INSTITUTE OF PHYSICS PUBLISHING PLASMA SOURCES SCIENCE AND TECHNOLOGY

Plasma Sources Sci. Technol. **15** (2006) S91–S108 doi:10.1088/0963-0252/15/2/S12

Problems in lightning physics—the role of polarity asymmetry

Earle R Williams

Massachusetts Institute of Technology, Parsons Lab Room 48-211, Cambridge,
MA 02139-4307, USA

E-mail: earlew@ll.mit.edu

Received 18 October 2005, in final form 24 March 2006
Published 26 April 2006
Online at stacks.iop.org/PSST/15/S91

Abstract
Many outstanding problems in lightning physics are linked with a difference in macroscopic behaviour between positive and negative polarity. Such differences are referred to broadly as 'polarity asymmetry'. As specific examples, the positive and negative ends of lightning propagate at different speeds, with different degrees of steadiness, and with different radiated electromagnetic energy. Positive and negative flashes to ground transfer their charge in markedly different ways—negative flashes with multiple discrete strokes (often) and positive flashes with single strokes followed by continuing current. Positive ground flashes cause sprites and negative flashes do not (generally). Positive intracloud flashes send gamma radiation upward to space and negative intracloud flashes do not (generally). Speculative arguments are presented that all of these macroscopic asymmetries are rooted in the microscopic asymmetry in mobility for free electrons and positive ions.

(Some figures in this article are in colour only in the electronic version)

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 behaviour have defied theoretical prediction and replication by models. Important insights about natural lightning behaviour 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 behaviour of positive and negative streamers and their thermalized counterparts, the leaders. Flashes that transfer positive charge to ground have 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. Among cloud-to-ground (CG) flashes with large charge moment, negative flashes are notably shorter in duration when they connect to ground than positive flashes. All 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 negative in the lower regions but sometimes positive (figure 1). The underlying reason for this well-defined cloud polarity remains elusive even today, though 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 temperatures and contains both supercooled water drops and ice crystals. Curiously, Michael

0963-0252/06/020091+18$30.00

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). It is plausible that the polarity asymmetry of the thundercloud shown in figure 1 is ultimately caused in some way by the asymmetry of the H_2O molecule, which also has the form of an electric dipole, with one end (the 'O' end) negative and the other end (the 'H_2' end) positive.

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 has been 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 explored further. 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 flashes to ground are roughly ten times more numerous than positive flashes to ground because of the proximity of the lower negative charge region to ground.

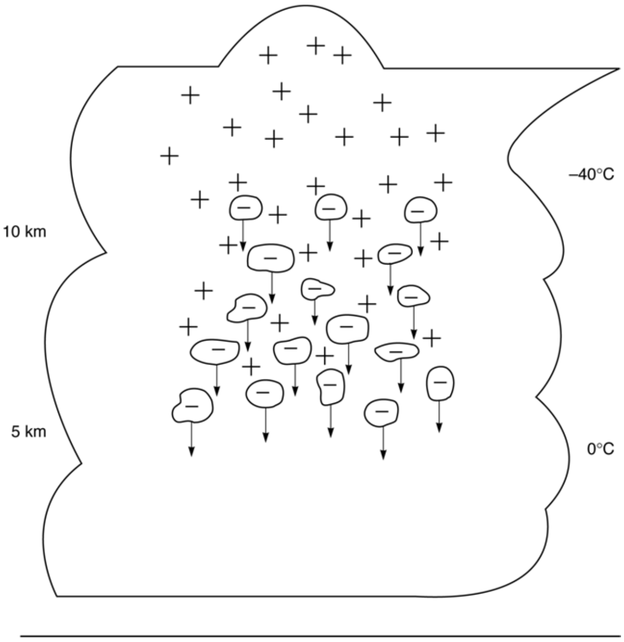
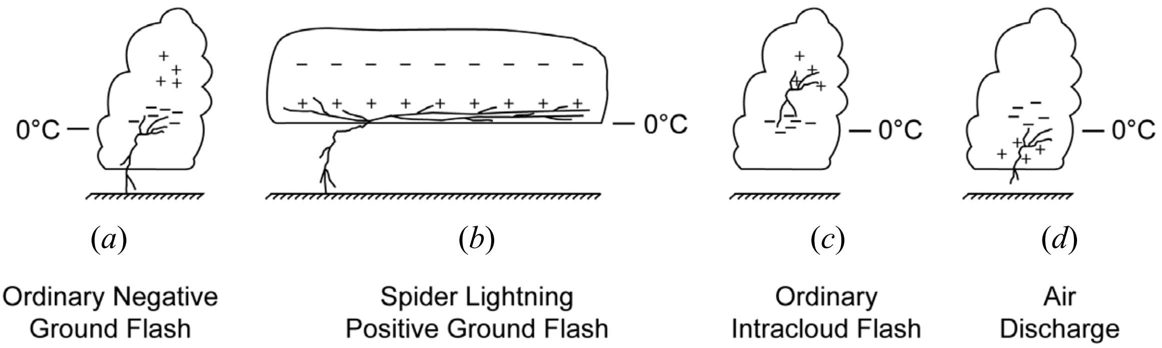


Figure 1. Thundercloud with typical positive dipole structure, maintained by differential motions of ice particles under gravity. The subsidiary pocket of lower positive charge beneath the main negative charge is not depicted here.

3. Lightning flashes as double-ended trees

Lightning in thunderclouds is distinctly different from conventional laboratory discharges that involve charge on metallic electrodes. In thunderclouds, the positive and negative charge is spatially distributed on scales of hundreds of metres to kilometres and is carried on the ice and water particles that compose the cloud. The great majority of all lightning flashes that occur in thunderclouds are double-ended 'trees' that bridge regions of space charge with opposite polarity. One tree propagates into positive charge and the other into negative charge. Common lightning flashes, all in this same general form, are illustrated in figure 2.

Ideas about the behaviour of lightning in figure 2 developed historically from studies of discharges in the laboratory, both on surfaces ('Lichtenberg figures', Töpler 1921a,1921b, Loeb 1965, Larigaldie 1987) and from point electrodes at high voltage in air (Loeb 1965). The morphology of surface discharges (figures 3(*a*) and (*b*)) clearly depends on the polarity. This notable contrast led to the development of the klydonograph, a method using photographic film for diagnosing the polarity and magnitude of lightning discharges to power lines (Viemeister 1972). The recognition in the laboratory that discharges with positive polarity were more readily produced than negative polarity, led Simpson (1926) to infer that lightning would branch away from regions with positive charge (figure 4). This picture of lightning as a single-ended tree with only positively charged branches was widespread through the early 1920s. It formed the basis for Simpson's (1927) early view that thunderclouds had a main dipole polarity opposite to the one upheld by C T R Wilson (1916) and recognized today in figure 1. Thunderstorm observations by Jensen (1933) and others then established that downwardly branched lightning most often emanated from the lower negative charge of the thundercloud, in contradiction to Simpson's (1926) picture in figure 4. The observations of the branching of lightning and its polarity thereby simultaneously



(*a*) Ordinary Negative Ground Flash

(*b*) Spider Lightning Positive Ground Flash

(*c*) Ordinary Intracloud Flash

(*d*) Air Discharge

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

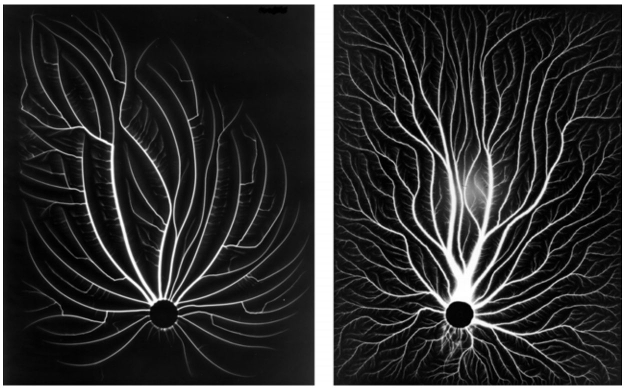


Figure 3. Surface discharges with (*a*) positively and (*b*) negatively charged surfaces, showing marked contrast in structure (courtesy of S Larigaldie 2005).

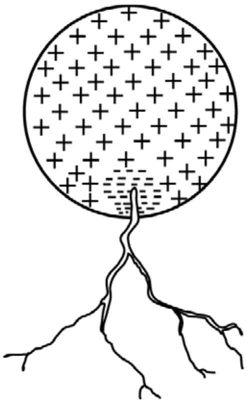


Figure 4. Simpson's (1926) picture of lightning as a single-ended tree, progressing out of positive charge regions, based on experience with laboratory experiments on positive streamers. Later observations by Jensen (1933) and others refuted this picture and supported a double-ended tree for lightning.

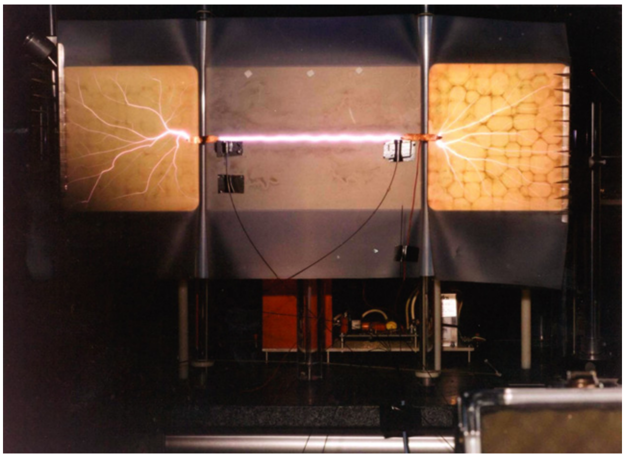


Figure 5. A double-ended tree linking positively (left side) and negatively charged (right side) surfaces in the laboratory (courtesy of S Larigaldie 2006).

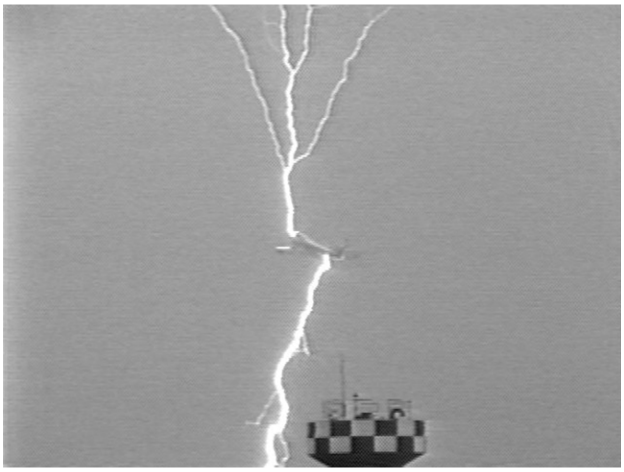


Figure 6. Bi-directional breakdown initiated on an airplane produced a double-ended lightning tree beneath a thundercloud (Courtesy of Z Kawasaki).

verified the polarity of thunderclouds and the double-ended tree of lightning.

More contrived experiments in the laboratory and the atmosphere clearly reveal the double-ended structure of discharges. Figure 5 illustrates a laboratory experiment involving charged surfaces of both polarities (Girard 1992, S Larigaldie, personal communication, 2005), linked by a single channel, but showing distinct asymmetry between the positive and negative surfaces. In the atmosphere, a technique called 'Typsy' is used for triggering lightning with an isolated wire carried upwards by rocket, that then launches the double-ended tree (Hubert 1985) in clear air. In many cases, the two ends of the tree are not the same, but this visual asymmetry remains to be quantified.

In the natural thunderstorm context, Mazur (1989a,1989b) documented the bi-directional development of a double-ended tree from an aircraft as the aircraft triggered lightning and has championed this concept in recent years. His aircraft observations supported 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 6 shows an exceptional example of lightning that was initiated by an aircraft beneath the cloud. Although spatial asymmetry of the branches is evident, it is presently not well established whether the polarity of the lightning tree can be determined from the spatial pattern of the channels. 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 6.

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 (1989a,1989b) 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 the breakdown processes that extend the two ends of the 'tree'. Curiously, the positive end that came to prominence in the earlier studies (Simpson 1926), based on laboratory experiments, radiates much less energy (and is often below the threshold for detection (Mazur 1989a,1989b)), whereas the negative end is more intense and 'noisy'. As will be shown in the next section, a possible explanation for this asymmetry rests on a well- recognized asymmetry in gaseous electronics.

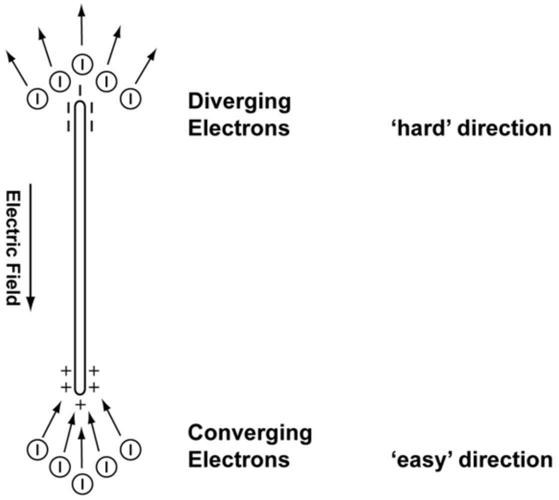


Figure 7. Illustration of polarity asymmetry for a long thin conductor in an electric field. Mobile electrons are convergent on one end and divergent at the other. The 'hard' and 'easy' directions of propagation are indicated.

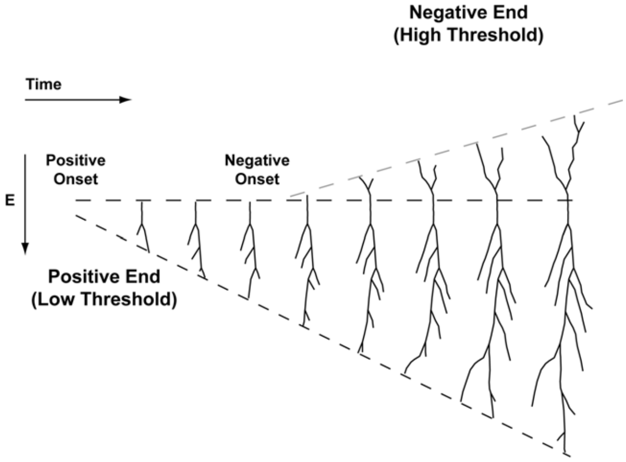


Figure 8. Schematic elongation in time of a bi-directional streamer/leader system, with positive polarity initiation, followed by extension of the negative end of a double-ended 'tree'. At small scale, the discharge is of the non-thermal streamer type and as the system elongates and the current increases, the discharge develops into a thermalized leader.

4. Fundamental aspects of polarity asymmetry

The mobility contrast between free 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 particle mass. Since the mass of positive ions in ionized air is $> 10^4$ times that of a free electron, the large electron mobility makes it the dominant charge carrier. This result in turn has important consequences on larger scales, as will be shown below.

Figure 7 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 towards positive charge, a condition favourable for continued extension (the 'easy' direction). At the opposite end, the mobile electrons are diverging into a region of weaker electric field, a less favourable process (the 'hard' direction). Consistent with Simpson (1926), the positive end of the tree is favoured for extension and will dominate the overall structure. Similar ideas pertaining to figure 7 in the lightning context have been advanced by Loeb (1958) and by Ogawa and Brook (1964).

Contemporary measurements of the threshold fields for the initiation and extension of positive and negative streamers are qualitatively consistent with the asymmetry illustrated in figure 7. The threshold field for positive streamers (at $P = 1000$ mb) is 5×10^5 V m^{-1} (Griffiths and Phelps 1976), whereas the threshold for negative streamers is 10×10^5 V m^{-1}, twice as large (Bazelyan and Raizer 2000). One theoretical approach to this issue is found in Mrázek *et al* (1982). 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 8. The positive streamer begins first until the field at the initiation point is sufficiently large to launch a negative streamer in the opposite direction.

Laboratory experiments with an elongated floating conductor aligned with an applied electric field (Castellani *et al* 1998a,1998b) have shown that the positive streamer initiates first at one end, followed by the negative streamer at the opposite end. This asymmetry is so pronounced in these experiments that electrode ends with different radii of curvature (a blunt positive end and a sharpened negative end) were crafted on the floating conductor to dilute the asymmetry and prevent the early positive streamer from shorting the high voltage gap prematurely (Castellani *et al* 1998a).

The asymmetry in streamer polarity is manifest at the large air-insulated Van de Graaff generator (maximum voltage ~3 MV) at Boston's Museum of Science, where sparks with a positive polarity terminal are notably more energetic. Streamers are initiated where the local electric field is strongest, and these locations tend to be not on the smooth metal surface of the high voltage electrode but rather on the conductors with smaller radii of curvature at ground potential in the vicinity of the Van de Graaff generator. Negative streamers from such sharp points are suppressed by the larger threshold field for that polarity and allow a larger buildup of positive voltage on the main terminal.

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 m gaps. Independent laboratory results in Russia (Stekolnikov and Shkilev 1960, Stekolnikov and Shkilyov 1963, Uman *et al* 1968)) and in France (Les Renardières Group 1977, 1981) demonstrated clear asymmetry in the behaviour of positive and negative leaders in point-to-plane discharges (Bazelyan and Raizer 2000). In essence, positive leaders begin at the point and progress smoothly across the air gap, whereas negative leaders require a higher voltage and are more 'fitful' and erratic. This contrast is illustrated in streak camera photographs for the two leader polarities in figure 9 (from Bazelyan and Raizer

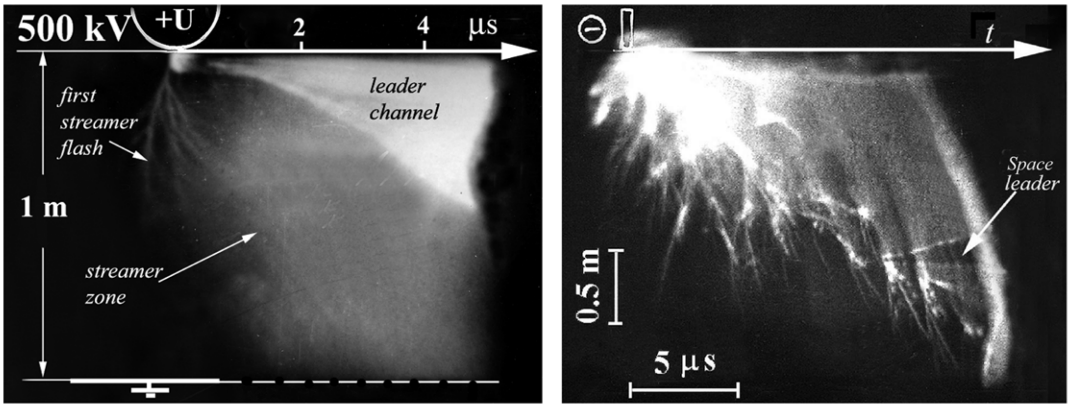


Figure 9. Streak camera imagery contrasting the extension of leaders with positive and negative polarity downwards towards a ground plane. The positive leader progresses smoothly, whereas the negative leader is fitful and erratic (from Bazelyan and Raizer 2000).

Table 1. Summary of quantitative polarity asymmetry in laboratory scale experiments.

Leader polarity	Gap length	Critical field	Recorded velocity range	Peak current
Positive	5–10 m	100–200 kV m^{-1}	1.2–4.2 × 10^4 m s^{-1}	∼1 A
Negative	5–7 m	200–300 kV m^{-1}	10^5 m s^{-1}	∼100 A

2000). Since an acceleration of electric charge is required to radiate electromagnetic energy, we have a physical basis for understanding pronounced asymmetry between positive and negative ends of the discharge.

Gallimberti *et al* (2002) and Lalande *et al* (2002) have recently delved more deeply into the asymmetry in behaviour 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 development of a negative leader is substantially more complicated. The asymmetry in the threshold fields for propagating positive and negative streamers is the reason for this behaviour. An intermittent bi-directional development occurs in the vicinity of the head of the negative leader, with positive streamers extending in a backward direction and negative streamers extending forward. Though the evolution is not sufficiently resolved in space and time for complete understanding, it is likely that the backward positive extension of streamers (the 'easy' direction) occurs first. The bi-directional segment is subsequently heated and becomes fully ionized by what has been referred to as an impulsive current. The current pulse that propagates up the leader channel peaks at hundreds to thousands of amperes. This current stands in marked contrast to the current flow that flows in positive leaders with similar gap geometry. The quantitative contrast in measureables for positive and negative leaders in 1–10 m gaps (Les Renardieres Group 1977, 1981, Lalande *et al* 2002) is summarized in table 1.

What is the connection between the development of laboratory scale discharges and lightning? The historical development of these observations and ideas is summarized in table 2. Schonland recognized in the 1930s, based on streak camera photographs and other observations, that the descending leaders in most CG flashes were 'stepped', i.e. developed in intermittent, downward surges with accompanying surges in current to values of kiloamperes. It now seems likely that each of these steps is in turn a bi-directional development 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 behaviour (M Uman, personal communication 2005), though moving-camera images of descending positive and negative leaders (Berger 1967, Salanave 1980) show distinctly different structures, not unlike that shown in figure 9. If the common behaviour is true, all theories for stepped leader behaviour 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 (1989a,1989b) and subsequently explored in greater detail by Thomas *et al* (2001).

Breakdown processes considered so far in this section all occur as expanding regions of ionization in un-ionized air—so-called 'virgin' breakdown. Non-thermal streamers and thermalized leaders are both in this category. A second important breakdown category in lightning is the recoil leader, or K-change, that propagates in lightning channels forged previously by streamers and leaders, at speeds greater than virgin breakdown by two orders of magnitude (e.g. Mazur *et al* (1997)). A specific example of a recoil leader in the pre-ionized CG lightning channel is the dart leader. A pronounced polarity asymmetry is recognized for recoil leaders. In the words of Mazur (2002):

> From the standpoint of physical interpretation, we should find out why recoil leaders are only of negative polarity, and positive recoil leaders have never been observed (or do not exist), in spite of seemingly similar conditions for the negative and positive breakdown at the end of the cutoff process.

Table 2. Summary of key historical observations and developments in bi-directional discharge and its polarity asymmetry.

1926	Simpson argues that lightning branches in one direction only—away from positive charge
1933	Jensen refutes Simpson's hypothesis; lightning can branch in both directions
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 (Stekolnikov and Shkilev) Stepping behaviour 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 of 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 and colleagues)

A speculative answer to Mazur's challenge is simply that recoil leaders are also bi-directional discharges, with a positive end that progresses smoothly and is rf-quiet and a negative end that is fitful, erratic and noisy. The mechanism for this asymmetry may therefore be the same as for virgin breakdown discussed above and may rest on the mobility contrast between free electrons and ions.

5. Polarity asymmetry in CG lightning

5.1. *Observed behaviour of natural CG lightning*

CG lightning flashes are known to transfer both negative and positive charge to ground, as noted above. 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 behaviour of these two lightning types is notably asymmetrical. Positive ground flashes almost invariably contain just a single stroke, followed by a continuing current (Orville *et al* 1987, Rakov and Uman 2003). In contrast, the more common negative ground flash usually has multiple discrete strokes, often without appreciable continuing current. This multiplicity of strokes in negative polarity lightning is illustrated in figure 10. Whether this multiplicity of strokes has its origin in the spatial distribution of the positive and negative charge regions that produce the lightning (Williams 1998), or is caused by the physics of the discharge process itself, has long been an open question. We will now revisit this issue.

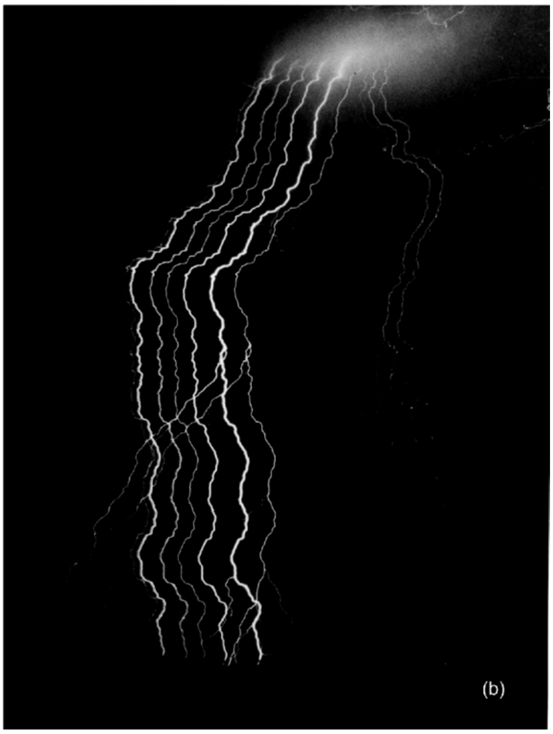


Figure 10. Moving camera image of a multiple stroke, negative CG lightning flash. Note that each stroke is cut-off before the next stroke appears (from Rakov and Uman 2003).

Observations from the US National Lightning Detection Network (NLDN) in figure 11 show a pronounced asymmetry in the stroke multiplicity with season for negative and positive ground flashes (Orville *et al* 1987). Positive ground flashes have a strong tendency to be single-stroke in all months, whereas negative flashes are more likely to contain multiple strokes. (More recent statistics on stroke count (Rakov and Huffines 2003) with the refined NLDN indicate an even stronger asymmetry between positive and negative ground flashes than is shown in figure 11.) The tendency for *both* polarities to move towards single strokes (with continuing current) will be addressed in a subsequent section.

The operation of VHF lightning mapping systems in recent years by the New Mexico Institute of Mining and Technology provides additional data on the asymmetry of the stroke multiplicity for specific flashes. Ron Thomas (personal communication 2005) notes that when multiple strokes are reported for positive ground flashes, the subsequent strokes usually 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 1989a,1989b, 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 a physical interpretation that 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.*

The literature review of the behaviour of leaders from metre scales in the laboratory to hundred-metre scales in rocket triggered lightning, to kilometre scales in upward propagating natural lightning, demonstrates a reasonably consistent polarity asymmetry in several key parameters: (1) threshold

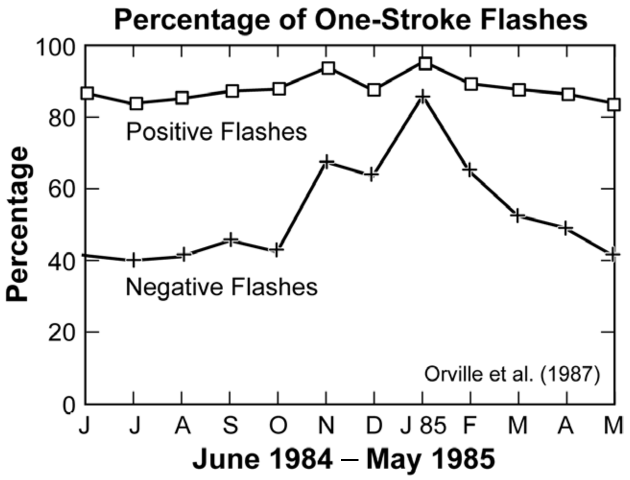


Figure 11. Seasonal variations in the percentages of single-stroke flashes for positive and negative flashes to ground (from Orville *et al* 1987).

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.

5.2.1. Threshold fields for propagation. Studies of leader propagation in 4 m gaps in the US (Udo 1964, Uman *et al* 1968) and in 5–10 m 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 positive polarity (table 1). Later theoretical studies (Lalande *et al* 2002), building on the asymmetry in threshold fields for streamer propagation, show similar results.

Investigations of triggered lightning using wire-trailing rockets have shown a need for larger surface electric fields for successful triggering when a negatively charged rocket is launched towards 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 the latter 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^{-1} or less. Unfortunately, no quantitative studies of polarity asymmetry in this case have been undertaken, as far as I am 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.

5.2.2. Propagation speed. Mean propagation speeds for leaders in 7 m gaps at Les Renardières were found to be $\sim 10^5$ m s^{-1} for negative leaders and $\sim$1–2 × 10^4 m s^{-1} for positive leaders (table 1).

In the case of rocket triggered lightning, Fieux *et al* (1975) reported upwards leader speeds towards negative clouds of 2 × 10^4 m s^{-1} but larger upward speeds of 10^5 m s^{-1} or more in the case of positive clouds.

Studies by Berger (1967) on lightning leaders propagating upwards from towers show a velocity range of 0.4–0.75 × 10^5 m s^{-1} for positive leaders and a range of 1.2–1.9 × 10^5 m s^{-1} for negative leaders, near the tower top (Berger's Table VI). These results are broadly consistent with both the laboratory scale findings and the rocket-triggered lightning results.

5.2.3. Continuity of propagation, stepping and branching. The conspicuous asymmetry in mode of leader extension described in Bazelyan and Raizer (2000), Cooray (2003) and 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 behaviour 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 behaviour for negative (strongly stepped) and positive (weak or unstepped) leaders is reasonably 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 at the positive end. It should be noted however that intermittency likened to stepping is apparent in the early stages of positive leader development in triggered lightning (Lalande *et al* 1998, 2002, V Idone, personal communication 2005). Numerous studies with digital lightning mapping systems in the US however find that the VHF radiation from positive leaders is most often below the sensitivity of the receivers (R Thomas, personal communication 2005).

In the case of rocket-triggered lightning, Horii and Nakano (1995) summarize the results on the continuity of propagation 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^{-1} and propagates continuously, while the negative leader to the positively charged cloud has the velocity of 10^5 to 10^6 m s^{-1} and propagates in steps (Higashiyama *et al* 1980, Horii *et al* 1983).

Any asymmetry in the numbers of branches and the branching angles is likely linked to the asymmetry in the leader development at the 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 developing upward towards 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^{-1}.

Similar findings can be found in Kito *et al* (1985). Only one set of observations on branching appears to contradict the findings noted above. Kawasaki and Mazur (1992) comment that

> The treelike channels in negative leaders appeared at the tip of an ascending wire and developed into multiple branches in a fraction of 1 ms after the rocket launch. Positive leaders, on the other hand, seen during the first several milliseconds as a fine light emission at the wire tip, developed into a single luminous channel.

The polarity ranking of leader luminosity and propagation speed in Kawasaki and Mazur (1992) are however consistent with other results.

Though it may be a fortuitous result, the photograph of the aircraft strike beneath a thundercloud in figure 6 (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 (1967) noted that

> Only negative leaders exhibit a very distinct and bright stepping. Positively charged leaders show a very faint or weak luminosity and less clear, or no stepping.

In summarizing, Berger (1967) states:

> It is interesting to note the great differences in appearance between leaders with negative charges and those having positive charges. The first class of leader shows very well-defined luminous lines with bright tips, sometimes even with the corona envelope visible in front of the tips. The second class of leader does not show distinct streamers but only faint bands which could better be described as irregularly oscillating, weak luminosity with somewhat brighter local tips. These tips sometimes produce a rather continuing trace, which proves that there are no real steps.

Berger and Vogelsanger (1969) later 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 breakdown in figure 9. 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 Töpler some 50 years ago in light of his observations of 'gliding' discharges on the surfaces of insulators.

5.2.4. Current flow. Perhaps the most important physical parameter in the interpretation (below) of the general asymmetrical behaviour of CG lightning is the magnitude of the current in the leader channel. In the 7–10 m gap experiments at Les Renardières, the impulsive 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 Mrázek (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 intermittent and erratic, in contrast to the smooth behaviour for current in positive leaders.

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

> Horii and Ikeda (1985,1985) 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. Considerable consistency is apparent in the various observations, but puzzles remain. Berger (1967) has drawn attention to an apparent contradiction between findings in the laboratory and in the behaviour of lightning initiated on towers: '*Why are streamer discharges* (leaders, in present parlance) *from a negative tower tip much longer than those from a positive tower?*' Given the information in table 1 for laboratory leaders, this contradiction remains. However, the distinction underlined in this review between the intermittent, high-peak-current negative leader and the quasi-steady, smaller-current positive leader may provide a resolution at a larger scale. The polarity dependence of the critical fields for propagation at larger scale is not presently known.

5.3. Heckman's study of the stroke multiplicity in CG 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 understand polarity asymmetry in lightning, a brief discussion is therefore provided here.

Heckman (1992) analysed 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

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

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 12. The equivalent circuit for the current-fed lightning channel to ground is shown in figure 13, 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,

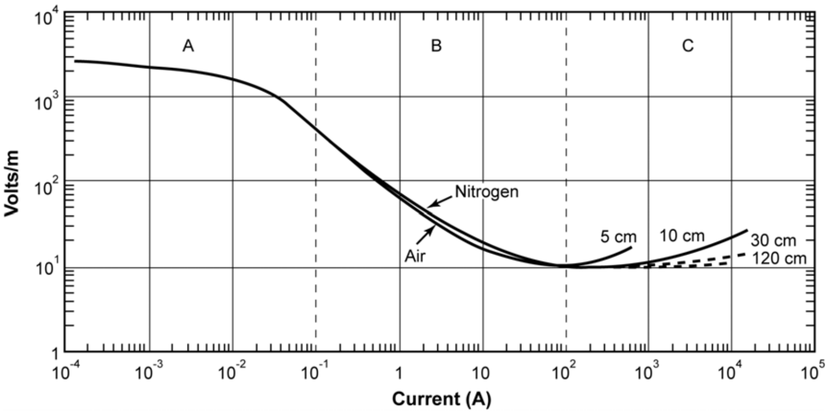


Figure 12. Longitudinal electric field versus current for a steady electric arc in air, showing negative differential resistance: the larger the current the smaller the resistance. From King (1961).

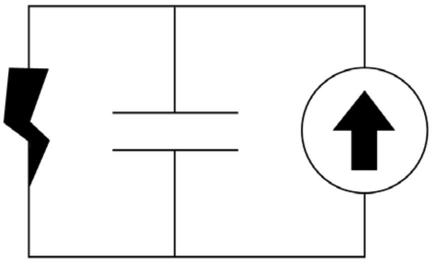


Figure 13. Equivalent circuit for a lightning channel to ground, analysed by Heckman (1992). The continued extension of lightning into the charged cloud constitutes the current source I (arrow symbol on right-hand side), the channel capacitance per unit length times the total channel length is the capacitor C and the (non-linear) arc resistance per unit length times the total channel length is the total arc resistance R.

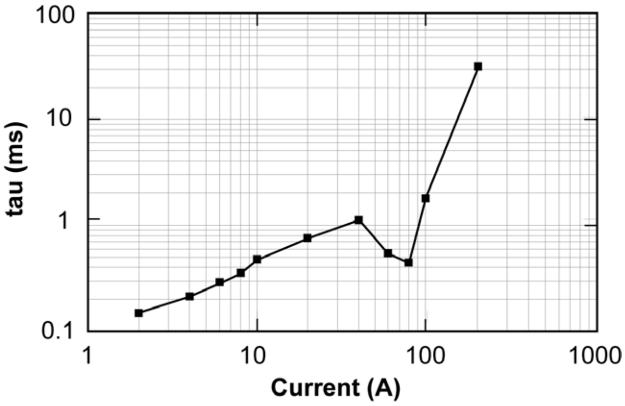


Figure 14. The time constant τ representing the e-folding time of an electric arc in series with a voltage source. Adapted from Frind (1960).

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 Lee (1975), and shown quantitatively in figure 14.

Linear analysis of the circuit in figure 13 results in a simple criterion ($RC = \tau$) separating stable ($RC < \tau$; sustained continuing current) from unstable ($RC > \tau$; current diminishment to cutoff, followed by electric field buildup to a new stroke) behaviour.

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

Tests of these predictions using lightning measurements from the lightning literature are shown in figure 16. The solid squares represent stable continuing current behaviour and the open spaces represent (unstable) discrete stroke behaviour. 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 the asymmetry in CG 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 CG 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 A, one is likely to lie on the right-hand side of the instability boundary in figure 15, for typical channel lengths in flashes to ground. Furthermore, at this current level, the electric field in the arc channel attains a minimum value (figure 12). In the case of positive CG lightning, the interstroke currents are large. Also in the case of positive CG lightning, the interstroke current is maintained by

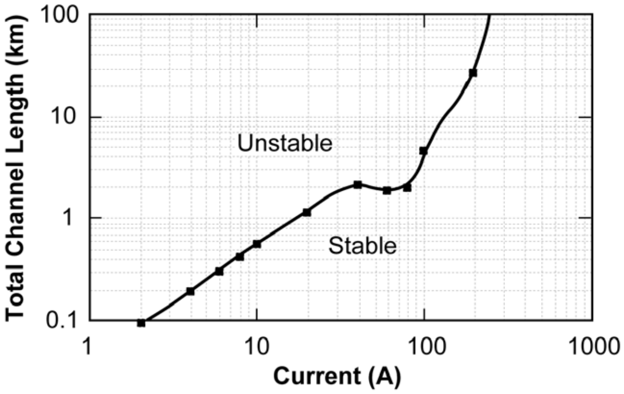


Figure 15. Stability diagram for a lightning channel represented by the equivalent circuit in figure 13. Unstable behaviour with current cutoff to upper left of stability line; stable behaviour with continuing current to lower right of stability line.

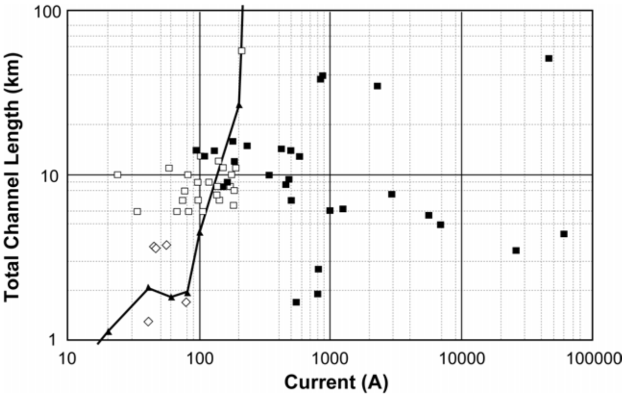


Figure 16. Stability diagram of figure 15 but now in comparison with observations on thunderclouds from the literature. Open squares represent scenarios with discrete strokes and without continuing current. Filled squares represent continuing current scenarios.

negative leader development into positively charged regions of the 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-strokes in positive flashes. It is important to note Thomas's observation in this context that *all* positive ground flashes, regardless of size and shape of the positive charge distribution, are single stroke if they stay in one channel.

The strong tendency of positive ground flashes to dominate the sources of the Q-burst transients that excite Schumann resonances (Ogawa *et al* 1967, Huang *et al* 1999) is also probably related to the tendency of negative leaders (at the other end of the lightning tree) to produce larger sustained ('continuing') currents as they develop in the cloud.

Heckman's (1992) instability result (figure 15) also depends on channel length, with the prediction that the stable, single-stroke/continuing current regime is favoured by shorter channel lengths. The results on stroke multiplicity in figure 11 show that single-stroke behaviour *for both lightning polarities* tends to increase in the winter months (Orville 1987). The established dependence of charge separation on in situ temperature (Takahashi 1978) guarantees that all charge regions are closer to the Earth's surface in the colder winter season. With the accompanying tendency of lightning channels from the main charge reservoirs to ground to shorten significantly, this tendency may account for the tendency towards single stroke behaviour. In summer months, the most common scenarios for negative ground flashes and positive ground flashes are shown in figures 2(*a*) and (*b*), respectively. Two differences between these two scenarios favour 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 cloud-intruding end of the lightning 'tree' has a negative polarity for the positive ground flash and hence a tendency (following the findings in section 5) to supply a larger continuing current than for a negative flash. Recalling again the instability predictions of figure 15, both the larger channel length and lower current in the negative ground flash favour discrete strokes with current cutoff. In contrast, both the shorter channel length and the larger source current for positive ground flashes favour 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 multiplicities of strokes reported by the NLDN.

6. Lightning initiation, electron runaways, and gamma radiation

An active and controversial area in lightning physics concerns the causes of runaway electrons and their role in the dielectric breakdown in thunderclouds and the sources of recently discovered x-rays and gamma radiation (Dwyer *et al* 2004, 2005, Smith *et al* 2005). The electron velocity distribution is fundamental to both conventional dielectric breakdown process and electron runaway (Gurevich and Zybin 2005), 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 3×10^6 V m^{-1}. 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 1.1×10^6 V m^{-1}. 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 1.1×10^6 V m^{-1}

6.2. Possible interpretations of the discrepancy in field magnitudes in thunderclouds

At least four different arguments have been put forward to account for this apparent discrepancy, based on the

Table 3. Summary of maximum measured electric fields in thunderclouds.

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* (1974)	Rockets	4×10^5
Winn *et al* (1981)	Balloons	1.4×10^5
Weber *et al* (1982)	Balloons	1.1×10^5
Byrne *et al* (1983)	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

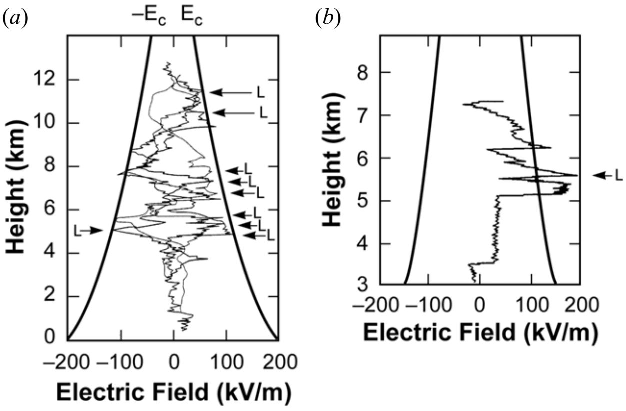


Figure 17. Electric field soundings in a thundercloud compared with the breakeven field for electron runaway, from Gurevich and Zybin (2005).

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.
Highly mobile electrons can in principle acquire exceptional energy in strong electric fields because their collision cross-sections with the surrounding medium decrease with increasing energy. Theoretical calculations (Gurevich and Zybin 2005) for the breakeven electric field needed to extend an electron avalanche by this process is about one order of magnitude less than the conventional breakdown field. Marshall *et al* (1995) and Gurevich and Zybin (2005) offer this theory as an explanation for the discrepancy in electric field magnitudes. Figure 17(*a*) shows their comparison of a balloon sounding with the theoretical breakeven field, showing that the measured field then just touches the theoretical envelope and thus 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 17(*b*)).

(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 (Dawson and Duff 1970, Craib and Latham 1974, Solomon *et al* 2002, Sentman and Christian 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 7) will 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 can be answered at present.

(3) Threshold field for streamer propagation and leader development.
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 m laboratory gap. At pressures typical of initiation heights of many lightning flashes (400–500 mb), the threshold field is in the range 100–200 kV m^{-1}, a value that is comparable to all the maximum field values in table 3. An initial ionization is needed of course, but this could be provided, in principle, by a suitable cosmic ray shower. Indeed, cosmic ray ionization is also postulated for the runaway process described in item (1) above. In the author's opinion, this explanation deserves more study (i.e. Sentman and Christian 2005) as an alternative to the one illustrated in figure 17.

(4) Sampling 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^{-1} through electrified regions of cloud. The electric field within the cloud, affected by both charge separation and 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 largest electric fields are expected, and so the maximum values may escape detection and the largest values recorded (table 2) may be less than the true maximum. Such biases could be evaluated with rocket measurements of electric field (Winn *et al* 1974) spaced closely in time, but such repeated measurements would be difficult and 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 emanating directly from lightning*

The working hypothesis of Gurevich and Zybin (2005) and item (1) of section 6.2 is that the runaway electrons are fundamental to the initiation of lightning. A far greater number of observations support an alternative idea that a special phase and polarity of lightning is needed to accelerate electrons into runaway, with subsequent production of high-energy photons. In other words, the evidence supports the idea that lightning is causing the runaways, rather than the runaways are initiating 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 CG lightning. Dwyer *et al* (2004) have identified x-ray bursts originating in negative dart leaders in triggered lightning. Cummer *et al* (2005) have 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). Williams *et al* (2006a) have considered candidate lightning types for launching gamma rays to space (figure 18) and have inferred that the parent flashes have positive polarity, identified by Cummer *et al* (2005) and numerous other investigators, and are intracloud flashes with their negative ends extending to high altitudes in the troposphere (∼16 km), thereby enabling the gamma rays to escape the atmosphere and be detected by the satellite. All these observations indicate that the negative end of the lightning tree is repelling electrons that ultimately run away to produce x-ray bursts, propagating in the same direction as the accelerated electrons. It is possible that the fitful bi-directional development at the negative end of the lightning tree may play a role in the acceleration of the runaway electrons.

Observations of x-rays in the vicinity of natural positive CG flashes and rocket-triggered flashes with positive polarity will be needed to establish the consistency of these relationships.

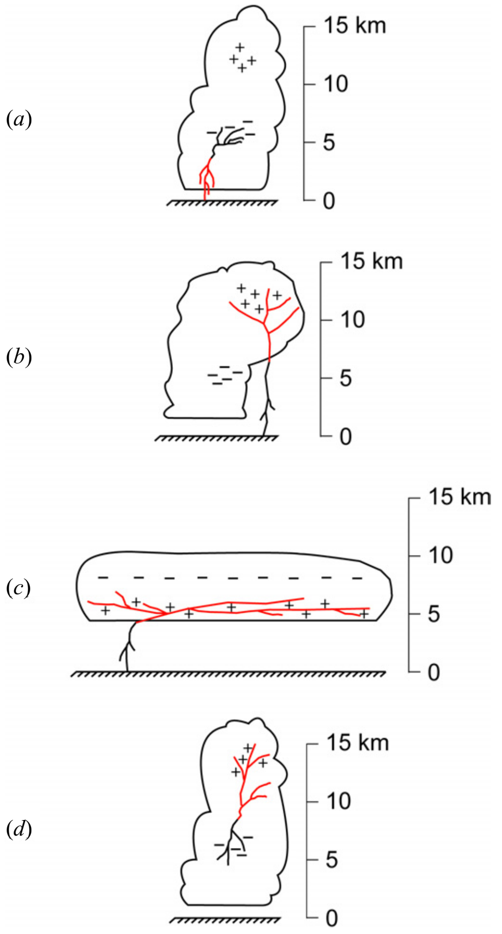


Figure 18. Candidate lightning flashes for producing runaway electrons and launching gamma ray upwards to space (from Williams *et al* 2006a, 2006b). Negative polarity branches are shown in red. The high-reaching intracloud flash with upper end negative (*d*) has been found to be preferred.

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 CG lightning flashes and is often referred to as the 'final jump'. Attachment processes involving upward-propagating streamers from the Earth's surface set the stage for the final jump in the lightning context (Uman 1987, Mazur *et al* 2000). Laboratory experiments in France with both leader polarities have clearly demonstrated a faster 'final jump' with negative polarity leaders (Les Renardières 1977, 1981).

The duration of the final jump is difficult to accurately measure. The values for (negative polarity leaders) are of the order of some microseconds, generally less than 5 μs, which is much shorter than in positive polarity.

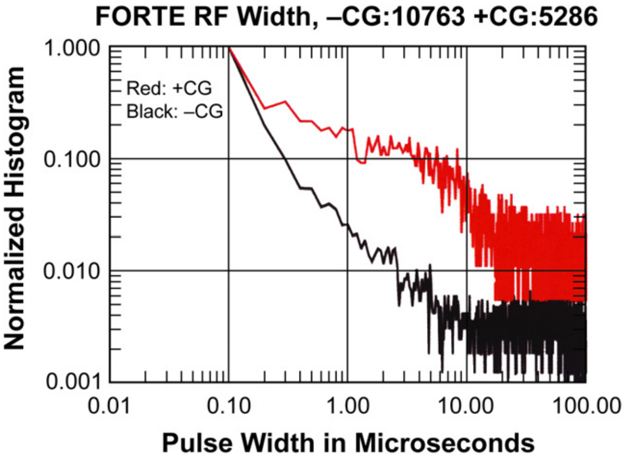


Figure 19. Durations (1/*e* widths) of VHF radiation from the 'final jump' of lightning flashes to ground, both positive (red) and negative (black) polarity. Observations extracted from Jacobson and Shao (2002) and courtesy of X-M Shao.

No physical explanation for the polarity asymmetry was provided.

In the larger scale context of lightning, numerous recent studies have shown evidence of anomalous behaviour of the amplitude of first strokes in negative polarity lightning flashes to an ocean surface. Lyons *et al* (1998), Jacobson and Shao (2002), Steiger and Orville (2003) and Cummins *et al* (2005) all have shown a clear-cut population of negative first strokes that have 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. This anomaly for negative flashes to the ocean is not present in subsequent strokes (Krider, personal communication 2005, Cummins *et al* 2005).

Other studies corroborate the lightning anomaly over the sea. Susczynski (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 19. The mean duration for the negative polarity is substantially less than for positive polarity, consistent with the results on laboratory gaps.

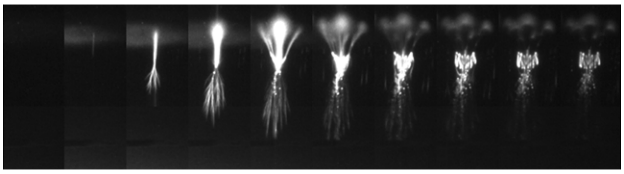


Figure 20. High-speed imager showing the vertical development of a sprite (with 1 ms resolution), another example of a double-ended lightning tree. For sprites initiated by positive ground flashes, the initial growth is positive end downwards, followed by the negative end upwards. (courtesy of H Stenbaek-Nielsen, University of Alaska).

7.2. *Physical interpretation*

It seems plausible that the shorter pulse width (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 CG 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 20 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 2000) suggests that the dendritic growth of lightning is mimicked by sprite growth.

Beginning with suggestions by 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 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 CG 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 μs) and location (∼1 km) for the ground contact point in 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, Sato and Fukunishi 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 with 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 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 ms. The global maps can then be used to examine distributions of charge moment organized by the '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 the change in charge moment showed a polarity-independent threshold for sprite initiation in the range 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 the region of deep convection and of the 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 (Williams *et al* 2006a, 2006b).

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 the 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 CG lightning has been discussed in section 5: negative flashes frequently exhibit multiple strokes, each with current cutoff and no continuing current, whereas positive flashes typically have a single-stroke followed by a continuing current.

In order to distinguish 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 response of the middle atmospheric to negative CG flashes will be impulsive and brief, whereas that for positive flashes will be long and sustained, even for the same total charge moment. This difference in forcing may have important implications for the nature of the ionization aloft. This distribution encourages discussion of two other kinds of luminous event in the mesosphere, elves and haloes.

The elve is a luminous event caused by CG lightning, which has substantially less polarity preference in the parent lightning than insprites (Barrington-Leigh and Inan 1999). The electric field radiated by the return stroke is the causal agent for elves (Inan *et al* 1996). The tendency of 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* 1996) and explained (Inan *et al* 1996), the halo was identified as another luminous discharge in the mesosphere.

Like the sprite before it, the halo 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 TLEs without corresponding NLDN-identified positive ground flashes was 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 CG 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 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 (Williams *et al* 2006a,2006b).

Thomas *et al* (2005) have recently raised the interesting suggestion that the threshold for positive streamer propagation is more relevant for 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 CG lightning compared with 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 in 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 some more recent questions about the physics of lightning involve asymmetries in electrical polarity. This review has considered several of these, including a consideration of the most fundamental polarity asymmetry: the mobility contrast between positive ions and free electrons. Appeal to the behaviour of long sparks on laboratory scales continues to guide our understanding of lightning physics. Theoretical studies are needed to quantify the effects of differences in the electron–ion mobility on larger scales.

Acknowledgments

The author is indebted to 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 presentation ultimately expanded into the present paper. Discussions on this topic with M Alexander, M Baker, C Cooke, D Davis, U Ebert, E Bazelyan, A Bondiou-Clergerie, J Dwyer, A Jacobson, P Lalande, S Larigaldie, P Laroche, W Lyons, V Mazur, J Mrázek, 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. P Krider provided extensive comments on the manuscript.

References

Barrington-Leigh C P and Inan U S 1999 ELVES triggered by positive and negative lightning discharges *Geophys. Res. Lett.* **26** 683–6

Barrington-Leigh C P, Inan U S, Stanley M, and Cummer S A 1999 Sprites directly triggered by negative lightning discharges *Geophys. Res. Lett.* **26** 3605–8

Bazelyan E M and Raizer Y P 2000 *Lightning Physics and Protection* (Bristol and Philadelphia: Institute of Physics Publishing) p 325

Berger K 1967 Novel observations on lightning discharges: results of research on Mt. San Salvatore *J. Franklin Inst.* **283** 478–525

Berger K and Vogelsanger E 1969 New results of lightning observations, *Planetary Electrodynamics* ed S C Coroniti and J Hughes (New York: Gordon and Breach) Chapter IV-5

Berger K 1977 The earth flash *Lightning* vol 1 *Physics of Lightning* ed R H Golde (New York: Academic Press) pp 119–90

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

Boccippio D J, Williams E, Heckman S J, Lyons W A, Baker I and Boldi R 1995 Sprites, ELF transients and positive ground strokes *Science* **269** 1088–91

Bruce C E R 1944 The initiation of long electrical discharges *Proc. R. Soc.* A **183** 228–42

Burke C P and Jones D L 1995 Global radio location in the lower ELF frequencyband *J. Geophys. Res.* **100** 26263

Byrne C J, Few A A and Weber M E 1983 Altitude thickness and charge concentration of charged regions of four thunderstorms during TRIP 1981 based up *in situ* electric field measurements *Geophys. Res. Lett.* **10** 39–42

Castellani A, Bondiou-Clergerie A, Lalande P, Bonany A and Gallimberti I 1998a Laboratory study of the bi-leader process from an electrically floating conductor. Part 1: General results *IEE Proc. Sci. Meas. Technol.* **145** 185–92

Castellani A, Bondiou-Clergerie A,Lalande P, Bonany A and Gallimberti I 1998b Laboratory study of the bi-leader process from an electrically floating conductor. Part 2: Bi-leader properties *IEE Proc. Sci. Meas.Technol.* **145** 193–9

Cobine J D 1958 *Gaseous Conductors—Theory and Applications* (New York: Dover) p 606

Cohen I B 1990 *Benjamin Franklin's Science* (Cambridge: Harvard University Press) p 273

Cooray G V 2003 *The Lightning Flash* (London: Institution of Electrical Engineers) p 574

Craib J A and Latham J 1974 Corona from colliding water drops as a possible mechanism for triggering of lightning *Q. J. R. Met. Soc.* **100** 191–202

Cummer S A and Lyons W A 2004 Lightning charge moment changes in US High Plains thunderstorms. *Geophys. Res. Lett.* **31** L05114

Cummer S A and Lyons W A 2005 Implications of lightning charge moment changes for sprite initiation *J. Geophys. Res.* **110** A04304

Cummer S A, Zhai Y, Hu W, Smith D M, Lopez L I and Stanley M A 2005 Measurements and implications of the relationship between lightning and terrestrial gamma-ray flashes *Geophys. Res. Lett.* **32** L08811

Cummins K L, Murphy M J, Bardo E A, Hiscox W L, Pyle R B and Pifer A E 1998 A combined TOA/MDF technology upgrade of the US National Lightning Detection Network *J. Geophys. Res.* **103** 9035–44

Cummins K L, Cramer J A, Brooks W A and Krider E P 2005 On the effect of land, sea and other Earth surface discontinuities on LLS-inferred lightning parameters *7th Int. Symp. on Lightning Protection (Sao Paulo, Brazil 2005)*

Dawson G A and Duff D G 1970 Initiation of CG lightning strokes *J. Geophys. Res.* **75** 5858–67

Dwyer J R *et al* 2004 Measurements of x-ray emission from rocket-triggered lightning *Geophys. Res. Lett.* **31** L05118

Dwyer J R *et al* 2005 X-ray bursts associated with leader steps in CG lightning *Geophys. Res. Lett.* **32** L01803

Eack K B, Beasley W H, Rust W D, Marshall T C and Stolzenburg M 1996 Initial results from simultaneous observations of X-rays and electric fields in a thunderstorm *J. Geophys. Res.* **101** 29637–40

Faraday M 1843 On the electricity evolved by the friction of water and steam against other bodies *Experimental Researches in Electricity (18th Series)* vol 2 (London: R and E J Taylor) pp 106–26

Fieux R, Gary C and Hubert P 1975 Artificially triggered lightning above land *Nature* **257** 212

Fitzgerald D R 1984 Electric field structure of large thunderstorm complexes in the vicinity of Cape Canaveral *7th Int. Conf. on Atmospheric. Electricity (Albany, New York) Am. Meteorol. Soc.* pp 260–2

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

Frind G 1960 Uber das Ablingen von Lichtbogen *Z. Angew. Phys.* **12** 515–21 (English discussion in Lee (1975), page 243)

Fukunishi H, Takahashi Y, Kubota M, Sakanoi K, Inan U S and Lyons W A 1996 Lightning-induced transient luminous events in the lower ionosphere *Geophys. Res. Lett.* **23** 2157–60

Füllekrug M and Price C 2002 Estimation of sprite occurrences in Central Africa *Meteorol. Z.* **11** 99

Gallimberti I, Bacchiega G, Bondiou-Clergerie A and Lalande P 2002 Fundamental processes in long air gap discharges *C. R. Phys.* **3** 1335–9

Gerken E A, Inan U S and Barrington-Leigh C P 2000 Telescopic imaging of sprites *Geophys. Res. Lett.* **27** 2637–40

Girard B 1992 Simulation en Laboratoire de laDécharge Intranuage *Thèse* de l'Université de Paris Sud-Orsay no 2120

Griffiths R F and Latham J 1974 Electrical corona from ice hydrometeors *Q. J. R. Met. Soc.* **10** 163

Griffiths R F and Phelps C T 1976 The effects of air pressure and water vapor content on propagation of positive corona streamers, and the implications for lightning initiation *Q. J. R. Met. Soc.* **102** 419–26

Gunn R 1948 Electric field intensity inside of natural clouds *J. Appl. Phys.* **19** 481–4

Gurevich A V and Zybin K P 2005 Runaway breakdown and the mysteries of lightning *Physics Today* **58** 37–43

Hardman S F, Dowden R L, Brundell J B, Bahr J L, Kawasaki Z-I and Rodger C J 2000 Sprite observations in the Northern Territory of Australia *J. Geophys. Res.* **105** 4689–97

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

Heckman S 1992 Why does a lightning flash have multiple strokes? *PhD Thesis* Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology

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

Hobara Y, Iwasaki N, Hayashida T, Hayakawa M, Ohta K and Fukunishi H 2001 Interrelation between ELF transients and ionospheric disturbances in association with sprites and elves *Geophys. Res. Lett.* **28** 935–8

Hobara T, Williams E, Hayakawa M, Boldi R and Downes E 2006 Lightning and electrical properties of sprite-producing lightning from a single ELF site *Sprites, Elves and Intense Lightning Discharges* ed M Füllekrug, (Dordrecht: Kluwer) at press

Horii K 1982 Experiment of artificial lightning triggered with rocket *Mem. Fac. Eng.* Nagoya Univ. **34** 77–112

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

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

Horii K and Sakurano H 1985 Observations of the final jump of the discharge in the experiments of artificially triggered lightning *IEEE. PES 1985 Winter Meeting (New York, NY)*

Horii K and Nakano M 1995 Artificially triggered lightning *Handbook of Atmospheric Electrodynamics* ed H Volland (Boca Raton, FL: CRC Press) chapter 6, pp 151–166

Hu W, Cummer S, Lyons W A and Nelson T E 2002 Lightning charge moment changes for the initiation of sprites *Geophys. Res. Lett.* **29** 1279

Huang E, Williams E, Boldi R, Heckman S, Lyons W, Taylor M, Nelson T and Wong C 1999 Criteria for sprites and elves based on Schumann resonance observations *J. Geophys. Res.* **104** 16943–64

Hubert P 1985 Triggered lightning in France and New Mexico *Endeavor (New Series)* vol 8 (Oxford: Pergamon) pp 85–9

Imyanitov I M, Chubarina Y V and Shvarts Y M 1971 *Electricity of clouds* (Leningrad: Gidrometeoizdat) p 92 (NASA Technical Translation from Russian NASA, TT-F-718, 1972)

Inan U S, Sampson W A and Taranenko Y N 1996 Space-time structure of optical flashes and ionization changes induced by lightning-EMP *Geophys. Res. Lett.* **23** 133–6

Jacobson E A and Krider E P 1976 Electrostatic field changes produced by Florida lightning *J. Atmos. Sci.* **33** 103–17

Jacobson A R and Shao X-M 2002 FORTE satellite observations of very narrow radio frequency pulses associated with the initiation of negative CG lightning strokes *J. Geophys. Res.* **107** ACL16-1-13

Jensen J C, 1933 The branching of lightning and the polarity of thunderclouds *J. Franklin Inst.* **216** 707–48

Kasemir H 1960 A contribution to the electrostatic theory of a lightning discharge *J. Geophys. Res.* **65** 1873–8

Kawasaki Z I, Matsuura K, Matsui T and Adachi M 1996 Is the bi-leader progression concept true? *Proc. 10th Int. Conf. on Atmos. Elec. (Osaka, Japan)* pp 596–8

Kawasaki Z-I and Mazur V 1992 Common physical processes in natural and triggered lightning in winter storms in Japan *J. Geophys. Res.* **97** 12935–45

King L A 1961 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

Kito Y, Horii K, Higashiyama Y and Nakamura K 1985 Optical aspects of winter lightning discharges triggered by the rocket-wire technique in Hokuriku district of Japan *J. Geophys. Res.* **90** 6147–57

Koshak W J and Krider E P 1989 Analysis of lightning field changes due to active Florida thunderstorms *J. Geophys. Res.* **94** 1156–86

Krehbiel P R 1986 The electrical structure of thunderstorms *The Earth's Electrical Environment (Studies in Geophysics)* (Washington DC: National Academy Press) pp 90–113 Chapter 9

Krehbiel P R, Brook M and McCrory R A 1979 An analysis of the charge structure of lightning discharges to ground *J. Geophys. Res.* **84** 2432–56

Lalande P, Bondiou-Clergerie A, Laroche P, Eybert-Berard A, Berlandis J-P, Bador B, Bonamy A, Uman M A and Rakov V A 1998 Leader properties determined with triggered lightning techniques *J. Geophys. Res.* **103** 14109–15

Lalande P, Bondiou-Clergerie A, Bacchiega G and Gallimberti I 2002 Observations and modeling of lightning leaders *C. R. Phys.* **3** 1375–92

Lang T J *et al* 2004 The severe thunderstorm electrification and precipitation study *Bull. Amer. Met. Soc.* **85** 1107–25

Larigaldie S 1987 The spark propagation mechanisms in ambient air at the surface of a charged dielectric I - Experimental: the main stages of thedischarge *J. Appl. Phys.* **61** 90–101

Lee T H 1975 *Physics and Engineering of High Power Switching Devices* (Cambridge, MA: MIT Press) pp 233–5

Les Renardières Group 1977 Positive discharges in long air gaps at LesRenardieres—1975 results and conclusions *Electra* **53** 31–153

Les Renardières Group 1981 Negative discharges in long air gaps at LesRenardieres—1978 results *Electra* **74** 67–216

Loeb L B 1958 The positive streamer in air in relation to the lightning stroke *Atmospheric Explorations* ed H G Houghton (Cambridge, MA/New York: MIT Press/Wiley) pp 46–75

Loeb L B 1965 *Electrical Coronas—Their Basic Physical Mechanisms* (Berkeley, CA: University of California Press) pp 694

Lyons W A, Uliasz M and Nelson T E 1998 A climatology of large peak current CG lightning flashes in the contiguous United States *Mon. Weather. Rev.* **126** 2217

Lyons W A 1996 Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems *J. Geophys. Res.* **101** 29641–52

Lyons W A, Nelson T E, Williams E R, Cummer S A and Stanley M A 2003 Characteristics of sprite-producing positive CG lightning during the 19 July 2000 STEPS mesoscale convective systems *Mon. Weather. Rev.* **131** 2417–27

MacGorman D R and Rust W D 1998 *The Electrical Nature of Thunderstorms* (New York: Oxford University Press)

Malan D J and Schonland B J F 1951 The electrical processes in the intervals between the strokes of a lightning discharge *Proc. R. Soc. Lond.* A **206** 145–63

Marshall T C and Rust W D 1991 Electric field soundings through thunderstorms *J. Geophys. Res.* **96** 2297–306

Marshall T C, McCarthy M P and Rust W D 1995 Electric field magnitudes and lightning initiation in thunderstorms *J. Geophys. Res.* **100** 7079–103

Mazur V 1989a Triggered lightning strikes to aircraft and natural intracloud discharges *J. Geophys. Res.* **94** 3311–25

Mazur V 1989b A physical model of lightning initiation on aircraft in thunderstorms *J. Geophys. Res.* **94** 3326–40

Mazur V 2002 Physical processes during the development of lightning flashes *C.R. Phys.* **3** 1393–1409

Mazur V, Williams E, Boldi R, Maier L and Proctor D E 1997 Initial comparison of lightning mapping with operational time-of-arrival and interferometric systems *J. Geophys. Res.* **102** 11071–85

Mazur V, Ruhnke L H, Bondiou-Clergerie A and Lalande P 2000 Computer simulation of a downward negative stepped leader and its interaction with a ground structure *J. Geophys. Res.* **105** 22361–9

McCarthy M and Parks G K 1985 Further observations of x-rays inside thunderstorms *Geophys. Res. Lett.* **12** 393–6

Moore C B, Eack K B, Aulich G D and Rison W 2001 Energetic radiation associated with lightning stepped-leaders *Geophys. Res. Lett.* **28** 2141–4

Mrázek J, Nìniéka V and Hlína J 1982 The intensity of the electric field in the long spark channel *Int. Conf. on Gas Discharges and their Applications (London)* pp 449–52

Mrázek J 1998 The thermalization of the positive and negative lightning channel *Proc. 24th Int. Conf. on Lightning Protection* (Birmingham, UK)

Neubert T, Allin T, Stenbaek-Nielsen H and Blanc E 2001 Sprites over Europe *Geophys. Res. Lett.* **28** 3585–8

Ogawa T and Brook M 1964 The mechanism of the intracloud lightning discharge *J. Geophys. Res.* **69** 5141–50

Ogawa T, Tanaka Y, Yasuhara M, Fraser-Smith A C and Gendrin R 1967 Worldwide simultaneity of occurrence of a Q-type ELF burst in the Schumann resonance frequency range *J. Geomagn. Geoelectr.* **19** 377–84

Orville R E, Weisman R A, Pyle R B, Henderson R W and Orville R E Jr 1987 Cloud to ground lightning flash characteristics from June 1984 through May 1985 *J. Geophys. Res.* **92** 5640–4

Pasko V P, Inan U S, Taranenko Y N and Bell T F 1995 Heating, ionization and upward discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields *Geophys. Res. Lett.* **22** 365–8

Proctor D E 1991 Regions where lightning flashes begin *J. Geophys. Res.* **96** 5099–112

Rakov V A 2004 Initiation of lightning in thunderclouds *Recent Res. Dev. Geophys.* **6** 1–35

Rakov V A and Huffines G R 2003 Return-stroke multiplicity of negative CG lightning flashes *J. Appl. Met.* **42** 1455–62

Rakov V A and Uman M A 2003 *Lightning—Physics and Effects* (Cambridge: Cambridge University Press) pp 687

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

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

Schonland B F J 1938 Progressive lightning IV—the discharge mechanism *Proc. R. Soc. Lond.* A **164** 132–50

Schonland B F J 1953 The pilot streamer in lightning and in the long spark *Proc. R. Soc.* A **220** 25–38

Sentman D D, Wescott E M, Osborne D L, Hampton D L and Heavner M J 1995 Preliminary results from the Sprites '94 aircraft campaign: 1. Red sprites *Geophys. Res. Lett.* **22** 1205–8

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

Sentman D D and Christian H J 2005 Electrical breakdown inside a thunder cloud—Cosmic rays vs hydrometeor effects *EOS 86: Fall Meeting of the American Geophysical Union (San Francisco, CA, December 2005)* No. 52 F255

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

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

Simpson G C 1926 On lightning *Proc. R. Soc. Lond.* A **111** 56–67

Simpson G C 1927 The mechanism of a thunderstorm *Proc. R. Soc. Lond.* A **114** 376–401

Smith D M, Lopez L I, Lin R P and Barrington-Leigh C P 2005 Terrestrial gamma-ray flashes observed up to 20 MeV *Science* **307** 1085–8

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

Solomon R, Adamo C and Baker M 2002 A lightning initiation mechanism: application to a thunderstorm electrification model *C. R. Phys.* **3** 1325–33

Stanley M A, Brook M, Krehbiel P and Cummer S A 2000 Detection of day time sprites via a unique sprite ELF signature *Geophys. Res. Lett.* **27** 871–4

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

Stekolnikov I S and Shkilyov A V 1963 The development of a long spark and lightning *Problems of Atmospheric and Space Electricity* ed S Coroniti *Proc. 3rd Int. Conf. on Atmosphere and Space Electricity (Montreux, Switzerland, May 5-10, 1963)* pp 466–81

Steiger S M and Orville R E 2003 Cloud-to-ground lightning enhancement over Southern Louisiana *Geophys. Res. Lett.* **30** 1975

Stratton J 1941 *Electromagnetic Theory* (New York: McGraw-Hill)

Su H T, Hsu R R, Chen A B C, Lee Y J and Lee L C 2001 Observation of sprites over the Asian continent and oceans around Taiwan *Geophys. Res. Lett.* **29** 1044

Takahashi T 1978 Riming electrification as a charge generation mechanism in thunderstorms *J. Atmos. Sci.* **35** 1536–48

Töpler M 1921a The physical bases of electrical discharges in relation to the technology of insulators *Archiv für Elektrotechnik* **10** 157–85

Töpler M 1921b Electrodenlose Gleitfiguren *Phys. Z.* **22** 59

Thomas R J, Krehbiel P R, Rison W, Hamlin T, Harlin J and Shown D 2001 Observations of VHF source powers radiated by lightning *Geophys. Res. Lett.* **28** 143–6

Thomas J N, Holzworth R H and McCarthy M P 2005 Predicting lightning-driven quasi-electrostatic fields at sprite altitudes using in-situ measurements and a numerical model *Geophys. Res. Lett.* **32** L10809

Udo T 1964 Sparkover characteristics of large gap spaces and long insulation strings *IEEE Trans. Power App. Syst.* **83** 471

Uman M A, Orville R E and Sletten A M 1968 Four-meter sparks in air *J. Appl. Phys.* **39** 5162–8

Uman M A 1987 *The Lightning Discharge (International Geophysics Series)* (New York: Academic) pp 377

Viemeister P E 1972 *The Lightning Book* (Cambridge, MA: The MIT Press) pp 326

Waldteufel P, Metzger P, Boulay J-L, Laroche P and Hubert P 1980 Triggered lightning strokes originating in clear air *J. Geophys. Res.* **83** 2861–8

Weber M E, Christian H J, Few A A and Stewart M F 1982 A thunder cloud electric field sounding: Charge distribution and lightning *J. Geophys. Res.* **87** 7158–69

Williams E R 1998 The positive charge reservoir for sprite-producing lightning *J. Atmos. Sol.-Terr. Phys.* **60** 689–92

Williams E R 2001 Sprites, elves and glow discharge tubes *Phys. Today* (November) pp 41–47

Williams E R 2003 The global electrical circuit *Encyclopedia of Atmospheric Sciences* ed J R Holton *et al* vol 2 (Amsterdam: Elsevier) pp 724–32

Williams E *et al* 2006a Lightning flashes conducive to the production and escape of gamma radiation to space *J. Geophys. Res.* at press

Williams E *et al* 2006b The polarityasymmetry of sprite-producing lightning: A paradox? *Radio Sci.* at press

Wilson C T R 1916 On some determinations of the sign and magnitude of electric discharges in lightning flashes *Proc. R. Soc.* A **92** 555–74

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

Winn W P, Schwede G W and Moore C B 1974 Measurements of electric field in thunderclouds *J. Geophys. Res.* **79** 1761–7

Winn W P, Moore C B and Holmes C R 1981 Electric field structure in an active part of a small isolated thundercloud *J. Geophys. Res.* **86** 1187–93