

# A REVIEW OF POSITIVE AND BIPOLAR LIGHTNING DISCHARGES

BY V. A. RAKOV

Knowledge of positive and bipolar lightning is needed for studying the electrification and evolution of thunderclouds and lightning effects in the middle and upper atmosphere, as well as for designing lightning protection systems.

**P**ositive lightning discharges (flashes) are defined as those effectively transporting a positive charge from a cloud to the earth. It is thought that less than 10% of global cloud-to-ground lightning is positive (e.g., Uman 1987). Lightning discharges (flashes) that transfer to ground both positive and negative charges are termed bipolar lightning discharges. Positive lightning discharges have recently attracted considerable attention for the following reasons:

- 1) The highest recorded lightning currents (near 300 kA) and the largest charge transfers to ground (hundreds of coulombs or even more) are thought to be associated with positive lightning (see Fig. 1).
- 2) Positive lightning can be the dominant type of

cloud-to-ground lightning during the cold season, during the dissipating stage of a thunderstorm, and in some other situations, discussed in the section titled “General characterization.”

- 3) Positive lightning has been recently found to be preferentially related to luminous phenomena known as sprites in the middle and upper atmosphere (e.g., Lyons et al. 1998a,b).
- 4) Reliable identification of positive discharges by lightning locating systems (LLS), such as the U.S. National Lightning Detection Network (NLDN), has important implications for various meteorological and other studies that depend on LLS data (e.g., Petersen and Rutledge 1992; Seimon 1993; MacGorman and Burgess 1994; MacGorman and Morgenstern 1998; Lyons et al. 1998a).

On the other hand, positive lightning largely remains a mystery. Experimental data on this type of lightning discharge are limited and often controversial. The various characteristics of positive flashes will be considered in this review. In particular, it will be shown that the well-known sample of 26 positive flashes reported by Berger et al. (1975) is likely to be a mix of two different types of lightning discharges, resulting in different types of current wave shapes.

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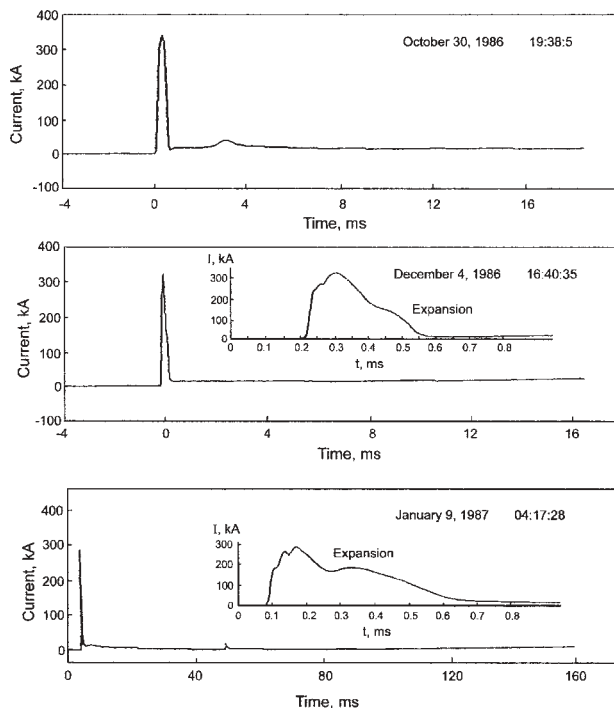
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**FIG. 1. Directly measured currents in three positive lightning discharges in Japan. Note the very large peaks, 340, 320, and 280 kA, of the initial pulses followed by low-level continuing currents whose durations are of the order of (top and middle) 10 or (bottom) 100 ms. The middle and bottom panels have inserts (labeled “Expansion”) that show the same current waveform, but on an expanded (1 ms) timescale. Transferred charges (currents integrated over time) are 330, 180, and 400 C, respectively. Adapted from Goto and Narita (1995).**

Bipolar lightning is generally not considered to be a significant component of the overall lightning activity, although this type of lightning discharge may not be less common than positive lightning. Currently available observations of bipolar lightning flashes, which can be grouped into three categories, will be discussed, this being the first review of the phenomenon.

A knowledge of the occurrence and characteristics of positive and bipolar lightning is needed for studying cloud electrification mechanisms, the charge structure and evolution of thunderclouds, and lightning effects in the middle and upper atmosphere, as well as for designing adequate lightning protection schemes for various objects and systems. A better understanding of positive and bipolar lightning is also needed for proper interpretation of outputs of the NLDN and other similar systems. Further, given their very large charge transfers and their tendency to produce sprites, positive discharges may play an impor-

tant role in the global electrical circuit. According to the “classical” view of atmospheric electricity, thunderstorms serve to resupply the negative charge on Earth that is constantly being lost due to the fair-weather leakage current between the earth and the electrosphere. Positive lightning apparently counteracts this global-circuit mechanism. It is possible that the monitoring of such an “abnormal” component of global lightning activity can be useful in climate change studies.

**POSITIVE LIGHTNING.** *Conditions conducive to the occurrence of positive lightning.* Although the overall percentage of positive lightning discharges is relatively low, there are five situations, listed below, that appear to be conducive to the more frequent occurrence of such discharges. The genesis of positive lightning in these situations is not yet fully understood.

- 1) The dissipating stage of an individual thunderstorm: The tendency for positive lightning to occur toward the end of a thunderstorm has been reported, for example, by Fuquay (1982) and Orville et al. (1983). Pierce (1955) suggested that positive flashes are initiated from the upper (main) positive charge region of thunderclouds after much of the main negative charge, located below the main positive charge, has been removed by negative ground flashes. On the other hand, Krehbiel (1981) reported on three positive flashes in Florida that apparently involved, or were a byproduct of, long (longer than 40 km) horizontal lightning discharges that effectively removed the positive charge from a layer near the 0°C isotherm where frozen precipitation was melting (i.e., from a region that was considerably lower than the main positive charge region). It has been recently suggested (Rust and MacGorman 2002) that some clouds may have “inverted” charge structure (the main positive charge below the main negative charge), which can facilitate the production of positive lightning by such clouds.
- 2) Winter thunderstorms: There is a clear tendency for positive lightning to occur during the cold season. Orville et al. (1987), using one year’s data from the U.S. East Coast lightning locating network, found that positive lightning accounted for about 80% of all ground discharges in the northeastern United States in February and for less than 5% during the summer. From the NLDN data for 1992–95, Orville and Silver (1997) reported that the monthly percentage of positive

flashes over the contiguous United States ranged from 3% (August 1992) to about 25% (December 1993). In 1995–97, the smallest percentage (6.5%) was observed in July 1995, and the largest (about 25%) in January 1996 (Orville and Huffines 1999). In the coastal area of the Sea of Japan, the percentage of positive flashes reached a maximum of 60% in December (Hojo et al. 1989). In France, a maximum percentage of positive flashes of 44% was observed in February (Le Boulch and Plantier 1990).

The production of large positive lightning discharges by winter storms in Japan has been reported by Takeuti et al. (1978) and by Brook et al. (1982) from multiple-station electric field measurements in conjunction with optical observations. Brook et al. (1982) observed that positive flashes constituted about 40% of the total number of cloud-to-ground flashes. About one-third of winter lightning currents recorded by Miyake et al. (1992) on two towers of 88- and 200-m height in Japan were of positive polarity. Brook et al. (1982) suggested that positive flashes originated from the upper positive charge that was displaced horizontally by vertical wind shear from the lower negative charge and was thereby exposed to the ground, which implies that winter clouds have a charge structure similar to that of summer clouds. Later studies (Kitagawa and Michimoto 1994), however, indicate that some winter thunderclouds in Japan may contain a predominantly positive charge, that is, they may have an essentially monopolar charge structure, as opposed to expected dipolar or tripolar charge structure, during most of their life cycle. According to Kitagawa and Michimoto (1994), graupel particles, which are thought to be both the main carriers of negative charges and also the carriers of the lower positive charges, are present in the cloud for only a relatively short period of time. As a result, the lifetime of the dipolar or tripolar charge structure is very short, usually less than 10 min in early or late winter and less than several minutes in midwinter.

- 3) Trailing stratiform regions of mesoscale convective systems (MCSs): The production of predominantly positive flashes by relatively shallow clouds, including the trailing stratiform regions of MCSs (Engholm et al. 1990), has been observed in both winter and summer seasons. This observation might be due largely to the tendency for the occurrence of negative flashes to decrease dramatically with decreasing cloud depth. (It is worth

noting that the difference between the main convective region and the trailing stratiform region of an MCS in terms of cloud depth is not very large.) Some thunderstorm systems produce positive and negative flashes whose ground strike locations tend to be separated in space by polarity, thereby forming the “bipolar” pattern (Orville et al. 1988). (This spatial bipolar pattern has nothing to do with bipolar flashes discussed in the section titled “Bipolar lightning.”) It has been found that most positive flashes are associated with the relatively shallow region of the system, while negative flashes tend to occur in the deepest convection region. Perhaps winter thunderstorms, discussed above, can be included in this category because their depth is usually small. Interestingly, the inner band region of hurricanes, which is typically characterized by lower cloud tops than the eyewall region, has been found to have characteristics similar to those of the trailing stratiform region of MCSs, including a relatively large fraction of positive flashes (Molinari et al. 1999).

- 4) Severe storms: The occurrence of infrequent, widely scattered positive flashes in the mature and later stages of severe springtime storms over the Great Plains in the United States was first observed by Rust et al. (1981), who used electric field measurements in conjunction with optical observations. More recently, some severe storms have been observed (e.g., Seimon 1993; MacGorman and Burgess 1994; Stolzenburg 1994; Perez et al. 1997; Carey and Rutledge 1998; Williams 2001) in which the positive flashes detected by lightning locating systems, such as the NLDN, occurred relatively frequently and outnumbered negative ground flashes for more than 30 min. The period of a storm’s lifetime in which positive flashes dominated varied, but was often during the earlier severe stages of the storm. The cause of this behavior and its relationship to severe weather production is unclear.
- 5) Thunderclouds formed over forest fires or contaminated by smoke: Vonnegut and Orville (1988) found that 25% of about 50 cloud-to-ground flashes apparently associated with the forest fires in Yellowstone National Park lowered positive charge to earth. Latham (1991), studying lightning discharges from a cloud generated by a prescribed forest fire, reported that in a sample of 28 lightning flashes, 19 (or two-thirds) were identified as positive flashes. A relatively high percentage of positive flashes in the central United States detected by the NLDN in the spring of 1998 has

been associated with cloud contamination by smoke from massive forest fires in Mexico that were up to thousands of kilometers away (Lyons et al. 1998a; Murray et al. 2000).

*General characterization.* The following is a list of observed lightning properties that are thought to be characteristic of positive lightning discharges.

- 1) Positive flashes are usually composed of a single stroke, whereas about 80% of negative flashes contain two or more strokes (e.g., Rakov et al. 1994). Multiple-stroke positive flashes do occur but they are relatively rare. Heidler et al. (1998), from electric field measurements in 1995–97 in Germany, found that out of a total of 36 positive flashes, 32 contained one stroke and 4 contained two strokes. On the other hand, Lyons et al. (1998b), using NLDN data for 14 selected summer months from 1991 to 1995, reported on 1002 positive flashes (about 0.04% of a total of 2.7 million positive flashes) composed of more than 10 strokes. However, in the author's view, it is likely that some of these multiple-stroke events are actually misidentified cloud discharges.
- 2) Positive return strokes tend to be followed by continuing currents that typically last for tens to hundreds of milliseconds (e.g., Fuquay 1982; Rust et al. 1981, 1985). Brook et al. (1982), from multiple-station electric field measurements, inferred continuing currents in positive flashes in excess of 10 kA, at least one order of magnitude larger than for negative flashes, for periods up to 10 ms. Directly measured positive continuing currents in the kiloamperes to tens of kiloamperes range in winter lightning in Japan are seen following the initial current pulses in Fig. 1. (For comparison, continuing currents in negative flashes are typically in the tens to hundreds of amperes range.) Such large continuing currents are probably responsible for the unusually large charge transfers by positive flashes. Brook et al. (1982), for one positive lightning in a winter storm in Japan, inferred a charge transfer in excess of 300 coulomb (C) during the first 4 ms. (For comparison, a typical negative flash transfers to ground a charge of 20 C.) Charge transfers during the first 2 ms estimated by Berger (1967) for summer positive lightning in Switzerland are of the order of tens of coulombs. Charge transfers of the order of 1000 C were reported, from direct current measurements, by Miyake et al. (1992) for both positive and negative winter lightning in Japan. However, these lat-

ter events may well be unusual forms of lightning discharges because the grounded strike-object tip was very close to or inside the cloud.

- 3) From electric field records, positive return strokes often appear to be preceded by significant in-cloud discharge activity lasting, on average, in excess of 100 (Fuquay 1982) or 200 ms (Rust et al. 1981). This observation suggests that a positive discharge to ground can be initiated by a branch of, or otherwise produced by, an extensive cloud discharge. Negative cloud-to-ground discharges are less often preceded by such long-lasting in-cloud discharge activity.
- 4) Several researchers (e.g., Fuquay 1982; Rust 1986) reported that positive lightning discharges often involve long horizontal channels, up to tens of kilometers in extent. It is presently not clear why.
- 5) It appears that positive leaders can move either continuously or intermittently (in a stepped fashion), as determined from time-resolved optical images. (A leader is a downward-moving lightning process that forms a charged channel to be discharged by the following upward-propagating return stroke.) This is in contrast with negative leaders, which are always optically stepped when they propagate in virgin air. Further, distant (radiation) electric and magnetic field waveforms due to positive discharges are less likely to exhibit step pulses immediately prior to the return-stroke waveform than are first strokes in negative lightning. Finally, positive leaders usually do not radiate at very high frequency (VHF) and at ultra high frequency (UHF) as strongly as negative leaders and therefore are usually not detected by VHF–UHF lightning imaging systems. In the case of a positive leader, electrons present or produced ahead of the leader tip move toward the tip because they are attracted to the positive charge on it, and the resultant ionization occurs in the strong field near the tip. In the case of a negative leader, electrons tend to “run ahead” of the moving leader tip to where the field is relatively low because they are repelled by the negative charge on the leader tip. Thus, ionization occurs under less favorable conditions for the negative leader than for the positive leader. As a result, streamer zone formation in the negative leader requires a higher tip potential than for the positive leader, which may be related to the apparently different intensity of VHF–UHF radiation produced by these two types of leaders.

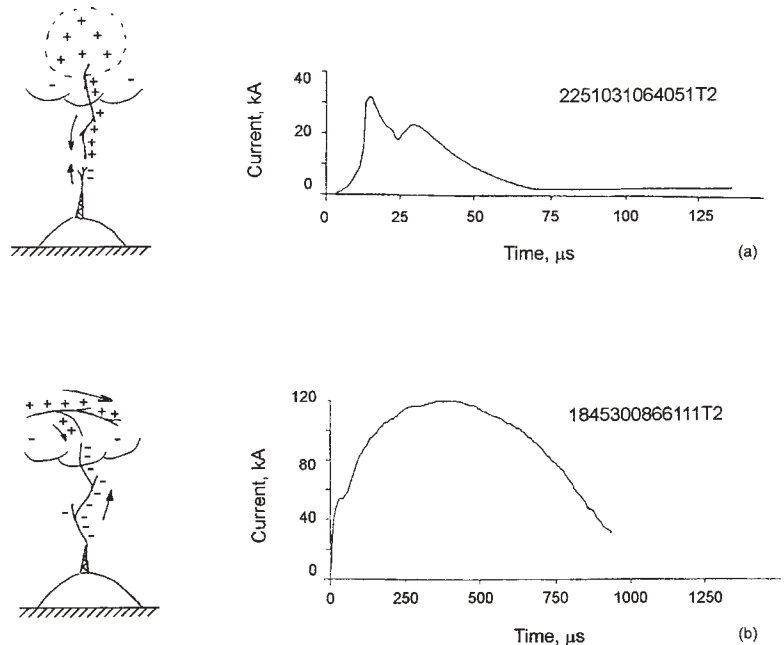
It follows from this list and accompanying discussion that positive discharges to ground often appear

to be preceded by significant in-cloud discharge activity, tend to be followed by continuing currents, and involve long horizontal channels. Positive flashes are usually composed of a single stroke, while the overwhelming majority of negative flashes contain two or more strokes, from three to five being typical. In contrast to negative leaders, positive leaders seem to be able to move either continuously or in a stepped fashion. (Note that the stepping mechanism is different for these two types of leaders.)

**Peak current.** A reliable distribution of positive lightning peak currents applicable to objects of moderate height on the flat ground is presently unavailable. The sample of 26 directly measured positive lightning currents analyzed by Berger et al. (1975) is commonly used as a primary reference both in lightning research and in lightning protection studies. However, this sample is apparently based on a mix of 1) discharges initiated as a result of junction between a descending positive leader and an upward-connecting negative leader within some tens of meters of the tower top and 2) discharges initiated as a result of a very long (1–2 km) upward negative leader from the tower making contact with an oppositely charged channel inside the cloud. These two types of positive discharges, which differ by the height above the tower top of the junction between the upward-connecting leader and the oppositely charged overhead channel (descending positive leader or positively charged in-cloud channel), are expected to produce very different current waveforms at the tower, as illustrated in Figs. 2a and 2b. The “microsecond-scale” current waveform shown in Fig. 2a is probably a result of processes similar to those in downward negative lightning, whereas the “millisecond-scale” current waveform shown in Fig. 2b is likely to be a result of the M-component mode of charge transfer to the ground (Rakov et al. 2001). (The M component is a transient process, an increase in current and associated luminosity, that occurs in a lightning channel carrying continuing current.) It is possible that such millisecond-scale waveforms are characteristic of tall objects capable of generating very

long upward-connecting leaders. On the other hand, the distribution of positive lightning peak currents inferred from electric or magnetic fields recorded by multiple-station LLSs, such as the NLDN, are influenced by the uncertainties of the conversion of the measured field to current. The NLDN formula that is used for this conversion is based on the linear regression equation relating the NLDN-measured field peak to the directly measured current peak for negative triggered lightning strokes and is extrapolated to natural positive strokes. Additionally, the lower end of the positive lightning peak current distribution is contaminated by misidentified cloud-flash pulses (e.g., Cummins et al. 1998).

From lightning locating systems data, the median value of the positive lightning peak current is greater in the winter than in the summer. Interestingly, Orville and Huffines (1999) reported, from 1995–97 NLDN data, that median positive peak currents exceeded 40 kA in regions of the U.S. upper midwest, but were less than 10 kA in Louisiana and Florida. Petersen and Rutledge (1992), working in Australia, observed a tendency for positive peak current maxima (determined over 30-min time intervals) to occur in



**FIG. 2.** Examples of two types of positive lightning current waveforms observed by K. Berger: (a) (right-hand side) microsecond-scale waveform, similar to those produced by downward negative return strokes, and (left-hand side) a sketch illustrating the lightning processes that might have led to the production of this waveform; (b) (right-hand side) millisecond-scale waveform and (left-hand side) a sketch illustrating the lightning processes that might have led to the production of this current waveform. Arrows indicate directions of the extension of lightning channels.

the trailing stratiform regions of MCSs. Conversely, the positive peak current minima tended to occur in the convective regions of the MCSs. Further, the positive peak current maximum in their study appears to vary during the storm life cycle, reaching the largest value when the stratiform region is most intense in terms of its radar reflectivity. MacGorman and Morgenstern (1998) examined 25 MCSs and found that the distribution of positive lightning peak currents varied widely from MCS to MCS, unlike that for negative flashes, which varied little from MCS to MCS.

**Return-stroke speed.** Mach and Rust (1993), from photoelectric measurements, reported on two-dimensional propagation speeds for 7 positive and 26 negative natural lightning return strokes. They presented their speed measurements in two groups: one included values averaged over channel segments less than 500 m and the other included values averaged over channel segments greater than 500 m. For the “short-segment” group, Mach and Rust (1993) found an average speed of  $0.8 \times 10^8 \text{ m s}^{-1}$  for positive return strokes and  $1.7 \times 10^8 \text{ m s}^{-1}$  for negative return strokes. (From a summary of measurements of the return-stroke speed in natural and rocket-triggered lightning published by Rakov et al. (1992), the typical negative return stroke speed is from  $1 \times 10^8$  to  $1.5 \times 10^8 \text{ m s}^{-1}$ .) Two-dimensional measurements of positive return-stroke speed were also reported by Idone et al. (1987) for one positive return stroke that was part of an eight-stroke rocket-triggered lightning flash at the Kennedy Space Center (KSC), Florida, the other seven strokes being negative, and by Nakano et al. (1987, 1988) for one natural positive lightning stroke in winter in Japan. Idone et al.’s (1987) measurements yielded a value about  $10^8 \text{ m s}^{-1}$  for the positive stroke and values ranging from  $0.9 \times 10^8$  to  $1.6 \times 10^8 \text{ m s}^{-1}$  for the seven negative strokes, all averaged over a channel segment of 850 m in length near the ground. Nakano et al. (1987, 1988) reported a significant decrease in two-dimensional speed with increasing height over a 180-m section of the channel, from  $2 \times 10^8 \text{ m s}^{-1}$  at 310 m to  $0.3 \times 10^8 \text{ m s}^{-1}$  at 490 m. On the other hand, Mach and Rust (1993) found no significant speed change with height for positive return strokes. Clearly, more data on positive return-stroke speed are needed.

**BIPOLAR LIGHTNING.** Lightning current waveforms exhibiting polarity reversals within the same flash were first reported by McEachron (1939, 1941) from his studies at the Empire State Building, in New York City, New York. According to Hagenguth and Anderson (1952), the number of bipolar flashes ob-

served over a 10-yr period was 11 (14%) from a total of 80 flashes for which polarity could be determined. The charge transfer was reported to be greater for negative polarity, probably due to the fact that the initial stage current (Miki et al. 2002) was mostly negative. Interestingly, no flashes transferring only a positive charge to the ground were observed in these studies. Berger (1978) reported that 72 (6%) of 1196 discharges observed in 1963–73 at Mount San Salvatore (Switzerland) were bipolar, with 68 of them being of the upward type, that is, initiated by an upward-propagating leader from the strike object. For 30 bipolar events, he found median current peaks for the negative and positive parts of the waveform to be 350 A and 1.5 kA, respectively. The corresponding median charge transfers were 12 and 25 C. Gorin and Shkilev (1984) reported that 6 (6.7%) of 90 upward discharges initiated from the Ostankino Tower in Moscow (Russia) were bipolar, all of which initially transported negative charge to ground. The total number of bipolar lightning discharges observed on the Peissenberg tower (Germany) was two (Heidler et al. 2000), both of which initially transported a negative charge to the ground. Many bipolar current waveforms have been observed in winter lightning studies in Japan, with the reported frequency of occurrence ranging from 5% to 33%. At least one bipolar lightning discharge was reported from each of the triggered lightning experiments in France, Japan, New Mexico, Florida, and China [see Rakov (1999) for a review of triggered lightning experiments in different countries].

There are basically three types of bipolar lightning discharges, although some events may belong to more than one category. The first type is associated with a polarity reversal during a slowly varying (millisecond scale) current component, such as the initial continuous current in object-initiated lightning or in rocket-triggered lightning. The second type of bipolar discharge is characterized by different polarities of the initial-stage current and of the following return stroke or strokes. The third type involves return strokes of opposite polarity. We now discuss these three categories in more detail.

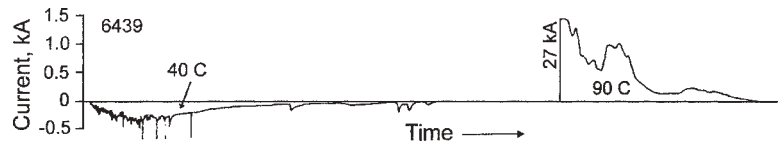
Category 1 shows polarity reversal during a slowly varying (millisecond scale) current component. The polarity reversal may occur one or more times and may involve a no-current interval between opposite polarity portions of the waveform. A bipolar, millisecond-scale current waveform associated with a summer rocket-triggered lightning in southeastern China is given by Liu and Zhang (1998). A similar waveform is found in McEachron (1939). Also,

Laroche et al. (1985) noted a polarity reversal from negative to positive during the initial stage in one rocket-triggered flash in Florida. Hubert et al. (1984) reported a bipolar, millisecond-scale current waveform produced by a rocket-triggered lightning in New Mexico. The magnitudes of positive and negative charge transfers were similar, 235 and 240 C, respectively. The positive current component appeared to be associated with a branch of large horizontal extent below the cloud.

A reversal of polarity of the continuing current from negative to positive at the end of an otherwise negative rocket-triggered lightning discharge in France was observed by Waldteufel et al. (1980) and Hubert and Mouget (1981). The occurrence of a positive continuing current at the end of an otherwise negative flash initiated from the Peissenberg Tower in Germany was reported by Fuchs (1998).

Davis and Standring (1947), who measured currents in the cables of kite balloons, flying at a height of 600 m under thunderstorm conditions, reported on a polarity change from negative to positive in a current record apparently associated with the initial stage of an upward discharge.

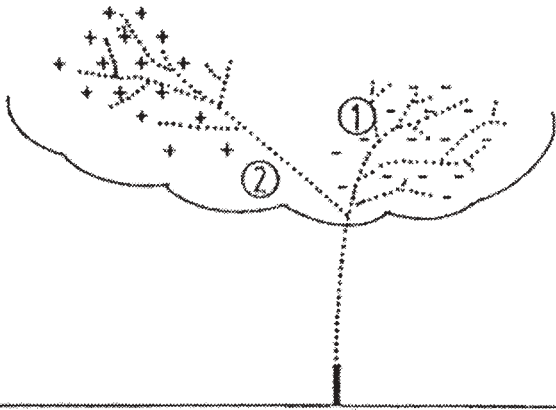
Category 2 has different polarities of the initial-stage current and of the following return stroke(s). An example of such a current waveform, reproduced in Fig. 3, is shown in Berger and Vogelsanger (1966) and in Berger (1978). The initial-stage current in this waveform is negative, with an amplitude of some hundreds of amperes and a total charge transfer of 40 C, and the return stroke current is positive with a peak value of 27 kA and a total charge transfer of 90 C. The positive return-stroke current was separated from the negative initial stage current by a zero-current time interval of about 100 ms. The positive return stroke was followed by a continuing current. Berger (1978) gives one more example of a bipolar current waveform in which the positive initial-stage current, approaching 4 kA, is followed by a negative current pulse having a peak of 6.5 kA, possibly due to a return stroke. The negative pulse exhibits fluctuations on its tail, including a brief polarity reversal, and is followed by a slow, positive waveform, having a peak approaching 3 kA. Nakahori et al. (1982) observed, in a lightning discharge to a 200-m smokestack during a winter storm in Japan, a negative initial-stage current with superimposed pulses up to 20 kA or so



**FIG. 3. Current of upward bipolar flash from tower I on Mount San Salvatore (event 6439). The current is shown as a function of time with the overall flash duration being about 550 ms. Charge transfers associated with the negative (40 C) and positive (90 C) portions of the overall current waveform are indicated, as is the peak current (27 kA) of the positive current waveform that is shown clipped at a 1.5-kA level. Currents of both polarities followed the same channel to ground but were associated with different, oppositely charged regions in the cloud. Adapted from Berger and Vogelsanger (1966).**

in amplitude followed by a positive return-stroke current pulse having a peak of 31 kA. Fernandez (1997) reported on a positive initial-stage current in triggered lightning at Camp Blanding, Florida, that was followed by leader/return-stroke sequences transferring a negative charge to the ground.

Category 3 shows return strokes of opposite polarity within the same flash. All of the documented bipolar discharges in this category are of the upward type. Examples of current waveforms produced by such discharges are found in McEachron (1939) and in Berger and Vogelsanger (1965). Janischewskyi et al. (1999) observed three return strokes in an upward discharge initiated from the CN Tower in Toronto, Ontario (Canada), with currents of  $-10.6$ ,  $+6.5$ , and  $-8.9$  kA. The time interval between the first and second strokes was 300 ms, and between the second and third strokes was 335 ms. All three strokes followed the same channel, as observed within about 535 m of the tower top. The wave shape characteristics of all three strokes were similar. As discussed in the section titled "Return-stroke speed," Idone et al. (1987) studied a Florida rocket-triggered flash that contained eight return strokes, one of which was positive and the other seven negative. The positive stroke was the third in the flash, with the preceding and following interstroke intervals being 374 and 369 ms, respectively. The time intervals between the negative strokes in this flash ranged from 39 to 101 ms. Gary et al. (1975), from summer triggered lightning experiments in France, reported on a negative discharge with a peak current of 19 kA and a rise time of  $1.5 \mu\text{s}$  followed by a positive discharge with a peak current of 4 kA and an unspecified rise time. It is possible that these two events were two return strokes of opposite polarity. The positive event occurred 280 ms after the beginning of the negative event and 140 ms after the cessation of luminosity of the negative event.



**FIG. 4. A possible explanation of observed bipolar lightning currents, such as that shown in Fig. 3. Currents of both polarities follow, in turn, the same channel to the ground, with negative charge transfer from the cloud charge region labeled “1” being followed by positive charge transfer from the charge region labeled “2.” Adapted from Narita et al. (1989).**

For winter lightning in Japan, Narita et al. (1989) suggested that, in a bipolar discharge, currents of both polarities follow the same channel to the ground, but from different, oppositely charged regions in the cloud, as illustrated in Fig. 4. It is likely that the explanation of bipolar current wave shapes suggested by Narita et al. (1989) for winter lightning also applies to summer bipolar lightning.

**SUMMARY.** Our knowledge of the physics of positive lightning remains much poorer than that of negative lightning. Many questions regarding the genesis of positive lightning and its properties cannot be answered without further research. It is worth noting that attempts to initiate positive lightning using the rocket-and-wire technique generally result in discharges that are composed of the initial stage (relatively low-level, long-lasting current component) that is not followed by positive leader/return-stroke sequences. Bipolar lightning is an even less understood and often unrecognized phenomenon. While some simple cloud charge distributions, such as a “tilted dipole,” an “inverted dipole,” or a “positive monopole,” can apparently explain the generation of positive lightning, the occurrence of bipolar lightning, as well as complex cloud discharges, suggests that the cloud charge structure cannot always be described by simple, vertically stacked charge models. It is likely that positively and negatively charged regions can exist at about the same height in the cloud.

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