Problems in Lightning Physics—The Role of Polarity Asymmetry

Earle R. Williams
Massachusetts Institute of Technology
(earlew@ll.mit.edu)
781-981-3744

Submitted to:
Plasma Sources, Science and Technology
Institute of Physics Publishing
Temple Back
Bristol
BS1 6BE
United Kingdom

October 2005

1. Introduction

Lightning is erratic, tortuous, fitful, chaotic and unpredictable. As the late Bernard Vonnegut remarked: "What theoretician would have predicted lightning?". Indeed, many aspects of lightning behavior have defied theoretical prediction and replication by models. Important insights about natural lightning behavior have come instead from the exploration of laboratory scale discharges and artificially triggered lightning.

This paper is concerned with contemporary problems in lightning physics. In contemplating this subject, it occurred to the author that many of these problems involve polarity asymmetry, and so it was decided to make this a central theme of the review. Examples include the asymmetrical behavior of positive and negative streamers, and their thermalized counterparts, the leaders. Positive ground flashes exhibit single strokes and continuing current, whereas negative flashes are prone to current cutoff and multiple strokes. Gamma rays in space are associated with flashes with positive polarity, but not the highly energetic flashes that also produce sprites in the mesosphere. Sprites in the mesosphere are also associated almost exclusively with positive polarity flashes, also flashes to ground, though negative flashes appear to have sufficient charge moment to make sprites. Negative ground flashes are notably shorter in duration when they connect to ground than positive flashes. All of these asymmetries will be discussed. Some of these issues have satisfactory interpretations, and some do not.

2. The Thundercloud—The Lightning Source

The two polarities of electricity were identified and named by Benjamin Franklin (Cohen, 1990). Franklin also discovered by clever experiment—and it is now well established—that thunderclouds are generally positive on top and negative in lower regions.

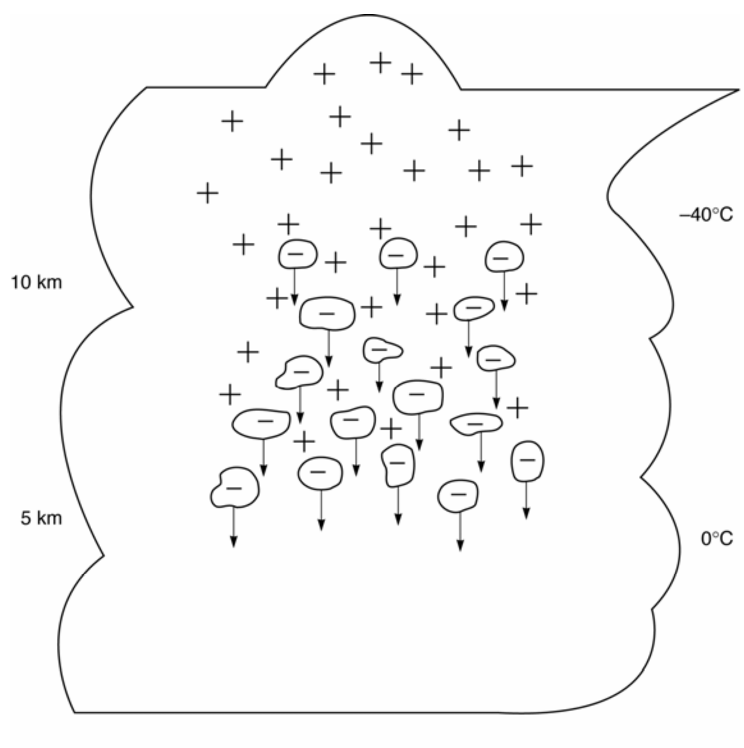

Figure 1: Thundercloud with typical positive dipole structure, maintained by differential motions of ice particles under gravity.

The underlying physical explanation for this well defined cloud polarity remains elusive even today, thought there is abundant evidence that ice microphysics is playing a central role (Krehbiel, 1986). The zone of major charge separation—the central dipole region—is invariably characterized by sub-freezing temperature for water substance. Curiously, Michael Faraday (1843), in studies of the triboelectric series, found that ice charged positively when contacted by many other substances. These systematic results were later confirmed by Sohnke (1886) and by Shaw (1929).

The Earth as a whole is known to carry a net negative charge, with the opposite positive charge in the lower troposphere. This polarity asymmetry is also generally attributed to the thundercloud itself, and is consistent with present thinking about the global electrical circuit (Williams, 2003).

This review is concerned primarily with lightning, and so the physical origin of thundercloud polarity will not be further explored. It is important to note however that the polarity asymmetry in the numbers of positive and negative lightning flashes to ground is attributable to the dominant dipole structure in Figure 1. Negative polarity ground flashes are roughly ten times more numerous than positive flashes because of the proximity of the lower negative charge reservoir to ground.

3. Lightning Flashes as Double-Ended Trees

Lightning in thunderclouds is distinctly different from conventional laboratory discharges involving charge on metallic electrodes. In thunderclouds the positive and negative charge is spatially distributed on scales of hundreds of meters to kilometers and is carried on the ice and water particles that compose the cloud. The great majority of all lightning flashes that are initiated in thunderclouds are double-ended 'trees' that bridge regions of space charge with opposite polarity. One 'tree' invades positive charge and the other negative charge. Common lightning flashes, all in this same general form, are illustrated in.

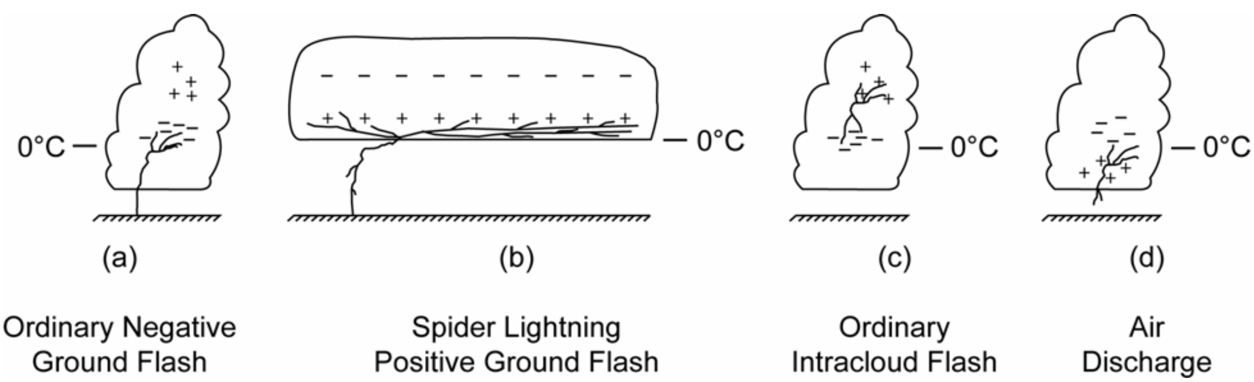

Figure 2: Common lightning types, all examples of double-ended 'trees' in thunderclouds. a) negative cloud-to-ground lightning in isolated thundercloud, b) positive cloud-to-ground lightning in stratiform precipitation of a mesoscale convective system, c) intracloud lightning in isolated thundercloud, and d) air discharge in an isolated thundercloud.

Observations have established that the two ends of this double-ended discharge are notably asymmetrical. Such asymmetry was first documented in surface discharges in the laboratory (Toepler, 1921; Simpson, 1926),

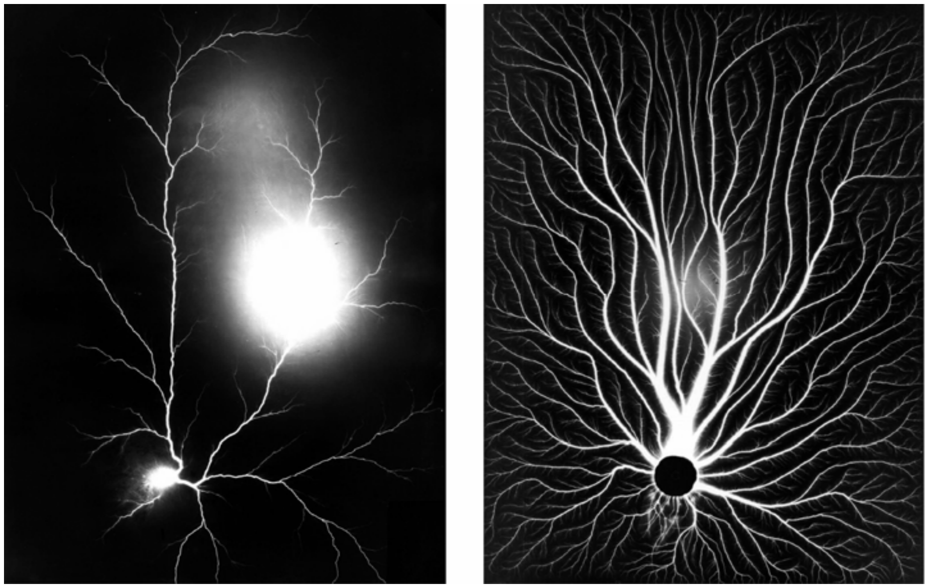

Figure 3: Surface discharges with a) positively, and b) negatively charged surfaces, showing marked contrast in structure.

from which it was concluded that only the positive end was likely to develop as a dendritic structure. The long-standing persistence of this view is supported by numerous sketches of lightning found in the literature, as well as with charged surfaces by Larigaldie and colleagues at ONERA in France clearly showed double-ended trees and with distinct spatial asymmetry.

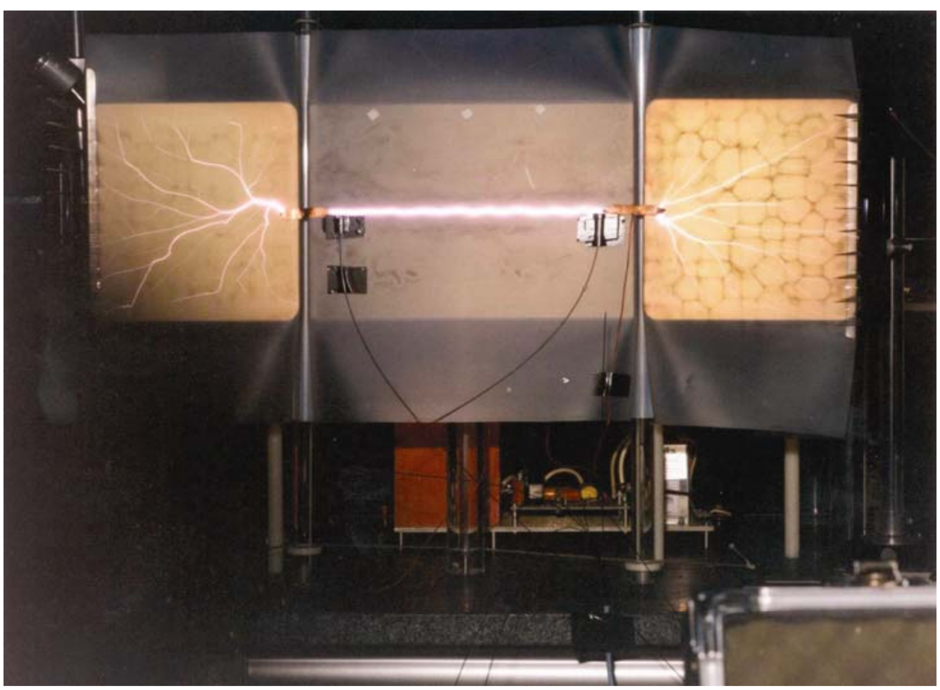

Figure 4: A double-ended tree linking positively and negatively charged surfaces in the laboratory.

The two ends of the discharge are often visible in the 'Typsy' technique in rocket-triggered lightning (Hubert, 1984) in which an isolated wire segment (as in Figure 6) serves to launch the double-ended tree. In many cases the two ends of the tree are notably dissimilar. This visual asymmetry remains to be quantified however.

In the thunderstorm context, Mazur (1989) documented double-ended tree development from aircraft as the lightning initiator and has championed this concept in recent years. His aircraft observations were interpreted in the context of the bi-directional leader concept of Kasemir (1960), the prototypical double-ended tree. Oftentimes the luminous channels of lightning are obscured from visual observation by cloud.

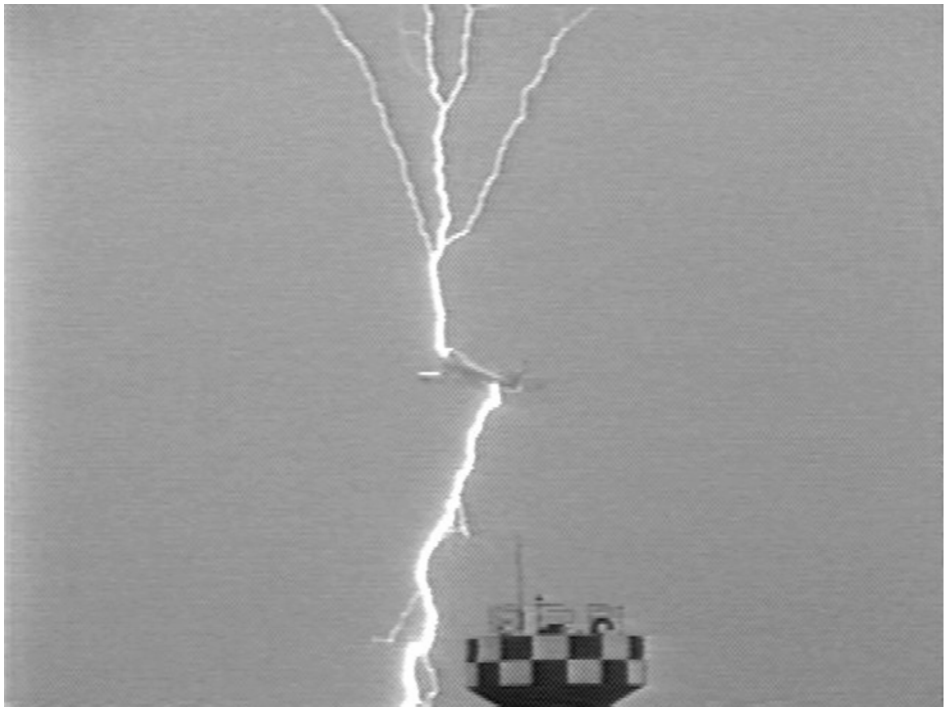

Figure 5: A double-ended lightning tree initiated on an airplane beneath a thundercloud. (Courtesy of Z. Kawasaki)

Figure 5 shows an exceptional circumstance of lightning initiation by aircraft beneath the cloud. Although spatial asymmetry is evident in the double-ended tree, it is presently not well established in general if the polarity of the lightning tree can be discerned on the basis of visual observations. Indeed, part of the problem here is having a large number of observations (Waldteufel et al, 1980) to study of the kind shown in Figure 5.

Detailed pictures of lightning can now be "painted" in three dimensions with radio frequency mapping methods in the VHF frequency range. As noted in early studies by Mazur (1989) and Mazur et al (1997), and in greater quantitative detail by Thomas et al (2001), these pictures show order-of-magnitude asymmetry in the radio frequency energy radiated by extending lightning channels in the two ends of the 'tree'. Curiously, the positive end that came to prominence in the earlier studies (Simpson, 1926) based on laboratory experiments, is relatively silent (often completely silent (Mazur, 1989)), whereas the negative end is extraordinarily 'noisy'. A possible explanation for this asymmetry rests on a well- recognized asymmetry in gaseous electronics, and a consideration of other unique behavior documented at the laboratory scale.

4. Fundamental Aspects of Polarity Asymmetry

The mobility contrast between electrons and positive ions is the most widely recognized asymmetry in gaseous electronics and is a key starting point in understanding asymmetry of all kinds. According to the Langevin equation (Cobine, 1958) the mobility of charged particles in gases is inversely proportional to the charge particle mass. Since the mass of positive ions in ionized air is $> 10^4$ times that of the electrons, the large electron mobility makes it immediately the dominant charge carrier. This result in turn has important consequences at larger scales, as will be shown.

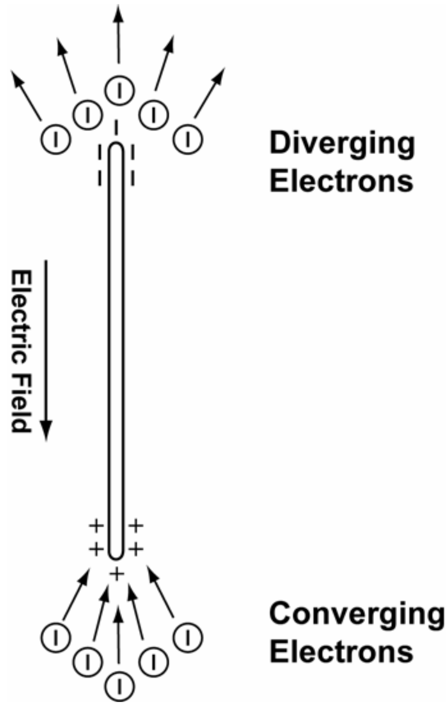

Figure 6: Illustration of polarity asymmetry for a long thin conductor in an electric field. Mobile electrons are convergent on one end and divergent at the other.

Figure 6 illustrates a conductive filament extending in an ambient electric field—a prototypical double-ended tree. At the positive end, any available (mobile) electrons are converging into higher field toward positive charge, a condition favorable for continued extension (the 'easy' direction). At the opposite end, the mobile electrons are diverging into a region of weaker electric field, a less favorable process (the 'hard' direction). Consistent with Simpson (1926), the positive end of the tree is favored for extension and will be most strongly manifest. Similar ideas pertaining to Figure 6 in the lightning context were advanced by Ogawa and Brook (1964).

Contemporary measurements of the threshold fields for the extension of positive and negative streamers are qualitatively consistent with the asymmetry illustrated in Figure 6. The threshold field for positive streamers (at P= 1000 mb) is 5×10^5 v/m (Griffiths and Phelps, 1976), whereas that threshold for negative streamers is 10×10^5 v/m, twice as large (Bazelyan and Raizer, 2000). Unfortunately there is presently no theory to account for this factor- of-two contrast. The implications for a discharge initiated at a point (a precipitation particle or the body of an aircraft), and developing as a double-ended tree are illustrated in Figure 7.

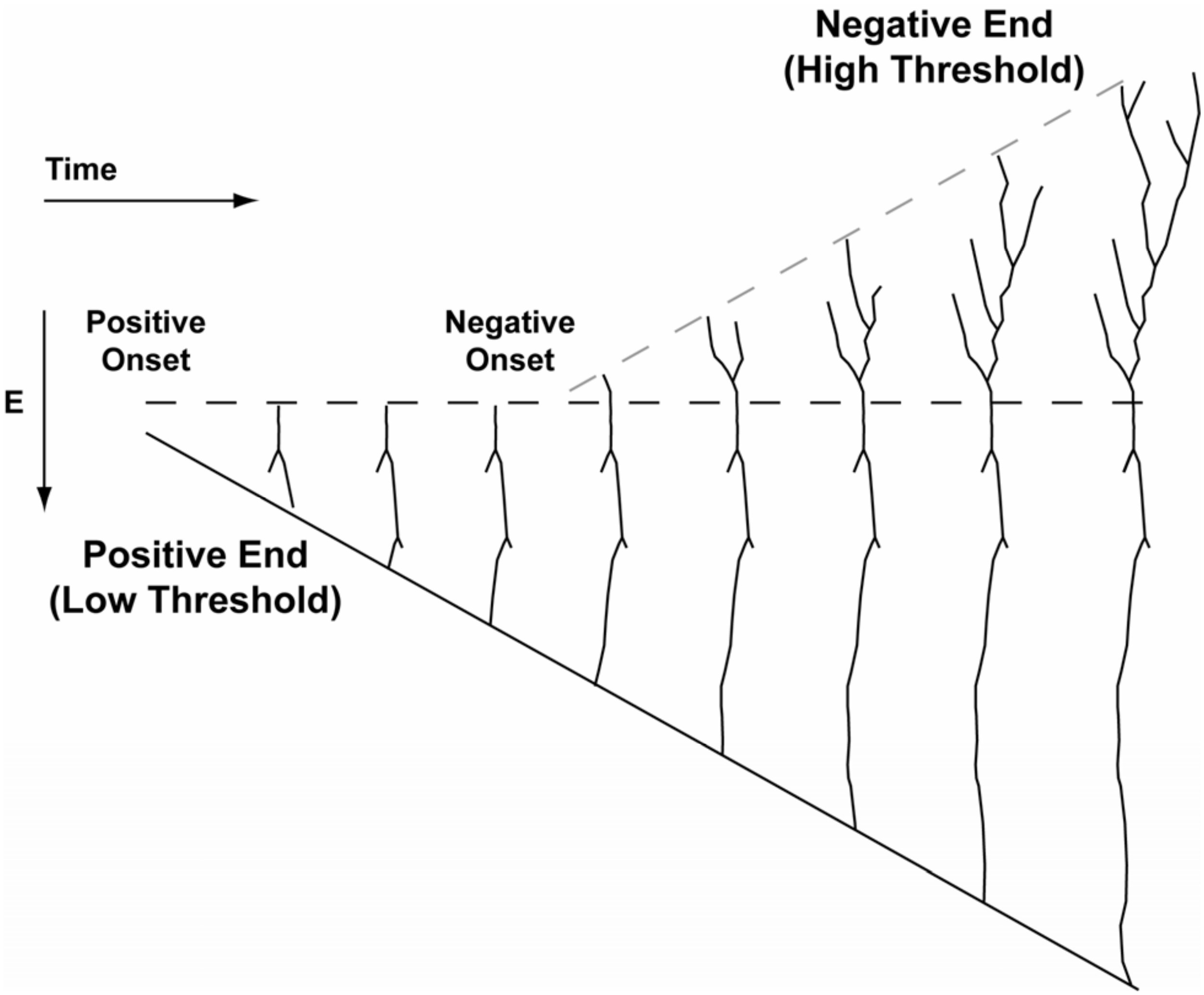

Figure 7: Schematic elongation of a bi-directional streamer/leader system, with positive polarity initiation, followed by extension of the negative end of the double-ended 'tree'.

The positive streamer extends first until the field at the initiation point is sufficiently large to launch the negative streamer in the opposite direction.

The streamer polarity asymmetry is manifest at the large air-insulated Van de Graaff generator (max. voltage ~ 3 Megavolts) at Boston's Museum of Science, where sparks with a positive polarity terminal are notably more energetic. Negative streamers from sharp points at ground potential around the terminal are suppressed by the larger threshold field for that polarity, and allow a larger buildup of positive voltage.

On the basis of the foregoing discussion for streamers, we have a basis for understanding discharge asymmetry, but not the dramatic asymmetry noted earlier in the radio frequency observations (Thomas et al, 2001). Key discoveries which may form the basis for further understanding here were made on laboratory discharges in 1-10 meter gaps. Independent laboratory results in Russia (Stekolnikov and Shkilev, 1960) and in France (Les Renardières Group, 1977; 1981) demonstrated black-and-white asymmetry in the behavior of positive and negative leaders (Bazelyan and Raizer, 2000). In essence, positive leaders progressed smoothly across the air gap, whereas negative leaders were fitful and erratic. This contrast is well illustrated in streak camera photographs for the two leader polarities in Figure 8.

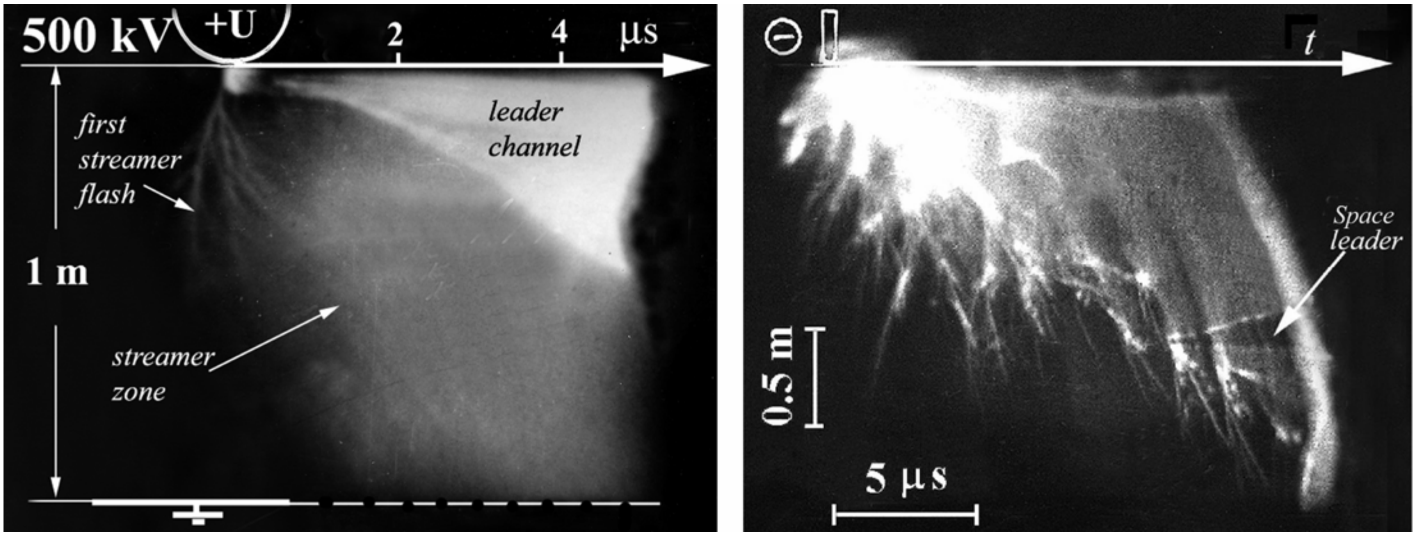

Figure 8: Streak camera imagery contrasting the extension of leaders with positive and negative polarity downward toward a ground plane. The positive leader progresses smoothly, whereas the negative leader is fitful and erratic.

Since the acceleration of electric charge is required to radiate electromagnetic energy, here we have a physical basis for understanding pronounced asymmetry between positive and negative ends of the discharge.

Gallimberti et al (2002) have recently delved more deeply into the asymmetry in behavior between positive and negative leaders in laboratory experiments in France (Les Renardières Group, 1977; 1981). The positive leader extends by virtue of the quasi-steady extension of a 'brush' of positive streamers at its head, whereas the negative leader is substantially more complicated. But as complicated as it appears, the asymmetry between threshold fields for positive and negative streamer extension sheds considerable light on the reasons for behavior. An intermittent bi-directional development occurs in the vicinity of the negative leader head, with positive streamer extension in a backward direction and negative streamer extension forward. Though the evolution is not sufficiently resolved in space and time for full understanding, it is likely that the backward positive extension (the 'easy' direction) occurs first. The bi-directional segment is subsequently fully ionized by what has been referred to as a K-change or mini-return stroke. The current through the entire leader channel then rises transiently to values of hundreds of amperes. This current stands in marked contrast with the peak (steady) current flowing in positive leaders in a similar gap geometry. The quantitative contrast in measureables for positive and negative leaders in 1-10 meter gaps is summarized in Table 1.

Leader Polarity	Gap Length	Recorded Velocity Range	Peak Current
Positive	5–10 m	$1.2–4.2 \times 10^4$ m/s	~ 1 A
Negative	5–7 m	10^5 m/s	~ 100 A

Faster negative polarity requires more voltage to drive it
→ greater heating

Reference: Les Renardieres

Table 1: Summary of polarity asymmetry in laboratory scale experiments

What is the connection between the laboratory scale behavior and lightning? The historical development of these observations and ideas is summarized in Table 2.

1938	B. Schonland identifies negative stepped leaders in streak camera observations
1960	Bidirectional streamer-leader concept (H. Kasemir)
1962	Russian work on long air gaps (Stekelnikov and Shkilev) Stepping behavior for negative leaders in the laboratory
1970s	French work at “Les Renardieres” on 10 m air gaps Image intensifier cameras document bi-directional development on negative leader tips
1989	Application of bi-directional lightning development to aircraft lightning strikes (V. Mazur)
2000	Application of lab results to lightning (No direct observations of bi-directional development on negative end of lightning tree) (Gallimberti and Bondiou; Bazelyan and Raizer)
2001	Pronounced asymmetry of VHF radiation from the lightning “tree” with new lightning mapping systems (R. Thomas)

Table 2: Summary of key historical observations and developments.

Schonland recognized in the 1930’s, based on streak camera photographs, that descending leaders with negative polarity were ‘stepped’—downward surges in the leader head with accompanying surges in current to values of kiloamperes. It now seems likely that these steps are bi-directional developments followed by thermalization/ionization, as in the laboratory scale phenomenon at a smaller scale (Les Renardières Group, 1981). As far as this author is aware, the space-time resolution in stepped leader observations is presently inadequate to verify this common behavior (M. Uman, personal communication, 2005), though moving-camera images of descending positive and negative leaders (Salanave, 1980) show distinctly different structure, not unlike that shown in Figure 8. If the common behavior is true, all theories for stepped leader behavior in lightning (Schonland (1938; 1953); Bruce (1944)) will require revision. In such a case, the intermittent bi-directional development serves as a radiating element that is completely absent for positive leaders, and furthermore provides a qualitative explanation for order-of-magnitude asymmetry in VHF radiation in the two ends of the lightning tree initially documented by Mazur (1989) and subsequently explored in greater detail by Thomas et al (2001).

5. Polarity Asymmetry in Cloud-to-Ground Lightning

5.1 Observed Behavior of Natural Cloud-to-Ground Lightning

Cloud-to-ground lightning flashes are known to occur in both negative and positive polarity, as noted. Negative flashes are more prevalent by nearly an order of magnitude, presumably because of the proximity to ground of the main negative charge in thunderclouds (Figure 1). The general behavior of these two lightning types is notably asymmetrical. Positive ground flashes are almost invariably single stroke only, followed by a continuing current (Orville et al, 1987; Rakov and Uman, 2003). In contrast, the more common negative ground flash is more prone to exhibit multiple discrete strokes, often without appreciable continuing current. This widely recognized multiple stroke behavior for negative polarity lightning is illustrated in Figure 9.

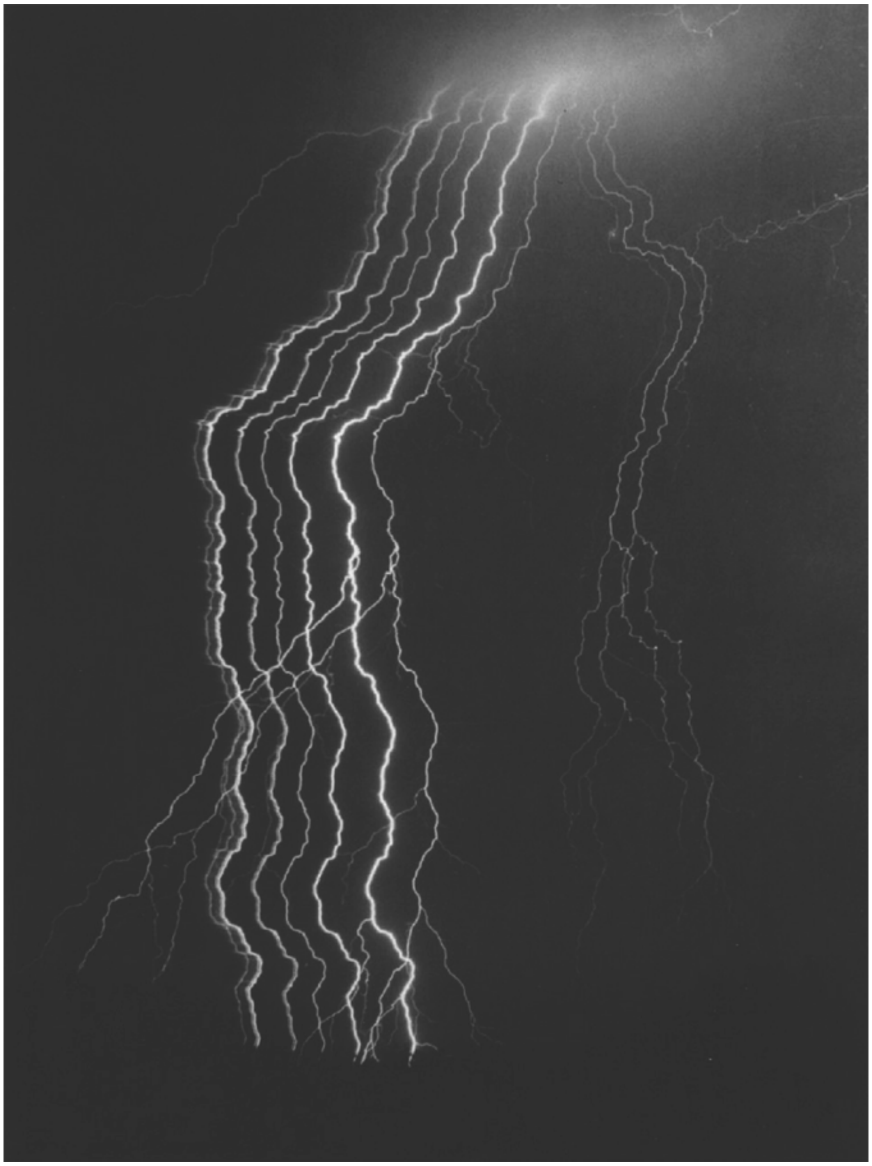

Figure 9: Moving camera image of a cloud-to-ground lightning flashes with negative polarity showing multiple strokes, each becoming cutoff to reinitiate the next stroke (from Rakov and Uman, 2003).

Whether this pronounced asymmetry in behavior has its origin in the spatial distribution of the positive and negative charge reservoirs for the lightning (Williams, 1998), or is caused by the physics of the discharge process itself, has long been an open question. Here this issue is revisited.

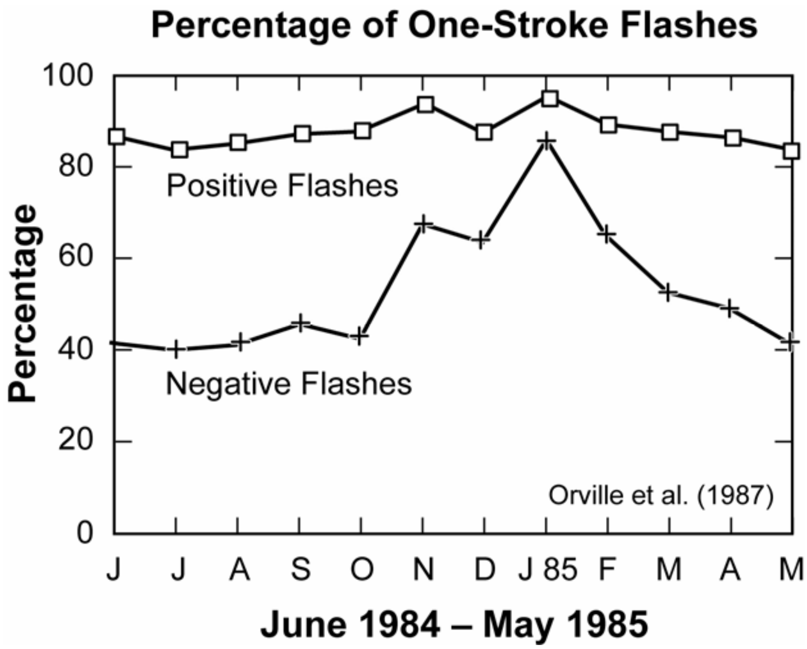

Figure 10: Seasonal variation of mean lightning stroke multiplicity for positive and negative flashes to ground (from Orville et al, 1987).

Observations from the National Lightning Detection Network in Figure 10 illustrate the pronounced asymmetry in stroke multiplicity for negative and positive ground flashes, with season (Orville et al, 1987). Positive ground flashes have a strong tendency for single-stroke multiplicity in all months, whereas negative flashes are more likely to exhibit multiple strokes. The tendency for BOTH flash polarities to move toward single stroke behavior (with continuing current) will be addressed in the subsequent interpretation section.

The operation of detailed VHF lightning mapping systems in recent years by the New Mexico Institute of Mining and Technology has enabled a closer look at the asymmetry issue for stroke multiplicity for specific flashes. Ron Thomas (personal communication, 2005) notes that when multiple strokes are observed in the case of positive ground flashes, the subsequent strokes generally do not follow the same channel to ground. Thomas is unaware of any cases of multiple strokes in the same channel, whether the flash be an extensive ‘spider’ lightning in a mesoscale convective system (Mazur, 1989; Williams, 1998; Lyons et al, 2003), or a more compact discharge in a thunderstorm supercell with inverted electrical polarity (Lang et al, 2004). This observation has important implications for the physical interpretation, as will be discussed in Section 5.4.

5.2 Common Asymmetries in Laboratory Discharges in 1-10 m gaps, Rocket-triggered lightning and Natural Upward Discharges Initiated on the Ground

A literature review of the behavior of leaders from meter scales in the laboratory to hundred-meter scales in rocket triggered lightning, to kilometer scales in upward propagating natural lightning, demonstrates a reasonably consistent polarity asymmetry in several key parameters: (1) threshold fields for propagation, (2) propagation speeds, (3) continuity of propagation and branching and (4) current flow in the leader channel. These different quantities are examined here in turn.

(1) Threshold fields for propagation

Studies of leader propagation in 5-10 meter air gaps in France (Les Renardières, 1977; 1981) have clearly shown the need for larger applied voltages and cross-gap electric fields in the case of negative leader progression than the opposite polarity. Later theoretical studies (Lalande et al, 2002), building on the asymmetry in threshold fields for streamer propagation, show consistent results.

Investigations of lightning with wire-trailing rockets have revealed the need for larger surface electric fields for successful triggering when a negatively charged rocket is launched toward a positive cloud, than the (more common) situation of opposite polarity (Rakov and Uman, 2003). This contrast is more apparent in summertime experiments (Rakov and Uman, 2003) than for trials in winter in Japan (Horii, 1982). The reasons for this difference are not entirely clear.

Lightning leaders of both polarities in natural lightning do succeed in reaching the ground from the cloud, despite the presence of ambient fields in that region on the order of 10 kV/m or less. Unfortunately, no quantitative studies of polarity asymmetry in this case have been undertaken, as far as we are aware. In laboratory experiments (e.g., Les Renardières) the applied high voltage cannot be applied/withdrawn fast enough to ascertain the critical fields for leader progression, once the leader is fully formed.

(2) Propagation speed

Mean propagation speeds for leaders in 7 meter gaps at Les Renardieres were found to be ~10^5 m/s for negative leaders and ~1-2 x 10^4 m/s for positive leaders (Table 1).
In the case of rocket triggered lightning, Fieux et al (1975) reported upward leader speeds toward negative clouds of 2 x 10^4 m/s but larger upward speeds of 10^5 m/s or more in the case of positive clouds.

(3) Continuity of propagation and branching

The conspicuous asymmetry in mode of leader extension described in Bazelyan and Raizer (2000) and in Rakov and Uman (2003) and reviewed earlier in Section 4, has been well documented for laboratory leaders, also at Les Renardières (1977, 1981). Unfortunately, this behavior has not been firmly established for lightning, though much of the thrust of this article depends on this circumstance. This remains today a high priority for research. The asymmetry in stepping behavior for negative (strongly stepped) and positive (unstepped) leaders is well established (Rakov and Uman, 2003), and so it seems likely that this is a reflection of the bi-directional streamer development in the negative leader end and its absence in the positive end.

In the case of rocket triggered lightning, Horii and Nakano (1995) summarize the results as follows:

> *"The characteristics of the leader depend on the polarity of the cloud. The positive leader aimed toward the negatively charged cloud has the velocity of 10^4 to 10^5 m/s and propagates continuously, while the negative leader to the positively charged cloud has the velocity of 10^5 to 10^6 m/s and propagates in steps (Higashiyama et al, 1980; Horii et al, 1983)"*

Asymmetry in branching is likely linked with the asymmetry in leader extension for positive and negative ends of the lightning tree. In the case of rocket triggered lightning, Fieux et al (1975) found branching more prevalent in the case of positive leaders projected toward negative clouds, than for the opposite situation. Horii and Sakurano (1985) reinforce this observation by noting that:

> *"The negative upward leader to positive cloud progresses without branching at about 10^5 to 10^6 m/s."*

Similar findings can be found in Kito et al (1985).

Though it may be a fortuitous result, the photograph of the aircraft strike beneath a thundercloud in Figure 5 (with presumed electrostatic structure similar to that in Figure 1) can be interpreted as an upward-going positive leader system that is extensively branched, and a downward-going negative leader that is not extensively branched.

In the case of natural lightning initiated from towers, Berger and Vogelsanger (1969) noted *"The progression of the positive streamers (note: 'leaders' in present parlance) is in most cases continuous, i.e., without steps."* A negative upward leader they documented showed evidence for stepping and a more fitful progression, as documented in the laboratory for negative polarity in Figure 8. These authors conclude by noting :

"Marked differences in the appearance of positive and negative paths may then be observed. These differences were in fact quantitatively predicted by Toepler some 50 years ago in light of his observations of "gliding" discharges on the surfaces of insulators".

(4) Current flow

Perhaps the most important physical parameter in the interpretation (below) of the general asymmetrical behavior of cloud-to-ground lightning is the magnitude of current flow in the leader channel. In the 7-10 m gap experiments at Les Renardières, the currents recorded in negative leaders are larger than the opposite polarity by an order of magnitude. Similar dominance of current in the case of the negative polarity in large air gaps was found in Mrazek (1998). It must also be emphasized that the current flow in the case of negative polarity, like the current in the lightning stepped leader, is highly erratic, in contrast to the smooth behavior for current in positive leaders.

Rakov and Uman (2003), summarizing results for rocket-triggered lightning, state:

"Horii and Ikeda (1985) reported, for winter lightning, that upward positive leaders were characterized by lower peak current than upward negative leaders, this observation being apparently consistent with the reported lower luminosity of positive leaders (Berger, 1977)."

In summary, distinct polarity asymmetries in four different characteristics have been revealed in a wide variety of observations.

5.3 Heckman's Study of Stroke Multiplicity in Lightning

Stan Heckman (1992) devised a simple but quantitative theory to distinguish lightning flashes composed of discrete strokes from those characterized by a continuing current in a single stroke. This work was submitted as a doctoral thesis at the Massachusetts Institute of Technology, but unfortunately was not subsequently published and so it is not widely known. Given the importance of this result to understanding polarity asymmetry in lightning, a brief discussion is therefore provided here.

Heckman (1992) analyzed the stability of current in a long lightning channel linking the charged cloud aloft and the conductive earth. The extension of the channel into the electric field of the space charge aloft provides for a quasi-steady current source. The lightning channel is characterized by a capacitance and a (non-linear) resistance. The capacitance of a long, thin conductor of length L and radius r is given by

$$C = 2\pi\varepsilon_o L/(\ln(L/r)) \quad \text{farads}$$

The channel resistance per unit length R = E/I is assumed to follow the negative differential resistance observed in laboratory arcs in air (King, 1961), as shown by the current-voltage plot in Figure 11.

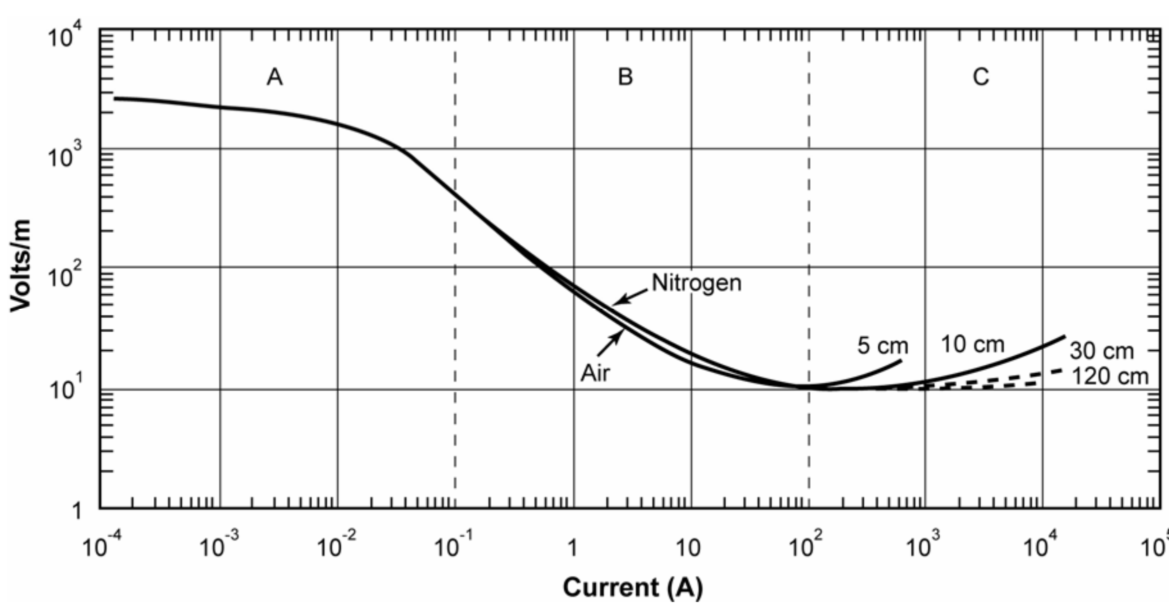

Figure 11: Current and voltage relationship for an electrical arc in air, showing negative differential resistance: the larger the current the smaller the resistance. From King (1961).

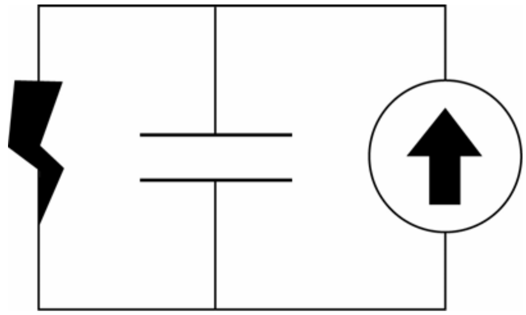

Figure 12: Equivalent circuit for a lightning channel to ground, analyzed by Heckman (1992). The continued extension of lightning into the charged cloud constitutes the current source I, the channel capacitance per unit length times the total channel length is the capacitor C, and the (non-linear) arc resistance per unit length times the total channel length is the total arc resistance R.

The equivalent circuit for the current-fed lightning channel to ground is shown in Figure 12, with the current source in parallel with the channel capacitance C per unit length and the nonlinear resistance R per unit length. The channel is assumed to lose energy by processes of conduction, turbulent convection and radiation, all of which are lumped together with an assigned time constant τ taken from empirical laboratory observations in Frind (1960), and shown quantitatively in Figure 13.

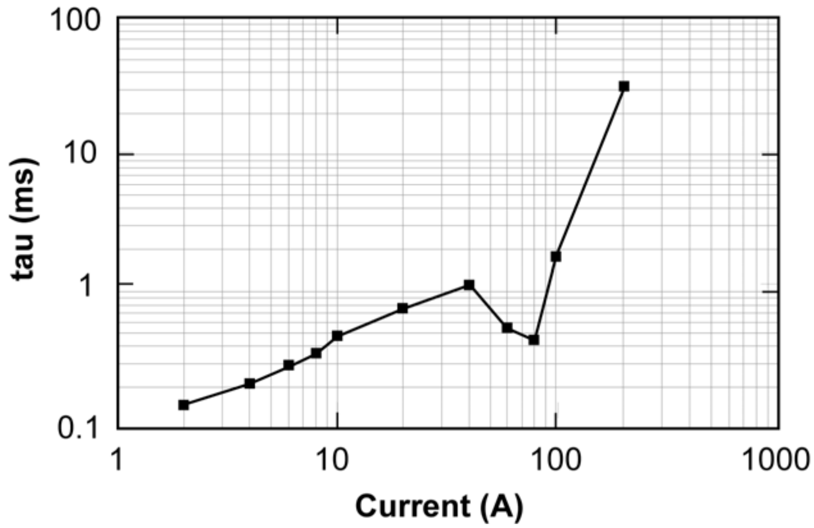

Figure 13: The time constant τ representing the e-folding time of an electric arc in series with a voltage source. Adapted from Frind (1960).

Linear analysis on the circuit in Figure12 results in a simple criterion (RC = τ) separating stable (RC<τ; sustained continuing current) from unstable (RC>τ; current diminishment to cutoff, followed by electric field build-up to a new stroke) behavior.

The 'RC' quantity is an electrical time constant and the 'τ' is a kind of thermodynamic time constant. The unstable condition can be understood as a nonlinear response to a decline in current—the channel resistance rises and the current in the arc declines still further until the channel cuts off entirely. The quantitative instability criterion is illustrated in two key lightning measureables, channel length L and channel current I, in Figure 14.

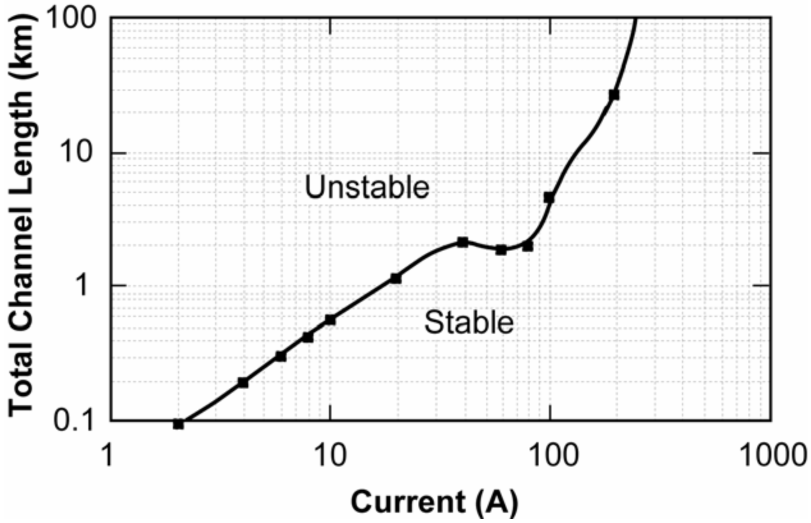

Figure 14: Stability diagram for a lightning channel represented by the equivalent circuit in Fig. 12. Unstable behavior with current cutoff to upper left of stability line; stable behavior with continuing current to lower right of stability line.

Multiple strokes are favored by both small interstroke currents and by long channels. Sustained continuing currents are favored by large interstroke current and by short channels.

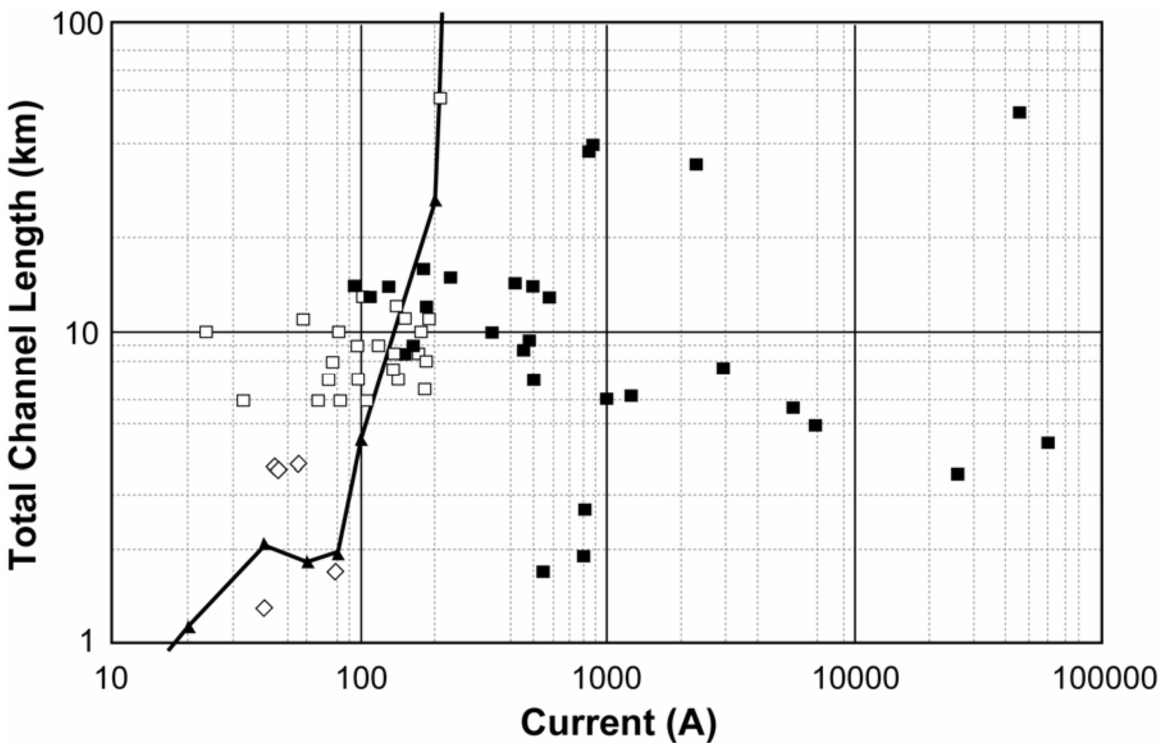

Figure 15: Stability diagram of Fig 14 but now in comparison with observations on thunderclouds from the literature. Open squares represent scenarios with discrete strokes and without continuing current. Filled squares represent continuing current scenarios.

Tests of these theoretical predictions using lightning measurements from the literature are shown in Figure 15. The solid squares represent stable continuing current behavior and the open spaces represent (unstable) discrete stroke behavior. To a good approximation, the stability line divides these two sets of experimental points, with a few outliers.

Heckman's (1992) analysis provides a quantitative foundation to the qualitative picture advanced by Malan and Schonland (1951) that lightning has multiple strokes because the channel to ground becomes resistive and ultimately becomes cutoff, while the upper channel tips continue to extend in the local electric field. The earlier picture of Schonland (1938) that lightning is composed of discrete strokes because the charge in the cloud is in discrete 'lumps' is not necessary according to the foregoing analysis.

5.4 Interpretation of Asymmetry in Cloud-to-ground Flashes

Based on the foregoing considerations of observed asymmetries over a wide range of scales, and the theoretical results of Heckman (1992), we are equipped to return to the fundamental polarity asymmetry of the cloud-to-ground discharge.

Heckman (1992) predicts a stronger tendency for stable continuing current flow without cutoff (and subsequent) strokes when interstroke currents are large. When the interstroke current exceeds 100 amperes, one is likely to lie on the right hand side of the instability boundary in Figure 14, given typical channel lengths in flashes to ground. Furthermore, at this current level, the electric field in the arc channel has attained a minimum value (Figure 11). In the case of positive cloud-to-ground lightning, the interstroke currents are large. Also in the case of positive cloud-to-ground lightning, the interstroke current is maintained by negative leader intrusion into positively charged cloud. The results in Section 5.2 have shown that currents in negative leaders are consistently larger than the opposite polarity, lending strong support to the tendency for single-stroke behavior for positive flashes. It is important to note R. Thomas's observation in this context that *all* positive ground flashes, regardless of size and shape of the positive charge reservoir, remain single stroke.

The strong tendency for positive ground flashes to dominate the single-stroke Q-burst population of transients in Schumann resonance excitation (Ogawa et al, 1967; Huang et al, 1999) is probably also related to the tendency for negative leaders to support larger sustained ('continuing') currents.

Heckman's (1992) instability result (Figure 14) also depends on channel length, with the prediction that the stable, single-stroke/continuing current regime is favored by shorter channel lengths. The results on stroke multiplicity in Figure 10 show that single-stroke behavior *for both lightning polarities* tends to increase in the winter months (Orville et al, 1987). The established dependence of charge separation on in situ temperature (Takahashi, 1978) guarantees that all charge regions of electrified storms are closer to the Earth's surface in the colder winter season. With the accompanying tendency for lightning channels from the main charge reservoirs to ground to shorten significantly, this tendency may account for the tendency toward single stroke behavior. In summer months, the most common scenarios for negative ground flashes and positive ground flashes are shown in Figure 2a and Figure 2b, respectively. Two differences between these two scenarios favor discrete strokes with current cutoff for negative ground flashes and single strokes with continuing current for positive ground flashes. The negative charge reservoir is higher above ground (Jacobson and Krider, 1976; Krehbiel et al, 1979; Koshak and Krider, 1989) than the positive charge reservoir in Figure 2 (Williams, 1998; Lyons et al, 2003), thereby assuring longer channel lengths for negative flashes, on average. Secondly, the intruding end of the lightning 'tree' has negative polarity for the positive ground flash, and hence a tendency (following the findings in Section 5) for larger supply current than the situation for the negative flash. Recalling again the instability predictions of Figure 14, both the larger channel length and lower current in the negative ground flash favor discrete strokes with current cutoff. In contrast, both the shorter channel length and the larger source current for positive ground flashes favor singles strokes followed by sustained continuing current.

These predictions can be examined further with detailed VHF mapping data on lightning for which channel lengths can be extracted and compared with the stroke multiplicities acquired by the National Lightning Detection Network.

6. Lightning Initiation, Electron Runaways, and Gamma Radiation

An active and controversial area in lightning physics concerns the physical origin of dielectric breakdown in thunderclouds, and the source of recently discovered gamma radiation (Smith et al, 2005). The mobile electrons are fundamental players in both a conventional dielectric breakdown process as well as one based on electron runaway (Gurevich and Zybin, 2005), and so polarity asymmetry is again at center stage in this topic.

6.1 Conventional Breakdown of Atmospheric Air

The dielectric strength of pristine air at atmospheric pressure is 3 x 10^6 V/m. The dielectric strength of gases is inversely proportional to gas density (Cobine, 1958). When this standard value is corrected for air density to one density scale height above the Earth's surface, where lightning initiation is most prevalent (Proctor, 1991), one has a reduced value of 1.1 x 10^6 V/m. A key finding and source of puzzlement (Rakov, 2004) is that maximum electric fields recorded in thunderclouds are substantially less than this value. Table 3 summarizes several of these observations. Typical field magnitudes are a factor of 2-3 times smaller than 1.1 x 10^6 V/m

Reference	Sounding Type	Maximum Electric Field, Vm^{-1}
Gunn (1948)	Aircraft	3.4×10^5
Imyanitov et al. (1971)	Aircraft	2.8×10^5
Winn et al.	Rockets	4×10^5
Winn et al.	Balloons	1.4×10^5
Weber et al.	Balloons	1.1×10^5
Byrne et al.	Balloons	1.3×10^5
Fitzgerald (1984)	Aircraft	1.2×10^5
Marshall and Rust (1991)	Balloons	1.5×10^5
Kasemir (as reported by MacGorman and Rust 1998)	Aircraft	3×10^5

Table 3: Summary of maximum measured electric field in thunderclouds.

6.2 Possible Interpretations of the Discrepancy in Field Magnitudes in Thunderclouds

At least four different arguments have been offered up to account for this apparent discrepancy, based on the following: (1) a threshold field for an electron runaway process, (2) heterogeneities in the cloud, (3) a threshold field for positive streamer propagation, and (4) a sampling problem in space and in time. These four arguments are briefly summarized in turn. We begin with the most recent suggestion (Gurevich and Zybin, 2005), and then treat the older hypotheses.

(1) Breakeven field for electron runaway

Mobile electrons are in principal capable of acquiring exceptional energy in electric fields because their collisional crossection with the surrounding medium tends to decrease with increasing energy. Theoretical calculations (Gurevich and Zybin, 2005) for the breakeven electric field needed for the extension of an electron avalanche by this process is about one order of magnitude less than the conventional dielectric strength.

Marshall et al (1995) and Gurevich and Zybin (2005) offer this theory as an explanation for the discrepancy in electric field magnitudes.

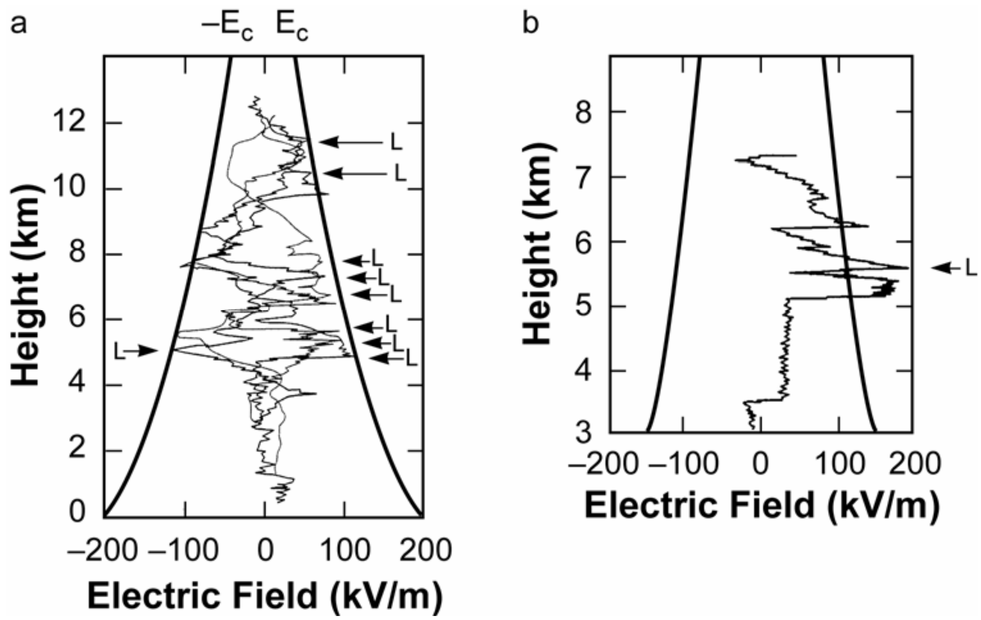

Figure 16: Electric field sounding in a thundercloud compared to the breakeven field for electron runaway, from Gurevich and Zybin (2005).

Figure 16 shows their comparison of a balloon sounding with the theoretical breakeven field, showing that the measured field then just touches the theoretical envelope, and so could provide a mechanism for lightning initiation when the electric field goes supercritical. Other indirect evidence for this process is the observation of X-ray transients in and around electrified clouds prior to any lightning (McCarthy and Parks, 1985) or for which lightning discharges were shown not to play a role (Eack et al, 1996). Contrary evidence to the idea that runaway breakdown is basic to all lightning initiations is also shown in Gurevich and Zybin (2005): on occasion, the measured electric fields in the cloud at the time of the lightning are substantially larger than the theoretical breakeven field (Figure 16).

(2) Heterogeneities in the cloud

Experiments in the laboratory with hydrometeors immersed in otherwise uniform electric fields have shown evidence that dielectric breakdown could be initiated by the locally enhanced fields of these hydrometeors (Craib and Latham, 1974; Solomon et al, 2002; Sentman et al, 2005). Theoretically, a conductive sphere immersed in a uniform field will enhance the local field by a factor of three (Stratton, 1941). Long ice needles (as for example, the long, thin conductor in Figure 6) can enhance the field by larger factors, but over smaller scales. The enhancement factors are of the order of what is needed to resolve the puzzle about the field magnitudes, but questions remain. Will ice particles be sufficiently electrically conductive at low temperatures to exhibit the large theoretical enhancement factors (Griffiths and Latham, 1974)? Will the enhanced fields over the small scales of the hydrometeor radii of curvature be capable of initiating dielectric breakdown? And once a streamer system is initiated from a collection of hydrometeors, can it succeed in expanding to a thermalized leader and a cloud-scale lightning flash? Unfortunately, none of these questions has well defined answers at present.

(3) The threshold field for streamer propagation

Griffiths and Phelps (1976) found experimentally that a localized pocket of ionization created in a uniform field could extend along the field as a sustained positive streamer and continue across the entire 1-meter laboratory gap. At pressures typical of initiation heights of many lightning flashes (400-500 mb), the threshold field is in the range of 100-200 kV/m, and so as small as all of the maximum field values in Table 3. The initial ionization of the laboratory experiment is needed of course, but this could be provided by a suitable cosmic ray shower, in principle. Indeed, this cosmic ray assistance is also postulated in the runaway process described in item (1) above. In the author's opinion, this explanation deserves more study as an alternative to the one illustrated in Figure 16.

(4) The sampling issue in space and time

The majority of reliable information on electric fields in thunderclouds is derived from balloon soundings (e.g., Marshall et al, 1995), with instruments rising slowly at speeds of order 5 m/s through electrified regions of cloud. The electric field within the cloud, affected by both charge separation and by lightning flashes, is strongly time- and space-dependent. With the available point measurements, there is little guarantee that the measuring instrument will coincide with the breakdown zone for lightning where the greatest electric fields are expected, and so the maximum values may escape detection and the largest values recorded (Table 2) will fall on the low side. This bias could be evaluated with rocket measurements of electric field (Winn et al, 1974) spaced closely in time, but such repeated measurements are expensive and have not been undertaken. This explanation for the electric field discrepancy based on sampling inadequacies also deserves greater attention.

6.3 Observations of X-rays and Gamma Rays Directly Emanating from Lightning

The working hypothesis of Gurevich and Zybin (2005) and described in item (1) of Section 6.2 is that the runaway electrons are fundamental to the initiation of lightning. A far greater number of observations in recent years support the alternative idea that a special phase and polarity of lightning are needed to accelerate electrons into runaway, with subsequent production of high-energy photons. In other words, the evidence supports the idea that the lightning is causing the runaways, rather than the runaways are initiating the lightning. The pertinent evidence follows.

Moore et al (2001) have documented x-ray bursts at the ground associated with descending leaders of negative polarity from overhead thunderclouds. Dwyer et al (2005) have observed x-ray emission at the ground for negative dart leaders in cloud-to-ground lightning. Dwyer et al (2004) have identified X-ray bursts originating in negative dart leaders in triggered lightning. Cummer et al (2005) has identified gamma ray bursts at RHESSI (Reuven Ramaty High Energy Solar Spectroscopic Imager) satellite altitude (~550 km), well-timed with remotely-detected lightning flashes, all with positive polarity (i.e., lightning double-ended trees with negative end uppermost).

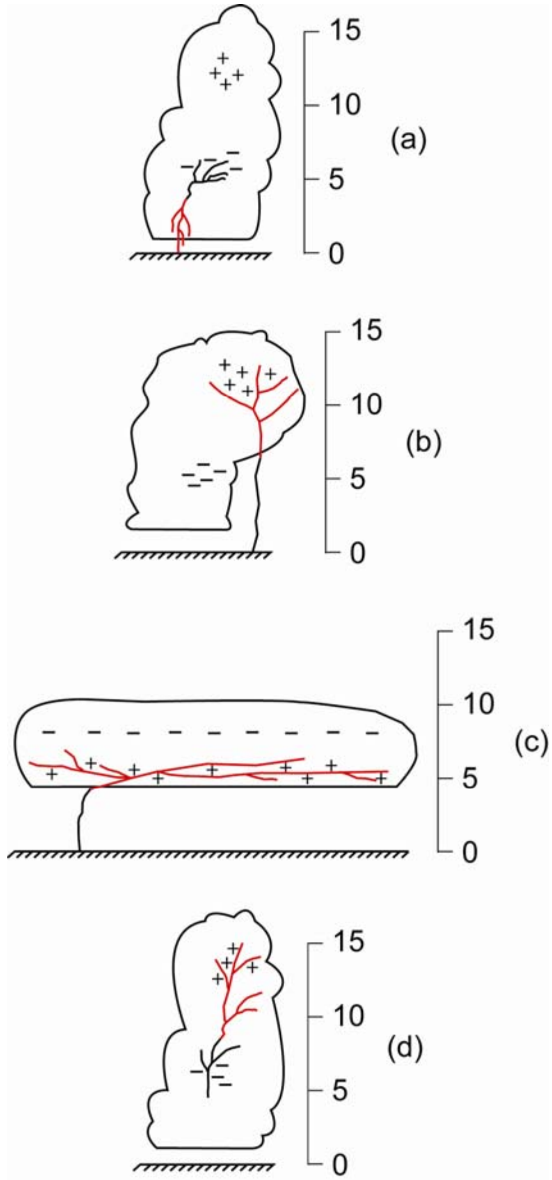

Figure 17: Candidate lightning flashes for accelerating runaway electrons and ultimately launching gamma rays to space (from Williams et al, 2005). The high-reaching intracloud flash with upper end negative has been found to be preferred.

Williams et al (2005) have considered candidate lightning types to launch gamma rays to space and have inferred that the parent lightnings with positive polarity, identified by Cummer et al (2005) and numerous other investigators, are intracloud flashes with negative ends that extend to high altitudes in the troposphere (~16 km), thereby enabling the gamma rays to escape the atmosphere to be recorded by the satellite. All of these observations are consistent in showing that the negative end of the lightning tree is the repeller of electrons which ultimately run away to produce the observed X-ray bursts, propagating in the same direction as the accelerated electrons. It seems plausible that the fitful bi-directional development at the negative end of the lightning tree may play some role in the acceleration of the runaway electrons.

Observations of X-rays in the vicinity of natural positive cloud-to-ground lightning and rocket-triggered lightning with positive polarity are needed to establish the consistency see of these relationships.

7. Polarity Asymmetry in the 'Final Jump' in Lightning Flashes to Earth

7.1 Basic Observations

The rapid electrical connection of a descending leader (at high voltage electrode potential or at cloud potential) with a conductive ground plane is an important phenomenon in both laboratory experiments and in cloud-to-ground lightning flashes, and is often referred to as the 'final jump'. Laboratory experiments in France with both leader polarities have clearly demonstrated a faster 'final jump' with negative polarity leaders (Les Renardieres, 1977; 1981). *"The duration of the final jump is difficult to measure accurately. The values for (negative polarity leaders) are of the order of some microseconds, generally less than 5 microseconds, which is much shorter than in positive polarity."* No physical explanation for the polarity asymmetry was provided.

In the larger scale context of lightning, numerous recent studies have shown evidence for anomalous behavior of negative polarity lightning flashes to the ocean surface (Lyons et al, 1998; Jacobson and Shao, 2002; Steiger and Orville, 2003) have all shown a clear cut population of negative ground flashes with short pulse width and high peak current, just beyond coastlines of the continental United States. Similar oceanic concentrations in positive polarity lightning have not been apparent, though to be sure, some of this asymmetry may be attributable to the substantially smaller numbers of positive ground flashes in general, and in particular over the sea. Evidence that the asymmetry in polarity is real, and not the result of this population difference, is found in Steiger and Orville (2003) where a longer integration of positive ground flashes is displayed in the vicinity of the Texas coastline, with a conspicuous enhanced concentration over seawater as one has with the population of negative flashes.

Other studies corroborate the lightning anomaly over the sea. D. Suszynski (personal communication, 2005) has found a large population of negative flashes to seawater, exhibiting a large amplitude electromagnetic pulse. The number of flashes with positive polarity with the same effect is disproportionately small.

Quantitative information on the pulse width of the 'final jump' in lightning flashes to ground (with no distinction between land and sea) has emerged from Jacobson and Shao (2002). The extraction of the pulse width for the VHF observations on the FORTE satellite is described in Shao et al (2005). The normalized statistics for pulse width for positive and negative ground flashes are shown in Figure 18. The mean duration for the negative polarity is substantially less than for positive polarity, consistent with the results on laboratory gaps.

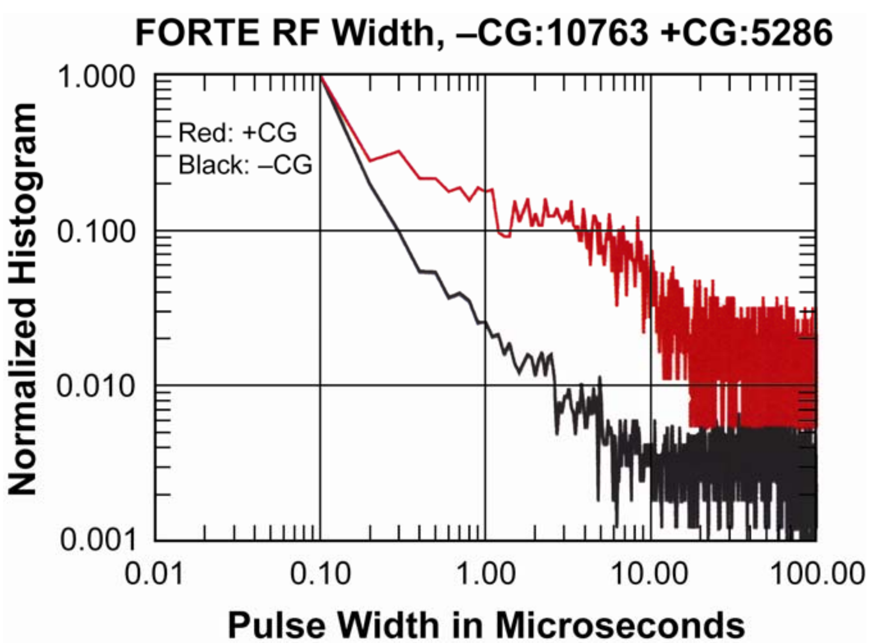

Figure 18: Durations (1/e widths) of VHF radiation from the 'final jump' of lightning flashes to ground, both positive (red) and negative (black) polarity. Observations extracted from Jacobson and Shao (2002), and courtesy of X.-M. Shao.

7.2 Physical Interpretation

It seems plausible that the shorter pulse with (faster gap closing) for negative polarity has an explanation in the other polarity asymmetries we have previously documented. The negative leader should be hotter and hence more electrically conductive than the positive leader, by virtue of the bi-directional streamer/leader action there, and the larger current flow. Secondly, the speed of advance of the negative leader should exceed that of the positive leader by a considerable margin, and so act to close the gap more quickly.

8. Polarity Asymmetry of Sprite-Producing Lightning

8.1 Background

Sprites in the mesosphere are increasingly recognized as dielectric breakdown caused by the sudden field change of an energetic cloud-to-ground lightning flash (Pasko et al, 1995; Boccippio et al, 1995; Williams, 2001). Like lightning in the troposphere (Figure 2), sprites are also double-ended trees that extend in opposite directions away from their point of origin. Figure 19 shows a sequence from a high-speed (1 ms resolution) imager, showing initial downward development of the positive end of the tree, followed almost immediately by upward (negative) development. Detailed telescopic imagery of sprite structure (Gerken et al, 2000) suggests that the dendritic growth of lightning is mimicked by sprite growth.

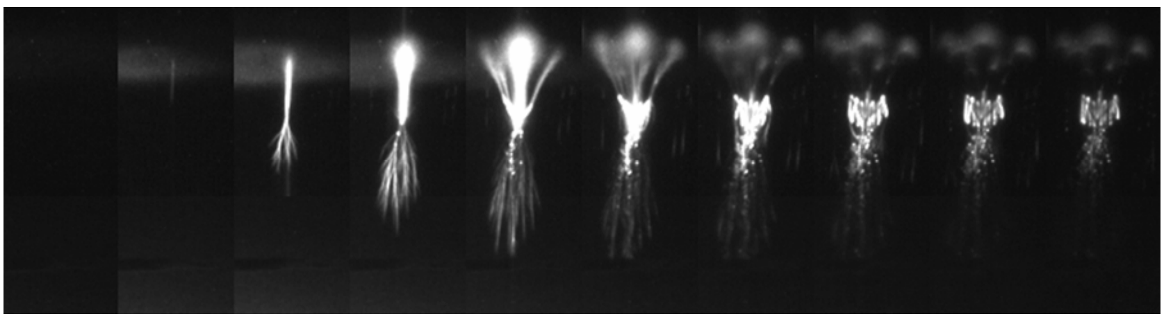

Figure 19: High-speed imager showing the vertical development of a sprite, another example of a double-ended lightning tree. For sprites initiated by positive ground flashes, the initial sprite growth is positive end downward, followed by negative end upward. (Courtesy of Geophysical Institute, University of Alaska).

Beginning with suggestions by C.T.R. Wilson (1925), the electrostatic field change of the lightning flash was sufficient to exceed the dielectric strength of the mesosphere and initiate the sprite. Wilson's idea involving the vertical charge moment of the parent lightning flash has been further quantified with ELF (Extremely Low Frequency) measurements in the Schumann resonance region (Burke and Jones, 1995; Huang et al, 1999) and the upper ELF band (Hu et al, 2002). Theoretical calculations (Huang et al, 1999; Williams, 2001; Lyons et al, 2003) have demonstrated that a charge moment change of 750 C-km in the 'parent' lightning flash is needed to account for the initiation of conventional dielectric breakdown at 75 km altitude. ELF measurements of charge moment changes are broadly consistent with this criterion, and when lightning charge moments are less than ~500 C-km, sprites are generally not observed (Huang et al, 1999; Hu et al, 2002)

This C.T.R. Wilson mechanism for sprites initiated by conventional dielectric breakdown is polarity independent—positive and negative changes in charge moment change in excess of the threshold should be equally effective in the initiation of sprites. And yet sprites associated with negative cloud-to-ground lightning flashes and with downward extension of the negative end of the double-ended sprite 'tree' are exceedingly rare. This circumstance constitutes the polarity paradox emphasized here.

Since their discovery by Franz et al (1990), sprites have now been observed over thunderstorms all over the world (Sentman et al, 1995; Lyons, 1996; Hardman et al, 2000; Su et al, 2001; Neubert et al, 2001; Fullekrug and Price, 2002; Hayakawa et al, 2004). Local lightning detection networks have often served a key role in identifying the timing and polarity of the parent lightning flash. This was definitely the case for studies within the United States (Boccippio et al, 1995; Lyons, 1996; Huang et al, 1999; Stanley et al, 2000; Hu et al, 2002). The National Lightning Detection Network (Cummins et al, 1998) in the US provides accurate timing (~1 μsec) and location (~ 1 km) for the ground contact point for flashes to ground. Thousands of positive ground flash-sprite associations have been identified through comparisons with video imaging/optical sensor verification of sprites. Yet only two well-documented cases of sprites originating from ground flashes with negative polarity have been published (Barrington-Leigh et al, 1999). Franz et al (1990) call attention to the possibility of 'negative' sprites in their observations, but the timing of their events is not sufficiently precise to verify these cases.

Procedures for determining the approximate vertical charge moment of an energetic lightning flash from single-station ELF electromagnetic measurements are now well established (Burke and Jones, 1995; Huang et al, 1999; Lyons et al, 2003; Hobara et al, 2005). For the measurements reported here, we have assumed an impulsive lightning source. This is to say that the characteristic duration of the lightning current to ground is short in comparison to the time required for light to propagate around the world (~130 ms) (Sentman, 1996). This assumption is safe for a large fraction of all lightning flashes to ground, though some sprite-producing lightning with extraordinarily long continuing currents will begin to violate this assumption.

Historically, the earliest determinations of the vertical charge moment change associated with lightning were obtained with electrostatic methods, also pioneered by C.T.R. Wilson (1916). In support of the accuracy of our determinations by ELF measurements, the electrostatic and electromagnetic methods have been compared on the same sprite-producing lightning flashes (Lyons et al, 2003). Though the number of events compared was small, the independently-determined charge moments generally agreed to well within a factor-of-two.

The single-station measurements were made from the MIT Schumann resonance station in West Greenwich, Rhode Island (Huang et al, 1999; Hobara et al, 2005). Three component (H_x, H_y, E_z) measurements also enable the geographical location of these energetic flashes that stand up against all the other lightning on the planet for periods of order 100 milliseconds. The global maps can then be used to examine distributions of charge moment organized by 'chimney' region—the Americas, Africa and the Maritime Continent. The polarity of charge moments is readily determined from the initial excursion of the E_z signal, and for events within North America also detected by the NLDN, this procedure is readily verified.

The bipolar distributions of charge moment change were marked with polarity-independent sprite threshold values in the range of 300-1000 C-km, and the tails of both positive and negative distributions were then integrated for quantitative comparison. The basic result, largely independent of chimney region and independent of chosen sprite threshold, is as follows: the super-critical events with positive polarity exceed the super-critical negative events by about 10 to 1. Stated differently, roughly 10% of all events exceeding the theoretical sprite threshold possess negative polarity. The fact that 10% is substantially greater than the percentage of all sprites documented to have been caused by negative ground flashes, simply deepens the central paradox.

8.2 Interpretation of Polarity Asymmetry in Sprites

At face value, the paradox remains. There are far more negative lightning flashes worldwide capable of initiating a sprite than observed 'negative' sprites. Other aspects of this story however also deserve discussion. One important aspect has surfaced earlier in this review.

The polarity asymmetry in the characteristics of cloud-to-ground lightning has been discussed in Section 5: negative flashes frequently exhibit multiple strokes, each with current cutoff and no continuing current, whereas positive flashes frequently show single-stroke behavior with a continuing current.

Toward distinguishing the characteristics of positive and negative ground flashes in the ELF region, the current moments were compared (in the Schumann resonance region 3-50 Hz) for a large number of energetic events. In particular, the slopes of the current moment frequency spectra were compared. For theoretical reference, an impulsive current (with short duration) should provide a white noise source and a current moment that is flat with frequency—a zero slope. In contrast, a long continuing current should be characterized by enhanced energy at low frequency—a red spectrum with a large negative slope (Sentman, 1996). Consistent with the broad generalities on lightning characteristics at the beginning of this section, the negative flashes do show a distribution of current moment slopes that peaks much closer to zero than the positive polarity events, the latter peaking at large negative slopes. The physical implication of these results is that the middle atmospheric forcing from negative flashes will be impulsive and brief, whereas that for the positive flashes will be long and sustained, even for the same total charge moment. This difference in forcing may have important implications in turn for the nature of ionization produced aloft. This distribution encourages discussion of two other kinds of luminous event in the mesosphere, elves and haloes.

The elve is a luminous event also caused by cloud-to-ground lightning, but with substantially less polarity preference in the parent lightning than sprites (Barrington-Leigh and Inan, 1999). The radiation electric field emanating from the return stroke is the causal agent for elves (Inan et al, 1996). The tendency for flat (white) current moment forcing spectra for elve lightning has been documented previously (Huang et al, 1999).

Several years after elves were first observed (Fukunishi et al, 1995) and explained (Inan et al, 1996), the haloe was identified as another luminous discharge in the mesosphere. Like the sprite before it, the haloe was attributed to the electrostatic field change of lightning. It then became apparent that some events previously identified in conventional video imagery as elves were in fact haloes. It is interesting to note that during early (~1996) video camera/ELF comparisons, a substantial fraction (5-10%) of all TLE's without corresponding NLDN-identified positive ground flashes were also tentatively identified as 'elves'. In retrospect, some of these events could have been haloes instead, and could possibly have been initiated by negative ground flashes. This scenario could provide a possible resolution to the paradox. This suggestion is further supported by recent optical observations by Bering et al (2004) who also associated haloes with NLDN-identified cloud-to-ground lightning with negative polarity. The statistics of ground flash polarity causal to haloes deserves greater attention.

In a recent study by Cummer and Lyons (2004), comparisons are made between ELF-measured charge moment and video-detected sprites for selected storms within the CONUS. Consistent with a larger body of evidence, the sprites are exclusively associated with supercritical charge moments with positive polarity. Few if any lightning discharges with supercritical negative charge moments are found in these storms. No paradox is presented by these results. This is the result one expects if the C.T.R. Wilson mechanism is representative. When compared with the global comparisons in the present study, the implications are that the lightning flashes with supercritical negative charge moments lie in meteorological situations other than the large storms selected by Cummer and Lyons (2004). This issue is presently receiving greater scrutiny.

Thomas et al (2005) have recently raised the interesting suggestion that the threshold for positive streamer propagation is more relevant to sprite initiation than the dielectric strength of air. They argue that such a condition might resolve the polarity asymmetry of sprites. This seems unlikely to the author, because the threshold field needed to initiate upward and downward positive streamers will not differ appreciably.

A clear paradox presents itself by the comparison of the few sprites produced by negative cloud-to-ground lightning compared to the number of lightning flashes observed at ELF with super-critical negative charge moments. The resolution of the paradox may lie in the asymmetry in the nature of the electrical forcing, with haloes from negative ground flashes less readily detected in video imagery than conventional 'positive' sprites because the former discharges are diffuse. Negative polarity ground flashes are more likely to exhibit current cutoff and hence a short duration because the channels needed to bridge the negative charge reservoir and the ground are systematically long and because the source currents for positive leaders (at the cloud end of the negative ground flash) are smaller than for negative leaders. More scrutiny of the observations, both electromagnetic and video, is now needed to verify this speculation, and characterize the scarce sprite-successful negative lightning flashes.

9. Summary

A number of long-standing problems and more recent problems in lightning physics involve asymmetries in electrical polarity. This review has considered several of these, including a consideration of the most fundamental polarity asymmetry: the mobility contrast in positive and negative charge carriers. Appeal to the behavior of electrical discharges at laboratory scales continues to illuminate lightning behavior. Theoretical studies are needed to quantify the effects of the electron-ion mobility contrast in larger scale behavior.

Acknowledgements

The author is indebted to Dr. Ute Ebert for her invitation to present a review paper on lightning at the 27th International Conference on Phenomena in Ionized Gases (ICPIG) in Veldhoven, the Netherlands, in July 2005. That talk ultimately expanded into the present paper. Discussions on this topic with M. Baker, C. Cooke, U. Ebert, E. Bazelyan, A. Bondiou-Clergerie, J. Dwyer, A. Jacobson, P. Krider, P. Lalande, S. Larigaldie, P. Laroche, W. Lyons, V. Mazur, J. Mrazek, R. Orville, V. Pasko, Y. Raizer, V. Rakov, R. Roussel-Dupré, R. Thomas, D. Sentman, X.-M. Shao, M. Stanley, D. Suszynski, M. Uman, and J. Willett are much appreciated.

References

Bazelyan, E.M. and Y.P. Raizer, *Lightning Physics and Protection*, Inst. of Physics Publishing, Bristol and Philadelphia, 2000, 325 pp.

Barrington-Leigh, C.P. and U.S. Inan, ELVES triggered by positive and negative lightning discharges. Geophys. Res. Lett., 26, 683-686, 1999.

Barrington-Leigh, C.P., U.S. Inan, M. Stanley, and S.A. Cummer, Sprites directly triggered by negative lightning discharges, Geophys. Res. Lett., 26, 3605-3608, 1999.

Berger, K. and E. Vogelsanger, New results of lightning observations, Chapter IV-5, in *Planetary Electrodynamics*, Ed., S.C. Coroniti and J. Hughes, Gordon and Breach, New York, 1969.

Berger, K., The Earth Flash, in Lightning, Vol. 1, *Physics of Lightning*, ed., R.H. Golde, pp. 119-190, Academic Press, New York, 1977.

Bering, E.A., III, E. Wescott, L. Bhusal, J.R. Benbrook, A. Jackson, D. Moudry, D.D. Sentman, H. Nielsen-Stenbaek, J. Garrett and W. A. Lyons, Observations of transient luminous events (TLEs) associated with negative cloud to ground (-CG) lightning strokes. Geophys. Res. Lett., 31, L05104, 2004.

Boccippio, D.J., E. Williams, S.J. Heckman, W.A. Lyons, I. Baker and R. Boldi, Sprites, ELF transients and positive ground strokes, Science, 269, 1088-1091, 1995.

Bruce, C.E.R., The initiation of long electrical discharges, Proc. Roy. Soc., A, 183, 228-242, 1944.

Burke, C.P. and D.L. Jones, Global radiolocation in the lower ELF frequency band, J. Geophys. Res., 100, 26263, 1995.

Cobine, J.D., *Gaseous Conductors—Theory and Applications*, Dover Publications, 1958, 606 pp.

Cohen, I.B., *Benjamin Franklin's Science*, Harvard University Press, Cambridge, 1990, 273 pp.

Craib, J.A. and J. Latham, Corona from colliding water drops as a possible mechanism for triggering of lightning, Quart. J. Roy. Met. Soc., 100, 191-202, 1974.

Cummer, S.A. and W. A. Lyons, 2004: Lightning charge moment changes in U.S. High Plains thunderstorms. Geophys. Res. Letts.,31, L05114, doi:10.1029/2003GL019043,2004.

Cummer, S.A. and W.A. Lyons, 2005: Implications of lightning charge moment changes for sprite initiation. J. Geophys. Res., 110, A04304, doi:10.1029/2004JA010812.

Cummer, S.A., Y. Zhai, W. Hu, D.M. Smith, L.I. Lopez, and M.A. Stanley, Measurements and implications of the relationship between lightning and terrestrial gamma-ray flashes, Geophys. Res. Lett., 32, no.8, L08811, doi:10.1029/2005GL022778, 2005.

Cummins, K.L., M.J. Murphy, E.A. Bardo, W.L. Hiscox, R.B. Pyle, and A.E. Pifer, A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network, J. Geophys. Res., 103, 9035-9044, 1998.

Dwyer, J.R., H.K. Rassoul, M. Al-Dayeh, L. Caraway, B. Wright, A. Chrest, M.A. Uman, V.A. Rakov, K.J. Rambo, D.M. Jordan, J. Jerauld, and C. Smyth, Measurements of X-ray emission from rocket-triggered lightning, Geophys. Res. Lett., 31, L05118, doi:10.1029/2003GL018770, 2004.

Dwyer, J.R., H.K. Rassoul, M. Al-Dayeh, L. Caraway, A. Chrest, B. Wright, E. Kozak,J. Jerauld, M.A. Uman, V.A. Rakov, D.M. Jordan, and K.J. Rambo, X-ray bursts associated with leader steps in cloud-to-ground lightning, Geophys. Res. Lett., 32, L01803, doi:10, 1029/2004GL021782, 2005.

Eack, K.B., W.H. Beasley, W.D. Rust, T.C. Marshall, and M. Stolzenburg, Initial results from simultaneous observations of X-rays and electric fields in a thunderstorm, J. Geophys. Res., 101, 29637-29640, 1996.

Faraday, M., On the electricity evolved by the friction of water and steam against other bodies, Experimental Researches in Electricity, Vol. 2, 106-126, (18^{th} Series), 1843.

Fieux, R., C. Gary and P. Hubert, Artificially triggered lightning above land, Nature (London), 257, 212, 1975.

Franz, R.C., R.J. Nemzak, and J.R. Winkler, Television image of a large upward electrical discharge above a thunderstorm system, Science, 249, 48-51, 1990.

Frind, G., Űber das Ablingen von Lichtbogen, Zeitschrift Angew. Physik, 12, (English discussion in Lee (1975), page 243), 515-521, 1960.

Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U.S. Inan and W.A. Lyons, Lightning-induced transient luminous events in the lower ionosphere, Geophys. Res. Lett., 23, 2157-2160, 1996.

Füllekrug, M. and C. Price, Estimation of sprite occurrences in Central Africa, Meteorologische Zeitschrift, vol. 11, 99, 2002.

Gallimberti, I., G. Bacchiega, A. Bondiou-Clergerie, and P. Lalande, Fundamental processes in long air gap discharges, C.R. Physique, 1335-1359, 2002.

Gerken, E.A., U.S. Inan and C.P. Barrington-Leigh, Telescopic imaging of sprites, Geophys. Res. Lett., 27, 2637-2640, 2000.

Griffiths, R.F. and J. Latham, Electrical corona from ice hydrometeors, Quart. J. Roy. Met. Soc., 10, 163, 1974.

Griffiths, R.F and C.T. Phelps, The effects of air pressure and water vapor content on propagation of positive corona streamers, and the implications for lightning initiation, Quart. J. Roy. Met. Soc., 102, 419-426, 1976.

Gurevich, A.V. and K.P. Zybin, Runaway breakdown and the mysteries of lightning, Physics Today, May, 37-43, 2005.

Hardman, S.F., R.L. Dowden, J.B. Brundell, J.L. Bahr, Z.-I. Kawasaki, and C.J. Rodger, Sprite observations in the Northern Territory of Australia, J. Geophys. Res., 105, 4689-4697, 2000.

Hayakawa, M., T. Nakamura, Y. Hobara, E. Williams, Observation of sprites over the Sea of Japan and conditions for lightning-induced sprites in winter, J. Geophys. Res., 109, A01312, doi:10.1029/2003JA0099905, 2004.

Heckman, S., Why does a lightning flash have multiple strokes? PhD thesis, Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA, June, 1992, 134 pp.

Higashiyama,Y., Y. Kito, K. Horii, and I Miyachi, Discharge aspects of lightning flashes in winter triggered by the rocket-wire technique, Trans. IEE Jpn., 100-B, 681, 1980.

Hobara, Y., N. Iwasaki, T. Hayashida, M. Hayakawa, K. Ohta and H. Fukunishi, Interrelation between ELF Transients and Ionospheric Disturbances in Association with Sprites and Elves, Geophys. Res. Lett., 28, 935-938, 2001.

Hobara, T., E. Williams, M. Hayakawa, R. Boldi, and E. Downes, Lightning and electrical properties of sprite-producing lightning from a single ELF site, Chapter in the book: *Sprites, Elves and Intense Lightning Discharges,* Ed., M. Füllekrug, Kluwer Publishing, (in press), 2005.

Horii, K., Experiment of artificial lightning triggered with rocket, Memoirs of the Faculty of Engineering, Nagoya University, 34, No. 1, 77-112, 1982.

Horii, K., G. Ikeda and S. Sumi, The mechanism of artificial lightning discharge triggered with rocket as an extremely long gap discharge, 4th Int'l. Symp. High Voltage Engineering, Athens, 1983.

Horii, K. and G. Ikeda, A consideration on success conditions of triggered lightning, IN Proc. 18th Int. Conf. on Lightning Protection, Munich, Germany, paper 1-3, 1985.

Horii, K. and H. Sakurano, Observations of the final jump of the discharge in the experiments of artificially triggered lightning, IEEE.PES 1985 Winter Meeting, New York, NY, Feb. 3-8, 1985.

Horii, K. and M. Nakano, Artificially triggered lightning, Chap. 6 in *Handbook of Atmospheric Electrodynamics*, 151-166, Ed., H. Volland, CRC Press, Boca Raton, FL, 1995.

Hu, W., S. Cummer, W.A. Lyons, and T.E. Nelson, Lightning charge moment changes for the initiation of sprites, Geophys. Res. Lett., 29, doi 10.1029/2001GL014593, 2002.

Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson and C. Wong, Criteria for sprites and elves based on Schumann resonance observations, J. Geophys. Res., 104, 16943-16964, 1999.

Hubert, P., Triggered lightning in France and New Mexico, Endeavor, New Series, Vol. 8, No. 2, 85-89, Pergamon Press, 1985.

Inan, U.S., W.A. Sampson and Y.N. Taranenko, Space-time structure of optical flashes and ionization changes induced by lightning-EMP, Geophys. Res. Lett., 23, 133-136,
1996.

Jacobson, E.A. and E.P. Krider, Electrostatic field changes produced by Florida lightning, J. Atmos. Sci., 33, 103-117, 1976.

Jacobson, A.R. and X.-M. Shao, FORTE satellite observations of very narrow radiofrequency pulses associated with the initiation of negative cloud-to-ground lightning strokes, J. Geophys. Res., 107, NO. D22, doi:10.1029/2001JD001542, 2002.

Kasemir, H., A contribution to the electrostatic theory of a lightning discharge, J. Geophys. Res., 65, 1873-1878, 1960.

Kawasaki, Z.I., K. Matsuura, T. Matsui, and M. Adachi, Is the bi-leader progression concept true? Proc. 10th Int'l Conf. Atmos. Elec., Osaka, Japan, 596-598, 1996.

King, L.A., The voltage gradient of the free-burning arc in air or nitrogen, Reference G/XT172, British Electrical and Allied Industries Research Association, Leatherhead, Surrey, England, 1961.

Kito, Y., K. Horii, Y. Higashiyama and K. Nakamura, Optical aspects of winter lightning discharges triggered by the rocket-wire technique in Hokuriku district of Japan, J. Geophys. Res., 90, 6147-6157, 1985.

Koshak, W.J. and E.P. Krider, Analysis of lightning field changes due to active Florida thunderstorms, J. Geophys. Res., 94, 1156-1186, 1989.

Krehbiel, P.R., The electrical structure of thunderstorms, Chapter 9 in *The Earth's Electrical Environment*, 90-113, Studies in Geophysics, National Academy Press, Washington, D.C., 1986.

Krehbiel, P.R., M. Brook and R.A. McCrory, An analysis of the charge structure of lightning discharges to ground, J. Geophys. Res., 84, 2432-2456, 1979.

Lalande, P., A. Bondiou-Clergerie, G. Bacchiega and I. Gallimberti, Observations and modeling of lightning leaders, C.R. Physique 3, 1375-1392, 2002.

Lang, T. J., Miller, L. J., Weisman, M., Rutledge, S. A., Barker, L. J., Bringi, V. N., Chandrasekar, V., Detwiler, A., Doesken, N., Helsdon, J., Knight, C., Krehbiel, P., Lyons, W. A., MacGorman, D., Rasmussen, E., Rison, W., Rust, W. D., Thomas, R. J.
The Severe Thunderstorm Electrification and Precipitation Study,
Bull. Amer. Met. Soc., 85: 1107-1125, 2004.

Larigaldie, S., The spark propagation mechanisms in ambient air at the surface of a charged dielectric I - Experimental : The main stages of the discharge. J. Appl. Phys., no. 6, (1), 1987.

Lee, T.H., *Physics and Engineering of High Power Switching Devices*, pp. 233-235, MIT Press, Cambridge, MA, 1975.

Les Renardières Group, Positive discharges in long air gaps at Les Renardières—1975 results and conclusions, Electra, 53, 1977.

Les Renardières Group, Negative discharges in long air gaps at Les Renardières—1978 results, Electra, 74, 1981.

Lyons, W.A., M. Uliasz and T.E. Nelson, A climatology of large peak current cloud-to-ground lightning flashes in the contiguous United States, Mon. Wea. Rev., 126, 2217, 1998.

Lyons, W.A., Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, J. Geophys. Res., 101, 29, 29641-29652, 1996.

Lyons, W.A., R.A. Armstrong, E.R. Williams, and E.A. Bering, The hundred year hunt for the sprite, EOS, Trans. Amer. Geophys. Union, 81, 373-377, 2000.

Lyons, W.A., T.E. Nelson, E.R. Williams, S.A. Cummer and M.A. Stanley, Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective systems. Mon. Wea. Rev., 131, 2417-2427, 2003.

Malan, D.J. and B.J.F. Schonland, The electrical processes in the intervals between the strokes of a lightning discharge, Proc. Roy. Soc. London, Ser. A, 206, 145-163, 1951.

Marshall, T.C., M.P. McCarthy and W.D. Rust, Electric field magnitudes and lightning initiation in thunderstorms, J. Geophys. Res., 100, 7079-7103, 1995.

Mazur, V., Triggered lightning strikes to aircraft and natural intracloud discharges, J. Geophys. Res., 94, 3311-3325, 1989.

Mazur, V., A physical model of lightning initiation on aircraft in thunderstorms, J. Geophys. Res., 94, 3326-3340, 1989.

Mazur, V. and L.H. Ruhnke, Common physical processes in natural and artificially triggered lightning, J. Geophys. Res., 98, 12913-12930, 1993.

Mazur, V., Physical processes during the development of lightning flashes, C.R. Physique, 3, 1393-1409, 2002.

Mazur, V, E. Williams, R. Boldi, L. Maier and D.E. Proctor, Initial comparison of lightning mapping with operational time-of-arrival and interferometric systems, J. Geophys. Res., 102, 11071-11085, 1997.

McCarthy, M. and G.K. Parks, Further observations of X-rays inside thunderstorms, Geophys. Res. Lett., 12, 393-396, 1985.

Moore, C.B., K.B. Eack, G.D. Aulich and W. Rison, Energetic radiation associated with lightning stepped-leaders, Geophys. Res. Lett., 28, No. 11, 2141-2144, 2001.

Mrazek, J., The thermalization of the positive and negative lightning channel, Proceedings of the 24th International Conference on Lightning Protection, Birmingham, UK, 1998.

Neubert,T., T. Allin, H. Stenbaek-Nielsen and E. Blanc, Sprites over Europe. Geophys. Res. Lett., 28, 3585-3588, 2001.

Ogawa, T. and M. Brook, The mechanism of the intracloud lightning discharge, J. Geophys. Res., 69, 5141-5150, 1964.

Ogawa, T., Y. Tanaka, M. Yasuhara, A.C. Fraser-Smith and R. Gendrin, Worldwide simultaneity of occurrence of a Q-type ELF burst in the Schumann resonance frequency range, J. Geomag. Geoelectr., 19, 377-384, 1967.

Orville, R.E., R.A. Weisman, R.B. Pyle, R.W. Henderson and R.E. Orville, Jr., Cloud to ground lightning flash characteristics from June 1984 through May 1985, J. Geophys. Res., 92, 5640-5644, 1987.

Pasko, V.P., U.S. Inan, Y.N. Taranenko, and T.F. Bell, Heating, ionization and upward discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields, Geophys. Res. Lett., 22, 365-368, 1995.

Price, C., M. Asfur, W. Lyons and T. Nelson, Observations of sprites in the United States from the Negev Desert, Israel, Geophys. Res. Lett., 29, 1.1-1.4, 2002.

Proctor, D.E., Regions where lightning flashes begin, J. Geophys. Res., 96, 5099-5112, 1991.

Rakov, V.A., Initiation of lightning in thunderclouds, Recent Res. Devel. Geophysics, 6, 1-35, 2004.

Rakov, V.A. and M.A. Uman, *Lightning—Physics and Effects*, Cambridge University Press, 2003, 687 pp.

Roussel-Dupre, R. and A.V. Gurevich, On runaway breakdown and upward propagating discharges, J. Geophys. Res., 101, 2297-2311, 1996.

Salanave, L.E., *Lightning and its Spectrum*, University of Arizona Press, Tucson, AZ, 1980.

Sato, M. and H. Fukunishi, Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events, Geophys. Res. Lett., 30, 1859, 2003.

Schonland, B.F.J., Progressive lightning IV—The discharge mechanism, Proc. Roy. Soc. London, Ser. A, A164, 132-150, 1938.

Schonland, B.F.J., The pilot streamer in lightning and in the long spark, Proc. Roy. Soc., A, 220, 25-38, 1953.

Sentman, D.D., E.M. Wescott, D.L. Osborne, D.L. Hampton and M.J. Heavner, Preliminary results from the Sprites 94 aircraft campaign: 1. Red sprites, Geophys. Res. Lett., 22, 1205-12108, 1995.

Sentman, D.D., Schumann resonance spectra in a two-scale height earth-ionosphere cavity, J. Geophys. Res., 101, 7097, 1996.

Sentman, D.D. and H.J. Christian, Electrical breakdown inside a thundercloud-Cosmic rays versus hydrometeor effects, AGU abstract, Fall Meeting, San Fransisco, CA, December, 2005.

Shao, X.-M., A.R. Jacobson and T.J. Fitzgerald, Radio frequency radiation beam pattern of lightning return strokes inferred from satellite observations, J. Geophys. Res., (in review), 2005.

Shaw, P.E., Tribo-electricity and friction, IV Electricity due to air-blown particles, Proc. Roy. Soc., A122, 49-58, 1929.

Simpson, G.C., On lightning, Proc. Roy. Soc. London, Ser. A, 147, 56-67, 1926.

Smith, D.M., L.I. Lopez, R.P. Lin, and C.P. Barrington-Leigh, Terrestrial gamma-ray flashes observed up to 20 MeV, Science, 307, 1085-1088, 2005.

Sohnke, L., Transfer of electricity between ice and water (in German), Ann. Physik, 28, 551, 1886.

Solomon, R., C. Adamo and M. Baker, A lightning initiation mechanism: application to a thunderstorm electrification model, C.R. Physique, 3, 1325-1333, 2002.

Stanley, M.A., M. Brook, P. Krehbiel and S.A. Cummer, Detection of daytime sprites via a unique sprite ELF signature, Geophys. Res. Letts. 27, 871-874, 2000.

Stekolnikov, I.S. and A.B. Shkilev, Dokl. Akad. Nauk SSSR, 145, 782, 1960.

Steiger, S.M. and R.E. Orville, Cloud-to-ground lightning enhancement over Southern Louisiana, Geophys. Res. Lett., 30, doi:10.1029/2003GLO17923, 2003.

Stratton, J., *Electromagnetic Theory*, McGraw-Hill, New York, 1941.

Su, H.T., R.R. Hsu, A.B.C. Chen, Y.J. Lee, and L.C. Lee, Observation of sprites over the Asian continent and oceans around Taiwan, Geophys. Res. Lett., 29(4), 1044, doi:10.1029/2001GL013737.

Takahashi, T., Riming electrification as a charge generation mechanism in thunderstorms, J. Atmos. Sci., 35, 1536-1548, 1978.

Toepler, M., Archiv. für Elektrotechnik, Vol. 10, No’s 5 and 6, 1921.

Thomas, R.J., P.R. Krehbiel, W. Rison, T. Hamlin, J. Harlin, and D. Shown, Observations of VHF source powers radiated by lightning, Geophys. Res. Lett., 28, 143-146, 2001.

Thomas, J.N., R.H. Holzworth and M. P. McCarthy, Predicting lightning-driven quasi-electrostatic fields at sprite altitudes using in-situ measurements and a numerical model, Geophys. Res. Lett., Vol. 32, No. 10, L10809,10.1029/2005GL022693, 24 May, 2005.

Waldteufel, P., P. Metzger, J.-L. Boulay, P. Laroche and P. Hubert, Triggered lightning strokes originating in clear air, J. Geophys. Res., 83, 2861-2868, 1980.

Williams, E.R., The positive charge reservoir for sprite-producing lightning, J. Atmos. Sol. Terr. Phys., 60, 689-692, 1998.

Williams, E.R., Sprites, elves and glow discharge tubes, Physics Today, November, 41-47, 2001.

Williams, E.R. The Global Electrical Circuit, in *Encyclopedia of Atmospheric Sciences*, Ed’s, J.R. Holton, J. Pyle and J.A. Curry, Elsevier, Vol. 2, 724-732, 2003.

Williams, E., R. Boldi, J. Bór, G. Sátori, G. Price, E. Greenburg, Y. Takahashi, K. Yamamoto, T. Chronis, E. Anagnostou, D. Smith, and L. Lopez, Lightning flashes conducive to the production and escape of gamma radiation to space, J. Geophys. Res., (in review), 2005.

Wilson, C.T.R., On some determinations of the sign and magnitude of electric discharges in lightning flashes, Proc. Roy. Soc., A., 92, 555-574, 1916.

Wilson, C.T.R, The electric field of a thundercloud and some of its effects, Proc. Roy. Soc. London, 37, 32D, 1925. 1925

Winn, W.P., G.W. Schwede and C.B. Moore, Measurements of electric field in thunderclouds, J. Geophys. Res., 79, 1761-1767, 1974. rocket measurements