch of a vertical cross-section through a portion of an EE volume of a thundercloud. As defined above, the EE volume has an average vertical component of $E > 0.28$–0.35 MV/(m·atm), and in the cross section shown, the average $E$ is downward pointing, as indicated by large, red “−” and “+” signs in upper right and lower right corners. The “−” and “+” signs stand for relatively distant regions of negative and positive charge (with dimensions of kilometers) that often occur in horizontal layers, such as the “main
negative” and “lower positive” thunderstorm charge regions depicted in Figure 3 of Stolzenburg et al. (1998). The red 3 (blue 2) shading in (I) indicates regions where $E$ is larger (smaller) than the average $E$. Small, dark-red dots (1) indicate $E_{th}$ volumes (where $E > 3 \text{ MV/(m-atm)}$); red regions around $E_{th}$ volumes are $E_{str+}$ volumes (where positive streamers can propagate). The four $E_{th}$ volumes shown imply that the approximate size of the sketch is about 20 m horizontally by 20 m vertically.

It is important to realize that the sketch does not show the $E$ vector or the $E$ magnitude in detail; rather, it roughly indicates the relative $E$ magnitudes across the 20 m $\times$ 20 m cross section. On scales <1 m, the small-scale charges will lead to a very complicated distribution of $E$ vectors pointing in many directions, including upward and horizontal as well as downward. This means that the pink and blue shadings are also only averages across the shaded regions on a scale of ~5 m.

5.1.3. EAS-RREA-Synchronized (Nearly Simultaneous) Start of a Large Number of Electron Avalanches and Streamer Flashes

When the necessary conditions in section 5.1.2 are fulfilled, then in order to start streamer flashes in the $E_{th}$ volumes, the $EE$ volume must be “sown” with ionizing particles (electrons, positrons, and photons). The number of nearly simultaneous ionizing particles in the $EE$ volume must be so large that in a few microseconds the ionizing particles get into most of the $E_{th}$ volumes: See Figure 5, II (6). The ionizing particles will produce thermal free electrons needed to start classic electron avalanches. For this, EASs ($\epsilon_0 > 10^{15} \text{ eV}$) are ideal; in strong $E > 0.284 \text{ MV/(m-atm)}$ they will generate avalanches of runaway electrons (Dwyer, 2003; Gurevich et al., 1999; Gurevich & Zybin, 2001). The general scheme of the process of synchronization of streamer flashes due to the EAS-RREA mechanism, for example, between an upper negative and a lower
positive charge, is shown in Figure 6. A cosmic ray particle with an energy \( E_0 > 10^{15} \) eV (labeled 1 in Figure 6) creates EAS (2). EAS electrons and positrons (3) enter the region of a strong electric field (5), which can support the propagation of RREA (4) and positive streamers (7). EAS-RREA electrons and positrons (labeled 6 in Figure 6) cross the region of a thundercloud with air electrodes (9) and synchronize the nearly simultaneous triggering of multiple streamer flashes (7), starting within the air electrodes through which the electrons pass (labeled 8 in Figure 6). Numerical simulation of this process is given in Kostinskiy et al. (2020).

RREA electrons leave behind about 29 thermal free electrons/cm of path length at 8 km altitude and about 18 electrons/cm at 12 km altitude (Rutjes et al., 2019). An avalanche of relativistic electrons (marked “4” in Figure 5, II) crosses the entire EE volume in 1.5–3 \( \mu \)s. When runaway electrons traverse an \( E_{th} \) volume (see Figure 5, II (6)), there is a high probability that discharge avalanches will develop and turn into streamers because most of the \( E_{th} \) volumes are inside a \( E_{app} \) volume (see Figure 5, I (3)). The flash of streamers will form a front of current in approximately 30 ns, and the total duration of the streamer flash will be in the range of 150–300 ns. Thus, individual streamer flashes occur (see Figure 5, II (5)) and produce electromagnetic pulses with a radiation maximum in the VHF range of 30–40 MHz.

The avalanches of runaway electrons seeded with EAS act as an initiation wave moving at a speed close to the speed of light, which creates, at different points in the EE volume, and in 1.5–3 \( \mu \)s, a “giant wave” of ordinary positive streamer flashes, which we described above (section 4.1). It can be said that a flash of a large number of runaway electrons “ignites” nearly simultaneously many of the \( E_{th} \) volumes (see Figure 5, II (6)), thereby forming the NBE radiation front in the VHF. The motion of the phase wave of ignition of an exponentially growing number of streamer flashes is shown in more detail in Figure 7 (the numerical simulation is given in Kostinskiy et al., 2020). Thus, an NBE begins with and is primarily caused by the superposition of all of the positive streamer flashes ignited by the EAS and RREA.

In this way, the NBE-IE Mechanism fulfills the conditions (c4 and c5) of generation in several microseconds of a giant flash of positive streamers during the time of emission of NBEs without preliminary formation of a hot plasma channel of high conductivity. At the same time, the generation of this giant positive streamer flash is inextricably linked with avalanches of runaway relativistic electrons that were initiated by secondary electrons of EAS \( 10^{15} \) eV \(< E_0 < 10^{16} \) eV). Without EASs, avalanches of runaway electrons initiated by background cosmic rays cannot cross into most small air electrodes. On the other hand, with EAS only, even with an initial particle energy \( E_0 \approx 10^{17} \) eV, the EAS will not be able to initiate a sufficient number of streamer flashes to provide a large VHF signal that accompanies NBEs (Kostinskiy et al., 2020).

In constructing this part of the Mechanism, we used ordinary streamer flashes, which can move at reasonable speeds for streamers \( v_{str} \approx 2 \times 10^5 \) to \( 3 \times 10^6 \) m/s. Meanwhile, the light speed of the relativistic runaway breakdown particles ignite the \( E_{th} \) volumes along the paths of the relativistic particles, thereby giving the NBE an apparent speed close to the speed of light and satisfying conditions c6 and c7 (above, section 2).

The direction of motion of energetic secondary particles (electrons and positrons with energies of 0.1–100 MeV) EAS-RREA will not determine the direction of motion of streamer flashes, since energetic particles initiate only the first seed electrons inside the air electrodes. Positive streamers always move along the lines of force of the electric field in the direction of the negative charge. Energetic electrons create about 74 thermal electrons (at atmospheric pressure) with an average energy of about 24 eV on each centimeter of...
their path (Rutjes et al., 2019). These thermal electrons initiate the classic electron avalanches that turn into streamers (when the Meek’s criterion is met; Bazelyan & Raizer, 1998). The streamer head is polarized in the direction of the ambient electric field, creating in front of the head its own very strong electric field of 10–20 MV/(m-atm). This strong electric field determines the characteristics and direction of movement of an individual streamer. EAS-RREA avalanches of energetic electrons and positrons can move even perpendicular to the electric field, and this still will not change the direction of movement of streamers.

5.1.4. Development of UPFs

After the start of the streamer flashes, some streamers will be able to advance for distances of ~1–10 m because they are in a more extensive $E_{\text{upf}}$ volumes (section 4.3.2); see Figure 5, III (12). During the movement of streamers, due to the ionization-heating instability, a network of strongly conducting plasma channels will appear in the plasma and remain after the streamers pass through (see Figure 5, III (7)). We will describe these strongly conducting plasma channels as “UPFs” since they develop like the UPFs reported in artificially charged aerosol clouds by Kostinskiy et al. (2015a, 2015b). It is important to note that the motion of one streamer flash will be able to simultaneously generate several UPFs, Figure 5, III (7). These UPFs will interact with each other after some time due to secondary positive streamers, as sketched in Figure 5, III (9), and as shown in experiments (Andreev et al., 2014) with a charged aerosol cloud, reproduced in Figure 8. The development time of the ionization-heating instability and the appearance of UPFs at atmospheric pressure is 0.2–0.5 μs; at altitudes where lightning is initiated, this time can increase by about a factor of ~2–8 (Riouset et al., 2010). Thus, 5–20 μs (depending on height) after the onset of the VHF front of the NBE, the entire $EE$ volume will consist of small hot plasma formations or UPFs, ranging in length from a few centimeters to tens of centimeters (see Supporting Information S2 for more discussion of the ionization-heating instability and positive streamer-UPF transition).

In order for the UPFs to “survive” for tens of microseconds, they must remain hot and conductive. Therefore, a current of no less than 0.2 A must flow through each hot channel UPF (Bazelyan & Raizer, 1998). UPFs that are close to each other will survive if they create an $E \geq 0.45$–0.5 MV/(m-atm) between themselves (i.e., greater than or equal to the minimum $E$ needed to sustain positive streamer propagation) and if they exchange secondary positive streamers, similar to the way in which positive streamers support the development of space leaders in the crown of a negative long spark (Gorin & Shkilyov, 1976; Les Renardières Group, 1981). Due to the streamers between pairs of UPFs, the interaction is analogous to a small breakthrough phase (e.g., Figure 5, III (9 and 10)), which ends by combining and increasing the total length of the hot plasma channels in a process similar to a small “return stroke” (or step of a negative leader in a long spark) with an increase in current up to 5–15 A in a time of ~1 μs. It is important to note that UPFs consist of a whole network of channels, where the current of small channels feeds large channels, helping them to survive longer: See Figure 9 (from Kostinskiy et al., 2015a), Andreev et al. (2014), and Figure 5, III (7). Thus, inside the $EE$ volume, many small channels are combined or merged into several large UPFs, Figure 5, IV (13). For long-term survival, each individual chain of UPFs must grow to such a length that the potential at its positive end reaches the 300–500 kV needed for starting a positive leader (Bazelyan & Raizer, 1998, 2000; Bazelyan, Raizer, et al., 2007) (see Supporting Information S3 for more discussion of the UPF-positive leader transition).

5.1.5. Development of Negative Leaders

According to the above sequence, many of the UPFs that have merged together in long chains and were able to become the “parents” of positive leaders have survived. As their positive leaders lengthen, the electric potential of their negative end will increase. A negative leader will be initiated from the negative end of a UPF chain when the potential at the negative end becomes approximately 1.5–2 times greater than the
potential for initiating a positive leader (Gorin & Shkilyov, 1974, 1976; Les Renardières Group, 1977, 1981). At this moment, the negative leader of Figure 5, IV (16), starts from the negative end of the network of the united UPFs, and the chain of UPFs turns into a “typical” bidirectional leader as shown in Figure 5, IV (13). The number of these bidirectional leaders in the EE volume might vary in different flash initiations from a several tens to several hundred channels with a length of 10–50 m. The number of bidirectional leaders will depend on the size of the initial EE volume and the number of electron avalanches caused by runaway electrons passing through the EE volume (see Supporting Information S4 for more discussion of the positive leader-bidirectional leader transition).

Thus, the NBE-IIE Mechanism explains the IEC period of a lightning flash initiation as follows: First, the approximately simultaneous, 3-D production of many small UPFs is followed by the merging of small UPFs into UPF chains or networks; these events can occur during the IEC without large and strong discharges. Second, there is the development of positive and negative leaders from UPF networks, in preparation for the first IB pulse. The currents in the UPFs, UPF networks, and positive and negative leaders cause the change in E of the IEC detected at nearby FAs. We assume that the merging of two larger UPF chains or small bidirectional leaders that are formed from these UPF chains cause the IEC “enhancing events” described above and discussed in Marshall, Stolzenburg, et al. (2014) and Marshall et al. (2019). In these ways the Mechanism fulfills the IEC part of Conditions c1 and c3.

5.1.6. Requirements for Making IB Pulses

By definition the IEC starts with the IE and ends with the first classic IB pulse. As introduced above (Idea i3), reported IEC durations average about 230 μs for CG flashes and 2,700 μs for IC flashes. Modeling of the first or second classic IB pulse in three CG flashes found that the IBP peak currents were 30–100 kA, had durations of 30–50 μs, and had corona sheath charges (estimated line charges) of 0.2–1.2 C (Karunarathne et al., 2014). Thus, during the short time of the IE and IEC, the electron avalanches, positive streamers, UPFs, UPF networks, and bidirectional leaders must have liberated the 0.2–1.2 C of charge needed for the first classic IB pulse.

It is important to estimate the total length of UPF networks that will store the 0.2–1.2 C of charge, but the line charge density, ω, of UPFs is unknown. For a long spark the measured ω = 0.05–0.07 mC/m (Les Renardières Group, 1977, 1981), while for a well-developed negative lightning leader ω = 0.7–1.0 mC/m (Rakov & Uman, 2003). To estimate the length of the UPF networks that combine to make an IBP, we use a linear charge density with a range of 0.07–0.7 mC/m and find lengths of 290–2,900 m for 0.2 C and 1,700–17,000 m for 1.2 C. These lengths are much longer than the observed lengths (from high-speed video data) of 75–90 m for the first two IBPs in two negative CG flashes (Stolzenburg et al., 2013), so it seems impossible that a single bidirectional leader of 75–90 m could accumulate a charge of 0.2–1 C on its corona sheath. Therefore, the Mechanism postulates that the IEC is a 3-D process with parallel development of many UPF networks at once and that each UPF network has its own 3-D structure (Kostinskiy et al., 2015a). In this way, during the IEC, the UPF networks can accumulate the required IBP charge. For an IBP length of roughly 100 m, the UPF networks would need 3–30 parallel elements for an IBP charge of 0.2 C and 17–170 parallel elements for an IBP charge of 1.2 C, depending on the UPF line charge density. Thus, the three-dimensionality of the UPF networks is fundamental for making an IBP. As the total length and volume of each UPF network increase and currents flow through them, the total charge in the corona sheath of each

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**Figure 8.** UPFs, formed after a positive streamer flash, interact with each other thanks to positive streamers. Negatively charged aerosol cloud. Infrared image with an 8 ms shutter speed. Two UPFs (indicated by red arrows) were born after the first streamer flash. UPFs interact through positive streamers. Upward positive leaders emerged and grew after the birth of UPFs (adapted from Andreev et al., 2014).
network increases; additional charge develops at the ends of the UPF network channels because the networks become polarized in the thundercloud electric field.

### 5.1.7. The First Classic IB Pulse

According to the NBE-IE Mechanism, the first classic IBP occurs when two volumetric plasma systems, each consisting of a network of connected UPFs, send out bidirectional leaders that meet and connect, as schematically shown in Figures 10a and 10b. The connection of the two networks involves a “breakthrough phase” (“4” in Figure 10a) and a “return stroke” (“10” in Figure 10b) (e.g., Jerauld et al, 2007) and accounts for the powerful flash of light associated with the first classic IB pulse (Campos & Saba, 2013; Stolzenburg et al., 2013, 2014). In this way the Mechanism fulfills Conditions c1 and c8 by explaining the cause of the first classic IB pulse or IBP#1.

In seven CG lightning flashes studied using high-speed video data, Stolzenburg et al. (2013) observed a burst of light coincident with each classic IB pulse, and successive bursts developed as “linear segments” that extended for 300–1,500 m. Stolzenburg et al. (2013) called the extending linear channel an “initial leader.” Using similar video data, Stolzenburg et al., 2014, 2020, have shown that an initial leader can transition to a stepped leader within 5 ms of flash initiation. This transition takes longer in some flashes.) Thus, the merged plasma networks (Figures 10a and 10b) that caused IBP#1 are the beginning of the flash’s initial leader.

![Figure 9.](image-url)
5.1.8. Subsequent Classic IB Pulses

For statistical reasons, plasma networks in some $E_{air}$ volumes form earlier than in other $E_{air}$ volumes, so the location of the first classic IB pulse is not predictable. However, after the first classic IB pulse, the rapid polarization of the nascent initial leader in the local electric field creates induced charges on the initial leader that produce an additional large electric field at and near the ends of the initial leader. The enhanced electric field accelerates the development of the existing UPF networks that lie closest to the negative end of the initial leader, as indicated by the multiple small networks marked “3” in Figure 10b. Due to the enhanced $E$ region, these UPF networks will develop into a common network of hot plasma channels (“3” in Figure 10c). Eventually, the initial leader and the lower plasma network send out bidirectional leaders that meet (“4” in Figure 10c) and connect (“10” in Figure 10d). This connection also has a “breakdown phase” (“4” in Figure 10c) and a “return stroke” (“10” in Figure 10d) that cause the second classic IB pulse or IBP#2.
The sequence of events leading to IBP#2 fits with the high-speed video and FA data of Stolzenburg et al. (2013, 2014, 2020), which showed that each new classic IBP extended the previous IBP channel. We note that unlike the generation of the first classic IBP, where the large $E$ was caused by hydrodynamics and statistics, the generation of the second classic IBP is caused by the superposition of electric fields due to (1) $E$ of the polarized plasma of IBP#1 and (2) $E$ caused by hydrodynamics and statistics.

The next IB pulses are caused in a way similar to IBP#2. For each subsequent IB pulse the field enhancement at the ends of the growing initial leader, combined with the statistically distributed, 3-D groups of nascent plasma networks, strongly influences the linear trajectory of the initial leader, thereby accounting for changes in initial leader direction (Stolzenburg et al., 2013) and for initial leader branches (Stolzenburg et al., 2014, 2020). It is well known that the series of IBPs is very different from one flash to another, including a seemingly random order of IBP FA amplitudes, IBP durations, and time between successive IBPs as shown by comparing Figures 11 and 12 below (see also Figures 4 and 5 in Bandara et al., 2019; and Figures 3–5 in Smith et al., 2018). However, the Mechanism proposed can account for these variations; indeed, a turbulent distribution of charges and ignition of positive streamers by an EAS-RREA essentially requires such variations.

As mentioned in section 1 (Term t4), we defined the IB stage of the flash initiation as starting with the first classic IBP, and with an implied end time after the last IBP or at the transition to a negative stepped leader. We also mentioned that the processes causing classic IBPs and small IBPs were unknown and might be different. In the Mechanism the physical process of classic IBPs is the connection of two bidirectional leaders, each of which developed from a large 3-D network of UPFs (or from a 3-D network of hot plasma channels developed from the UPF network). In the Mechanism a different physical process causes both (i) small IBPs and VHF pulses between classic IBPs and (ii) the FA pulses and VHF pulses that occur during the IEC (before the first classic IBP): namely, the connection/merging of two UPFs, of a UPF to chain or network of UPFs, or a two chains (or small networks) of UPFs. We will group these three ways together under the name of “preparatory mergers.” The largest of the preparatory mergers that occur during the IEC are the IEC enhancing events discussed above.

### 5.1.9. Transition to Typical Negative Stepped Leader

As described above (section 5.1.5), negative leaders will be initiated from the negative ends of UPF networks (or a 3-D network of hot plasma channels developed from the UPF networks) when the potential at the negative ends becomes 1.5–2 times greater than the potential for initiating a positive leader. These positive leaders are shown in Figure 10 (6). If there are other UPF networks (or another 3-D network of hot plasma channels developed from the UPF networks) nearby, then more IB pulses are possible; if not, then the negative stepped leader will survive if the UPF channel has become hot and conductive and the electric field is sufficient. When the negative leader (similar to the one shown in Figure 10d (8), in the process of developing bidirectional leaders, becomes self-propagating (i.e., becomes a negative stepped leader), then the process of forming the lightning channel is complete and the lightning initiation phase ends.

Thus, in the Mechanism the spatial movement of IBPs is fundamentally different from the development of a negative stepped leader, since the stepped leader mechanism requires a preexisting plasma channel. Stolzenburg et al. (2014) hypothesized that the initial leader (the IBPs) heat the initial leader channel with each successive IB and that this heating eventually causes the initial leader to transition to a stepped leader with a hot, conducting channel. Recently, Karunarathne et al. (2020) presented model results for sequences of IBPs that support this hypothesis. Plasma networks may also be developing in other cells of the EE volume, distant from the first IBPs, and they may also contribute to the series of IBPs.

### 5.1.10. Comparison of NBE-IE Mechanism to Data

Rison et al. (2016) studied in detail three positive NBEs that initiated IC flashes; the NBEs moved downward, and the following IB pulses moved upward. For each flash, immediately after the downward moving positive NBE, the digital interferometer detected a series of scattered, low-power, upward moving events that Rison et al. (2016) identified as corresponding to the beginning of the IEC. These low-power sources are shown in Figures 2a, 2b, and 3a in Rison et al. (2016). In addition, their Figure 3c shows that these low-power sources continued until the first IB pulse of the flash. We speculate that these low-power sources were mergers of UPFs into UPF chains and UPF networks, with two UPF networks finally connecting to make the first IB pulse, as described above in sections 5.1.4, 5.1.5, and 5.1.7 and shown diagrammatically in Figures 10a and 10b.
Figure 3c of Rison et al. (2016) also shows that low-power, upward moving sources were almost continuously detected by the digital interferometer between the first and second IB pulses, and again between the second and third IB pulses. We speculate that the low-power sources between each pair of IB pulses were also mergers of UPFs into UPF chains and eventually into a UPF network that caused the next IB pulse, when the newly merged UPF network connected to the growing series of UPF networks (from previous IB pulses), as briefly described above in section 5.1.8. Figures 10b and 10c show diagrammatically the process leading to the second IB pulse of a flash via the merging of UPFs into the new UPF network (marked “3” in the Figures 10b and 10c). Figures 10c and 10d show diagrammatically that the second IB pulse occurs when the new UPF network (“3”) connects to the pair of UPF networks that connected and made the first IB pulse.

Bandara et al. (2019) investigated negative NBEs (NNBEs) that initiated negative CG (−CG) flashes. NBE polarity is based on the polarity of the initial peak of the FA NBE waveform using the physics convention.

Figure 11. Example of a stronger-power NNBE (1,290 W) that apparently initiated a −CG flash (called NNBE(L) in Bandara et al., 2019). FA data (blue, uncalibrated linear scale) and Log-RF data (red, uncalibrated logarithmic scale) plotted as normalized voltage versus time (i.e., for each curve the largest peak-to-peak pulse amplitude is scaled to 1.0 V). $E_{\mathrm{100km}}$ is the FA zero-to-peak amplitude (in V/m) of the NNBE(L), range-normalized to 100 km, while $P_S$ is the VHF power (in watts) of the NNBE(L). (a) Overview showing 10 ms of FA data and Log-RF data. Light blue dots represent altitudes (right-hand vertical scale) of FA pulses determined using $\frac{\int E\,dt}{E_{\mathrm{100km}}}$. Altitude of the NNBE(L) was 6.3 km. (b) Expanded view (1 ms) of first events in (a). (c) Expanded view (100 μs) of the NNBE(L). (d) FA pulse altitudes with error bars for the same 1 ms shown in (b). (e) Histogram of time intervals between adjacent FA pulses for the same 1 ms shown in (b) and (d). The time interval between the NNBE(L) and the next pulse location is shown in black in the histogram (Bandara et al., 2019).
of electric field polarity. We assume that positive streamer flashes are the underlying source of the NBE waveform. Hence, for −CG flashes, NNEEs move positive charge upward, and the following IBPs move downward and transition into a downward moving negative stepped leader.

In our opinion, the NBE-IE Mechanism for initiating lightning is qualitatively confirmed by the measurements of Bandara et al. (2019), as seen in Figures 11 and 12. Figure 11a shows a 10 ms overview the initial events in the −CG flash as detected by a FA and a VHF power sensor (called Log-RF, bandwidth 186–192 MHz); note that the initial event in the flash, the NNEE, had the largest Log-RF power and that the Log-RF powers of the classic IB pulses were also relatively large. The blue dots in Figure 11 represent (z, t) locations of FA pulses; the (x, y, z, t) locations were determined using a time-of-arrival technique with an array of dE/dt sensors. Note that because of the amplitude scale used, some of the FA pulses with blue dot locations are not discernable in Figure 11. Figure 11c shows a 100 μs view of the NNEE: The FA bipolar pulse had an amplitude of −1.16 V/m (range-normalized to 100 km) and a duration of about 20 μs, while the VHF pulse (Log-RF) had a power of 1,290 W and a duration of 15–17 μs. Note that the chaotic nature of the Log-RF pulse is consistent with the Mechanism’s hypothesis that NNEEs are an incoherent superposition of many positive streamer flashes.

Figure 11b shows the FA data, Log-RF data, and FA pulse altitudes for the first 800 μs of the flash; Figure 11d shows the FA pulse altitudes with z error bars for the same 800 μs. The time between the NNBE and the first classic IB pulse was 390 μs (Figure 11b). From the point of view of the NBE-IE Mechanism, we assume in...
Figure 11b that the FA pulses (with blue dot locations) were caused by linking together UPFs into relatively long chains (long enough to make an FA pulse). The connections into UPF chains began only 140 μs after the IE, as indicated by the locations of the very weak FA and VHF pulses. Many chain mergers occurred in the time range from 220 to 340 μs after the IE. We assume that some of the merged UPF networks produced bidirectional leaders. When two of these leaders met and connected, the substantial “return stroke” current produced the first classic IB pulse. Note that the “preparatory mergers” from 220 to 340 μs occurred at short time intervals in the range of 2–15 μs (Figures 11d and 11e). Similar preparatory mergers occurred before the second classic IBP (IBP#2 at about 530 μs after the IE) and before the third classic IBP (IBP#3 at about 750 μs after the IE). The preparatory mergers of UPFs chains (or networks) before IBP#2 and IBP#3 might have involved only UPFs caused by the original avalanches/positive streamer flashes but might also have included a new UPFs caused by later avalanches/positive streamer flashes. Overall, the NBE-IE Mechanism qualitatively fits with the data in Figure 11 of a strong NNBE initiation of a −CG flash reported by Bandara et al. (2019).

Figure 12 (Bandara et al., 2019) shows the initiation of a −CG flash by a weaker NNBE, and this initiation is also consistent with the NBE-IE Mechanism. The FA bipolar IE pulse had an amplitude of only −0.01 V/m (range-normalized to 100 km) and a duration of about 10 μs; the Log-RF pulse had a VHF power of 4 W and a duration of about 5 μs. Note that the FA pulse was not clearly bipolar; instead, it was “more monopolar in nature,” as in one NNBE reported by Rison et al. (2016). The NNBE was the first event in the flash and had a fairly large power, larger than the power of the first classic IBP, but much smaller than later classic IBPs. The first classic IBP (IBP#1) occurred about 290 μs after the NNBE; apparent preparatory mergers began 150 μs after the NNBE with more mergers in the 20 μs before IBP#1. Classic IBP#2 occurred 530 μs after the IE, and preparatory mergers began 80 μs before IBP#2. Classic IBP#3 occurred 700 μs after the IE; preparatory mergers occurred throughout the time between IBP#2 and IBP#3 and increased just before IBP#3. Immediately before each of the first three classic IBPs, the mergers occurred at short time intervals in the range of 2–10 μs (Figures 12d and 12e).

The short measured times (e.g., 5–150 μs; Figures 11 and 12) between the mergers might be accounted for by the close distances between the interacting channels. We can support this idea using a simple estimation.

Consider that the average leader speed in the initial stage of lightning development is in the range \( vL \approx 0.02 \) – 0.1 m/μs (Gorin & Shkilyov, 1976; Les Renardières Group, 1977, 1981; Rakov & Uman, 2003). Further, consider that the average speed of leaders in the breakthrough phase is in the range \( vLbr \approx 0.1 – 0.3 \) m/μs (Gorin & Shkilyov, 1976; Les Renardières Group, 1977, 1981; Rakov & Uman, 2003). Hence, the distance between the plasma channels would be in the range \( D_{ch} \approx 0.1 \frac{m}{\mu s} \cdot (5 – 150) \mu s \approx (0.5 – 15) \) m. This general estimate is consistent with our previous estimates (section 5.1.2) of the distance between the air electrodes (4.6 m) from which the entire process of network formation begins.

The −CG flash in Figure 12 was initiated with a much weaker NNBE than the flash in Figure 11, but after the IE, the development of these two flashes seems quite similar. Both initiations seem to fit reasonably well with the NBE-IE Mechanism.

5.1.11. NBE-IE Mechanism for Precursor Events and Isolated NBES

Rison et al. (2016) described a kind of “short duration discharge,” isolated in time and space, that they called “precursors (PCs)” since they “sometimes occur seconds before an IC discharge initiates at the same location.” The two PCs shown in Rison et al. (2016) had durations of 250 μs and 3 ms. The respective PCs had IEs with durations of <1 and 2 μs and VHF powers of 10.8 and 21.6 dBW. The IE powers of the PCs were 20–30 dBW greater than the other PC events. Another type of short duration discharge is an NBE that is isolated in time and space; originally, all NBES were thought to be isolated discharges (e.g., Willett et al., 1989). From the point of view of the Mechanism, it is likely that precursors and isolated NBES develop with the NBE-IE Mechanism but their EE volumes have only small \( E_{str} \) volumes (with \( E \) sufficient for the development of positive streamers), so that the development of large UPF networks and bidirectional leaders cannot occur, thereby preventing IBPs from occurring. Without IBPs, the precursors and isolated NBES cannot develop into full lightning flashes.
5.2. The Weak-IE Mechanism for Lightning Initiation

In this section, we describe how the Mechanism accounts for lightning initiation by short duration (<1 μs), low VHF power (<1 W) IEs, as described by Marshall et al. (2019) and Lyu et al. (2019). We call this part of the Mechanism the Weak-IE Mechanism. These IEs are weaker than all of the NBE IEs described above and are clearly not NBEs. As mentioned in section 1, recent measurements indicate that 88% of 26 nearby IC flashes were initiated by Weak-IEs (Lyu et al., 2019) while 96% of 868-CG flashes were initiated by Weak-IEs (Bandara et al., 2019), so lightning flashes are 10–25 times more likely to begin with Weak-IEs rather than NBE-IEs. Thus, we can expect that conditions needed for the Weak-IE Mechanism will be more likely to occur in a thundercloud than the conditions for the NBE-IE Mechanism.

5.2.1. The First Condition of Weak-IE Initiations

In agreement with the above-cited observations, *the VHF power of the IE should be <1 W*. From the point of view of the Mechanism, the magnitude of the VHF power of the IE essentially depends on the number of \( E_{th} \) volumes (or “air electrodes”) in the EE volume that start avalanches. If there are relatively few \( E_{th} \) volumes starting avalanches, then the VHF signal of the IE will be small. Compared to the NBE-IE Mechanism, the Weak-IE Mechanism must have fewer \( E_{th} \) volumes involved or fewer relativistic particles to start avalanches or a combination of these two conditions.

5.2.2. The Second Condition of Weak-IE Initiations

As described in section 5.1.6., *the IEC must collect 0.2–1.2 C of charge for the first classic IB pulse*. The Weak-IE Mechanism (like the NBE-IE Mechanism) assumes that the first classic IBP is caused by the connection of two bidirectional leaders which developed from two UPF networks. To have sufficient charge for the first classic IBP, the total charge (total system capacity) distributed on the corona sheaths of the two merging bidirectional leaders (and the plasma networks that these leaders support) must be 0.2–1.2 C. This total charge is needed even for the shortest duration IECs (of order 100 μs). The amount of charge that will be moved during the IBP breakthrough phase and “return stroke” must be accumulated during the IEC.

5.2.3. The Weak-IE Mechanism

In order for these two conditions to be fulfilled and the lightning to be initiated by the same Mechanism proposed for NBE-IEs, it is necessary that much of the EE volume must include large \( E_{str^+} \) volumes; see Figure 13, I. (The reason for this requirement will be given in the next paragraph.) Also, many fewer \( E_{th} \) volumes (air electrode) are needed (of order \( 10^{2}–10^{4} \) vs. \( 10^{5} \)). Since the minimum electric field magnitude in the \( E_{str^+} \) volumes (\( \geq 0.45–0.5 \) MV/(m-atm)) is only about 50% larger than the average electric field in the EE volume (0.28–0.35 MV/(m-atm)), the electric field “landscape” of the Weak-IE Mechanism is more easily (and more frequently) realized from statistical fluctuations than the \( E \) landscape needed for the NBE-IE Mechanism with its very large number (\( 10^{7} \)) of \( E_{th} \) volumes. This landscape should also be crossed by a sufficient number of relativistic runaway electrons to start avalanches and positive streamer flashes (Figure 13, I (5)), but not more than needed in the NBE-IE Mechanism.

The key difference between the Weak-IE Mechanism and the NBE-IE Mechanism is based on the \( E_{str^+} \) volumes. Because most of the \( E_{th} \) volumes are located in the \( E_{str^+} \) volumes, streamer flashes starting in an \( E_{th} \) volume will have very long streamer trajectories (tens of meters) (Figure 13, II (6)) because the trajectories will continue for the extent of the \( E_{str^+} \) volume (Figure 13, I (3 and 4)). Due to the long trajectories, the ionization-heating instability will produce many UPFs in each streamer flash (Figure 13, III (7)). A few microseconds after the Weak-IE, the UPFs will be connected into long UPF chains by their own second-ary positive streamer crowns (Figure 13, III (9)) because inside these chains the electric field is higher than the propagation threshold of positive streamers \( E_{str^+} \geq 0.45–0.5 \) MV/(m-atm). Inside each long chain of UPFs, a current flows in the range of 5–20 A. The average speed of each UPF chain or plasma channel, which survives and moves due to the current of positive streamers connecting them, will be about 1–2 cm/μs (Les Renardières Group, 1977). When UPF channels are combined or merged into a few longer chains, then they can move 3–6 m toward each other in 150 μs. If UPFs are quasi-uniformly distributed, then the chaining of UPFs into one large hot channel can occur in a series of current pulses, with a time between pulses of 1–3 μs. Each UPF or small UPF chain that merges into the main local UPF chain will produce a significant current pulse in the combined, highly conductive channels Figure 13, IV (11). We hypothesize that these mergers cause VHF pulses of different amplitudes depending on the lengths of the UPF chains that are merging. Eventually, connecting one more UPF chain with a long UPF chain will produce a single plasma channel that is several meters long, long enough that strong negative and positive streamer flashes occur at the
ends of the combined channel and a bidirectional leader is born, Figure 13, IV (14 and 15). These streamer flashes will be similar to positive and negative flashes of a long spark (Kostinskiy et al., 2018, 2015b) and will produce a strong VHF signal. The merging of long UPF chains and/or the creation of a bidirectional leader may produce IEC enhancing events, which have a FA pulse (from the long current) coincident with the VHF pulse.

Several 3-D plasma networks that create bidirectional leaders should develop close to each other. Then, as in the NBE-IE Mechanism, the first classic IBP, IBP#1, occurs when two of the bidirectional leaders connect to each other with a breakthrough phase and a “return stroke,” Figure 13, IV (13). These events emit high-power VHF pulses and large FA pulses of the first classic IBP.

The rest of the Weak-IE Mechanism is identical to the NBE-IE Mechanism. After the IBP#1, the \( E \) below the negative end of the two connected bidirectional leaders (Figure 13, IV (14)) will be much enhanced by the “return stroke” of IBP#1, and one or more of the existing UPF networks in the enhanced \( E \) region will create bidirectional leaders and connect to IBP#1, thereby making the second classic IBP or IBP#2, and so forth. After enough IBPs have occurred to make a sufficiently conducting channel spanning a sufficient potential difference, a self-propagating negative stepped leader will begin, signaling the end of the lightning flash initiation.

**5.2.4. Comparison of Weak-IE Mechanism to Data**

Marshall et al. (2019) show two examples of CG flashes with Weak-IEs, reproduced in Figure 14. Compared to the NBE-IE shown in Figures 11 and 12, the IE in Figure 14a had a much smaller VHF power and a much
shorter duration of 0.14 W and 1 μs; an expanded view (not shown) found no FA pulse with the VHF initiating pulse. During the 130 μs IEC, there were many VHF pulses and only a few FA pulses; we assume that the VHF pulses were caused by UPFs connecting into UPF chains. There were two enhancing events (coincident FA and VHF pulses: −0.1 V/m and 0.18 W, and −0.2 V/m and 0.14 W) that occurred within 20 μs of the IE; these first events after the IE occurred much sooner than in the NBE-IE initiations discussed above. In the next 90 μs there were 7–10 small VHF pulses. In the next (last) 20 μs, there were many larger VHF pulses and one enhancing event (−0.2 V/m and 0.55 W) leading up to the first classic IBP (IBP#1, −0.32 V/m and 3.0 W). These larger VHF pulses are consistent with the merging of longer UPF chains described in the Weak-IE Mechanism and similar to the late events in the IEC of NBE-IE flashes. The charge moment change of the IEC was 36 C m.

Figure 14b shows another Weak-IE CG flash initiation; it is similar to the initiation just discussed in many ways. However, the IE in Figure 14b was much stronger with VHF power and duration of 0.64 W and 2 μs and was coincident with a weak FA pulse. The IEC lasted 124 μs and had a charge moment change of only 9 C m. In the first 30 μs after the IE, there were several substantial VHF pulses followed by one weak enhancing event (−0.08 V/m and 0.09 W). In the next 60 μs there were only a few VHF pulses. There were more than 20 relatively large VHF pulses in the last 40 μs before the first classic IBP (IBP#1, −0.32 V/m and 0.32 W).

Both flash initiations in Figure 14 seem to fit reasonably well with the Weak-IE Mechanism, and, except for two differences, they are similar to the initiations via NBE-IE Mechanism shown in Figures 11 and 12. One of the differences is expected: the character of the IE itself (NBE-IE vs. Weak-IE). The other difference is that the Weak-IE was immediately followed by VHF pulses while for the NBE-IE the VHF pulses did not begin for 140–150 μs. This difference can be explained by the Mechanism. The NBE-IE produces a large number of widely scattered (separated by 5–10 m), short UPFs. Apparently, about 150 μs was needed before these UPFs had merged into short UPF chains, which could then merge and make observable VHF pulses. In the
Weak-IE Mechanism, the long positive streamer flashes in the $E_{\text{str+}}$ volumes immediately developed multiple UPFs in each streamer flash. These UPFs quickly connected, and in 3–5 $\mu$s they developed lengths such that mergers would make detectable VHF pulses.

6. Conclusions

In this article, we have described a qualitative model of the physical processes of lightning initiation from the first event of the flash through the first few IBPs (section 5). Our Mechanism suggests that lightning initiations develop as follows:

1. An IE begins the process of changing the nonconducting air into a conductor. The IE can be either weak or strong, called herein a Weak-IE or a NBE-IE, respectively. In both types of IEs, relativistic runaway particles seeded via Extensive Air Showers in a strong electric field, start classic electron avalanches in many small volumes in the thundercloud where the electric field, $E > 3 \text{ MV/(m·atm)}$. The 3-D group of electron avalanches causes multiple, nearly simultaneous (synchronized), ordinary positive streamer flashes which radiate strongly in the VHF radio band. In this manner, the Mechanism produces the IE and its characteristic VHF pulse.

2. The Initial E-Change (IEC) follows the IE in all (successful) flashes and involves UPFs. The UPFs develop within the positive streamer flashes via the ionization-heating instability process; the UPFs then merge together to form UPF chains or small networks. The electrical currents in the UPF networks make the relatively slow E-change of the IEC. Pairs of UPF chains also merge into longer and more complex chains. Then the chains form a 3-D network of hot plasma channels, which ultimately creates and supports the development of a bidirectional leader. The various mergers cause the weak VHF pulses and small FA pulses seen during the IEC.

3. The first classic IBP ends the IEC and starts the IB stage. To produce the first classic IBP, two of the 3-D UPF networks (established during the IEC) must develop bidirectional leaders and then merge when their leaders contact each other. Each subsequent classic IBP is caused by the merger of a new 3-D UPF network to the string of previously connected UPF networks that caused the previous IBP(s).

As described above, the Mechanism is consistent with published data of lightning initiation for strong and weak NBE-IE flashes (Bandara et al., 2019; Lyu et al., 2019; Rison et al., 2016) and for Weak-IE flashes (Marshall et al., 2019) that do not begin with an NBE. The Mechanism can also be reasonably extended to explain small precursor-type events and isolated NBEs that are not IEs, in cases where the conditions for the IEC and/or the IBPs do not develop. Despite the qualitative character of the proposed Mechanism, it seems to us sufficiently concrete to test its main points in future experiments.

We conclude with a few important implications of the proposed Mechanism. First, the Mechanism assumes that the regions having sufficient $E$ magnitudes to start ordinary positive streamer flashes are due to small-scale hydrodynamic instabilities and statistical variations of the electric field, and not due to the interaction of the electric field with hydrometeors. However, if hydrometeors are proven able to produce cloud volumes with fields $E_{\text{th}} \geq 3 \text{ MV/(m·atm)}$ necessary for starting streamers, then this circumstance will not significantly change the rest of the Mechanism. All the other components of the Mechanism would stay the same independent of the physical cause for the suitable large $E$ magnitudes within small cloud volumes.

Second, in our Mechanism positive streamer flashes play the key role in making the IE, whether a Weak-IE or a strong NBE-IE. Although each streamer flash moves with a reasonable speed $< 5 \times 10^8 \text{ m/s}$, the apparent motion during the IE can be much larger, $3–10 \times 10^7 \text{ m/s}$. This fundamental difference between actual motion and apparent speed is because the streamer flashes are initiated along the paths of a group of relativistic charged particles which are moving essentially at the speed of light. In contrast, Rison et al. (2016) and Tilles et al. (2019) have postulated mechanisms for NBEs that initiate flashes based on FPB moving downward and FNB moving upward at speeds of $4–10 \times 10^7 \text{ m/s}$. To us, such speeds for streamers do not seem
reasonable, and, as far as we know, there is no experimental evidence for such high speeds of streamers in air at pressures of 0.3–1 atm.

The Mechanism proposes slightly different physical processes for the large-amplitude, long-duration, “classic” IBPs (e.g., Weidman & Krider, 1979) and weaker, shorter IBPs (e.g., Nag et al., 2009). Weaker, shorter duration IBPs occur with the merging of two UPFs, a UPF with a UPF chain, or two UPF chains. Classic IBPs occur instead by the merging of two plasma networks, each of which evolved from a large UPF network. This result can help explain one mystery of the wide variation of activity observed in the IB stage.

Finally, an important feature of the proposed Mechanism is the fundamental three-dimensionality of the physical processes proposed, including the IE, rather than a single linear bidirectional leader. This approach makes it possible to explain short IEC times followed by powerful IBPs. Furthermore, because of the hypothesis of small-scale 3-D variations in E, the Mechanism also readily explains the varied development of initiation events in different flashes, including the wide range of IEC durations and amplitudes (e.g., Marshall, Schulz, et al., 2014), the wide range of IBP durations, inter-IBP times, IBP amplitudes, number of subpulses in the classic IBPs (e.g., Bandara et al., 2019; Marshall et al., 2013; Stolzenburg et al., 2013, 2014), and the seemingly random amplitude order of the classic IBPs (e.g., Smith et al., 2018). These variations among real lightning flashes are much harder to understand if initiation occurs a single smooth region of large E.

Data Availability Statement

The important data supporting the conclusions of this paper are included in the main text. More detailed data are available through Andreev et al. (2014); Karunarathne et al. (2014, 2015, 2020); Kolmasova et al. (2019); Kostinskiy et al. (2015a, 2015b, 2018); Marshall, Stolzenburg, et al. (2014); Marshall, Schulz, et al. (2014); Marshall et al. (2019); and Stolzenburg et al. (2013, 2014).

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References

Andreev, M. G., Bogatov, N. A., Kostinskiy, A. Yu., Makal’sky, L. M., Mareev, E. A., Suhharevsky, D. I., & Syssoev, V. S. (2014). First detailed observations of discharges within the artificial charged aerosol cloud, XV International Conf. on Atmospheric Electricity, June 2014, Norman, OK, USA. https://www.nssl.noaa.gov/users/manseil/iae2014/preprints/Andreev_11.pdf

Attansio, A., Krehbiel, P. R., & da Silva, C. L. (2019). Griffiths and Phelps lightning initiation model, revisited. Journal of Geophysical Research: Atmospheres, 124, 8076–8094. https://doi.org/10.1029/2019JD030399

Babich, L. P., Bochkov, E. I., Kutsyk, I. M., Neubert, T., & Chanrion, O. (2016). Positive streamer initiation from raindrops in thundercloud fields. Journal of Geophysical Research: Atmospheres, 121, 6393–6403. https://doi.org/10.1002/2016JD024960

Babich, L. P., Donskoy, E. N., Ilkev, R. I., Kutsyk, I. M., & Roussel-Dupre, R. A. (2004). Fundamental parameters of a relativistic runaway electron avalanche in air plasma. Physics Reports, 387(7), 616–624. https://doi.org/10.1016/j.physrep.2003.11.001

Bandara, S., Marshall, T., Karunarathne, S., Karunarathne, N., Siedlecki, R., & Stolzenburg, M. (2019). Characterizing three types of negative narrow bipolar events in thunderstorms. Atmospheric Research, 227, 263–279. https://doi.org/10.1016/j.atmosres.2019.05.013

Bazelyan, E. M., Aleksandrov, N. L., Raizer, Y. P., & Konchakov, A. M. (2007). The effect of air density on atmospheric electric fields required for lightning initiation from a long airborne object. Atmospheric Research, 88(2), 126–138. https://doi.org/10.1016/j.atmosres.2007.04.001

Bazelyan, E. M., & Raizer, Y. P. (1998). Spark discharge. Boca Raton, FL: CRC Press.

Bazelyan, E. M., & Raizer, Y. P. (2000). Lightning physics and lightning protection. Bristol: IOP Publishing.

Bazelyan, E. M., Raizer, Y. P., & Aleksandrov, N. L. (2007). The effect of reduced air density on streamer-to-leader transition and on properties of long positive leader. Journal of Physics D: Applied Physics, 40, 4133–4144. https://doi.org/10.1088/0022-3727/40/14/007

Betz, H. D., Marshall, T. C., Stolzenburg, M., Schmidt, K., Oettinger, W. P., Defer, E., et al. (2008). Detection of in-cloud lightning with VLF/LF and VHF networks for studies of the initial discharge phase. Geophysical Research Letters, 35, L23802. https://doi.org/10.1029/2008GL035820

Brothers, M. D., Bruning, E. S., & Mansell, E. R. (2018). Investigating the relative contributions of charge deposition and turbulence in organizing charge within a thunderstorm. Journal of the Atmospheric Sciences, 75(9), 3265–3284. https://doi.org/10.1175/JAS-D-18- 0007.1

Bruning, E. S., & MatCGorman, D. R. (2013). Theory and observations of controls on lightning flash size spectra. Journal of the Atmospheric Sciences, 70(12), 4012–4029. https://doi.org/10.1175/JAS-D-12-0289.1

Campos, L. Z. S., & Saha, M. M. F. (2013). Visible channel development during the initial breakdown of a natural negative cloud-to-ground flash. Geophysical Research Letters, 40, 4756–4761. https://doi.org/10.1002/2013GL059904

Chapman, R., Marshall, T. C., Stolzenburg, M., Karunarathne, S., & Karunarathne, N. (2017). Initial electric field changes prior to initial breakdown in nearby lightning flashes. Journal of Geophysical Research: Atmospheres, 122, 3718–3732. https://doi.org/10.1002/ 2016JD025859

Colgate, S. A. (1967). Enhanced drop coalescence by electric fields in equilibrium with turbulence. Journal of Geophysical Research, 72, 479–487. https://doi.org/10.1029/JZ072i002p0479

da Silva, C. L., & Pasko, V. P. (2012). Simulation of leader speeds at gigantic jet altitudes. Geophysical Research Letters, 39, L13805. https://doi.org/10.1029/2012GL052251
Lyu, F., Cummer, S. A., Qin, Z., & Chen, M. (2019). Lightning initiation processes imaged with very high frequency broadband interferometry. Journal of Geophysical Research: Atmospheres, 124, 2994–3004. https://doi.org/10.1029/2019JD029817

Mareev, E. A., Sorokin, A. E., & Trakhtengerts, V. Y. (1999). Effects of collective charging in a multiflow aerosol plasma. Plasma Physics Reports, 25(3), 261–272.

Marshall, T., Bandara, S., Karunarathne, N., Karunarathne, S., Kolmasova, I., Siedlecki, R., & Stolzenburg, M. (2019). A study of lightning flash initiation prior to the first initial breakdown pulse. Atmospheric Research, 217, 10–23. https://doi.org/10.1016/j.atmosres.2018.10.013

Marshall, T., Schulz, W., Karunarathna, N., Karunarathne, S., Stolzenburg, M., Vergeiner, C., & Warner, T. (2014). On the percentage of lightning flashes that begin with initial breakdown pulses. Journal of Geophysical Research: Atmospheres, 119, 445–460. https://doi.org/10.1002/2013JD020854

Marshall, T., Stolzenburg, M., Karunarathne, N., & Karunarathne, S. (2014). Electromagnetic activity before initial breakdown pulses of lightning. Journal of Geophysical Research: Atmospheres, 119, 12,558–12,574. https://doi.org/10.1002/2014JD022155

Marshall, T. C., & Rust, W. D. (1991). Electric field soundings through thunderstorms. Journal of Geophysical Research, 96, 22,297–22,306. https://doi.org/10.1029/91JD02486

Marshall, T. C., & Stolzenburg, M. (1998). Estimates of cloud charge densities in thunderstorms. Journal of Geophysical Research, D103, 19,769–19,775.

Marshall, T. C., Stolzenburg, M., Karunarathne, S., Stolzenburg, M., Lu, G., Betz, H.-D., & Briggs, M. (2013). Initial breakdown pulses in intracloud lightning flashes and their relation to terrestrial gamma ray flashes. Journal of Geophysical Research: Atmospheres, 118, 10,907–10,925. https://doi.org/10.1002/jgrd.50866

Marshall, T. C., Stolzenburg, M., Maggio, C. R., Coleman, L. M., Krehbiel, P. R., Hamlin, T., et al. (2005). Observed electric field values observed near initial lightning initiation. Geophysical Research Letters, 32, L03813. https://doi.org/10.1029/2004GL021802

Nag, A., DeCarlo, B. A., & Rakov, V. A. (2009). Analysis of microsecond- and submicrosecond-scale electric field pulses produced by cloud and ground lightning discharges. Atmospheric Research, 91, 316–325. https://doi.org/10.1016/j.atmosres.2008.01.014

Nag, A., Rakov, V. A., Tsalikis, D., & Cramer, J. A. (2010). On phenomenology of compact intracloud lightning discharges. Journal of Geophysical Research, 115, D14115. https://doi.org/10.1029/2009JD012957

Nighan, W. L. (1977). Causes of thermal instability in externally sustained molecular discharges. Physical Review A, 15(4), 1701–1720. https://doi.org/10.1103/PhysRevA.15.1701

Panchenko, V. Y., Zavalov, Y. N., Galushkin, M. G., Grishchev, R. V., Golubev, V. S., & Dubrov, V. D. (2006). The development of turbulence in the active medium of a fast-flow gas-discharge laser. Laser Physics, 16(1), 40–51. https://doi.org/10.1134/S1054660X0601004X

Petersen, D., Bailey, M., Beasley, W. H., & Hallett, J. (2008). A brief review of the problem of lightning initiation and a hypothesis of initial lightning leader formation. Journal of Geophysical Research, 113, D17205. https://doi.org/10.1029/2007JD009036

Petersen, D., Bailey, M., Hallett, J., & Beasley, W. (2015). Laboratory investigation of corona initiation by ice crystals and its importance to lightning. Quarterly Journal of the Royal Meteorological Society, 141, 1283–1293. https://doi.org/10.1002/qj.2436

Phelps, C. T. (1974). Positive streamer system intensification and its possible role in lightning initiation. Journal of Atmospheric and Terrestrial Physics, 36, 103–111. https://doi.org/10.1016/0021-9169(74)90070-1

Popov, N. A. (2009). Study of the formation and propagation of a leader channel in air. Plasma Physics Reports, 35(9), 785–793. https://doi.org/10.1007/s11143-009-90074

Raiser, T. (1991). Gas discharge physics (p. 1–449). Springer-Verlag.

Rakov, V. A., & Uman, M. A. (2003). Lightning: Physics and effects. Cambridge: Cambridge Univ. Press.

Riousset, J. A., Pasko, V. P., & Bourdon, A. (2010). Air-density-dependent model for analysis of air heating associated with streamers, leaders, and transient luminous events. Journal of Geophysical Research, 115, A12321. https://doi.org/10.1029/2010JA015918

Rison, W., Krehbiel, P. R., Stock, M. G., Edens, H. E., Shao, X., Thomas, R. J., et al. (2016). Observations of narrow bipolar events reveal how lightning is initiated in thunderstorms. Nature Communications, 7, 10721. https://doi.org/10.1038/ncomms10721

Rutjes, C., Ebert, U., Butiáik, S., Scholten, O., & Trinh, T. N. G. (2019). Generation of seedextensive air showers, and the lightning inception problem including narrow bipolar events. Journal of Geophysical Research: Atmospheres, 124, 7255–7269. https://doi.org/10.1029/2018JD029040

Smith, E. M., Marshall, T. C., Karunarathne, S., Siedlecki, R., & Stolzenburg, M. (2018). Initial breakdown pulse parameters in intracloud and cloud-to-ground lightning flashes. Journal of Geophysical Research: Atmospheres, 123, 2129–2140. https://doi.org/10.1002/2017JD027729

Stolzenburg, M., & Marshall, T. C. (2009). Charge structure and dynamics in thunderstorms. Space Science Reviews, 137(1–4), 355–372. https://doi.org/10.1007/s11214-008-9338-z

Stolzenburg, M., Marshall, T. C., & Karunarathne, S. (2020). On the transition from initial leader to stepped leader in negative cloud-to-ground lightning. Journal of Geophysical Research: Atmospheres, 125, e2019JD031765. https://doi.org/10.1029/2019JD031765

Stolzenburg, M., Marshall, T. C., Karunarathne, S., Karunarathne, N., & Orville, R. E. (2014). Leader observations during the initial breakdown stage of a lightning flash. Journal of Geophysical Research: Atmospheres, 119, 12,198–12,221. https://doi.org/10.1002/2014JD021994

Stolzenburg, M., Marshall, T. C., Karunarathne, S., Vickers, L. E., Warren, T. A., et al. (2013). Luminosity of initial breakdown pulses in lightning. Journal of Geophysical Research: Atmospheres, 118, 2918–2937. https://doi.org/10.1002/jgrd.50276

Stolzenburg, M., Marshall, T. C., Rust, W. D., Bruning, E., MacGorman, D. R., & Hamlin, T. (2007). Electric field values observed near lightning flash initiations. Geophysical Research Letters, 34, L04804. https://doi.org/10.1029/2006GL028777

Stolzenburg, M., Rust, W. D., & Marshall, T. C. (1998). Electrical structure in thunderstorm convective regions: 3. Synthesis. Journal of Geophysical Research, 103, 14097. https://doi.org/10.1029/98JD03545

Tilles, J. N., Liu, N., Stanley, M. A., Krehbiel, P. R., Rison, W., Stock, M. G., et al. (2019). Fast negative breakdown in thunderstorms. Nature Communications, 10(1), 1648. https://doi.org/10.1038/s41467-019-09621-z

Trakhtengerts, V. I. (1989). On the nature of electric cells in a thundercloud. Reports of the USSR Academy of Sciences (Doklady Akademii Nauk SSSR), 308(3), 584–586. (in Russian)

Trakhtengerts, V. Y., & Iudin, D. I. (2005). Current problems of electrodynamics of a thunderstorm cloud. Radiophysics and Quantum Electronics, 48(9), 720–730. https://doi.org/10.1007/s11141-005-0116-4

Trakhtengerts, V. Y., Iudin, D. I., Kulchitsky, A. V., & Hayakawa, M. (2002). Kinetics of runaway electrons in a stochastic electric field. Physics of Plasmas, 9(6), 2762–2766. https://doi.org/10.1063/1.1473782
Trakhtengertz, V. Y., Mareev, E. A., & Sorokin, A. E. (1997). Electrodynamics of a convective cloud. *Radiophysics and Quantum Electronics, 40*(1–2), 77–86. https://doi.org/10.1007/BF02677826

Velikhov, E. P., Pis'mennyi, V. D., & Rakhimov, A. T. (1977). The non-self-sustaining gas discharge for exciting continuous wave gas lasers. *Soviet Physics Uspekhi USSR, 20*(7), 586–602. https://doi.org/10.1070/PU1977v020n07ABEH005445

Weidman, C. D., & Krider, E. P. (1979). The radiation field waveforms produced by intracloud lightning discharge processes. *Journal of Geophysical Research, 84*(C6), 3159–3164. https://doi.org/10.1029/JC084iC06p03159

Willett, J. C., Bailey, J. C., & Krider, E. P. (1989). A class of unusual lightning electric field waveforms with very strong high-frequency radiation. *Journal of Geophysical Research, 94*, 16255. https://doi.org/10.1029/JD094iD13p16255

Yuter, S. E., & Houze, R. A. Jr. (1995). Three-dimensional kinematic and microphysical evolution of Florida cumulonimbus. Part I: Spatial distribution of updrafts, downdrafts, and precipitation. *Monthly Weather Review, 123*, 1921–1940. https://doi.org/10.1175/1520-0493(1995)123<1921:TDKAME>2.0.CO;2