POSITIVE AND BIPOLAR LIGHTNING DISCHARGES: A REVIEW

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Abstract: Characteristics of lightning discharges that transport either positive charge or both negative and positive charges to ground are reviewed. Different types of positive and bipolar discharges are discussed.

Keywords: Positive Lightning, Bipolar Lightning, Review

1. INTRODUCTION

Positive lightning discharges have recently attracted considerable attention for the following reasons:

1) The highest recorded lightning currents (up to 300 kA or so) and the largest charge transfers to ground (up to 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.
3) Positive lightning has been recently identified as a major source of various effects in the middle and upper atmosphere, such as sprites and elves.
4) Reliable identification of positive discharges by lightning locating systems (LLS) has important implications for various studies that depend on LLS data.

The various characteristics of positive discharges will be considered in this review. In particular, it will be shown that the well-known sample of 26 positive flashes recorded by Berger is likely to be a mix of two different types of lightning discharges. Further, observations of bipolar lightning discharges, which can be grouped into three categories, will be reviewed.

2. POSITIVE LIGHTNING

2.1 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 percent of negative flashes contain two or more strokes (e.g., Rakov et al. 1994 [1]). Multiple-stroke positive flashes do occur but they are relatively rare. Heidler et al. (1998) [2], from electric field measurements in 1995-1997 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) [3], using NLDN data for 14 selected summer months from 1991-1995, reported on 1002 positive flashes (about 0.04 percent of a total of 2.7 million positive flashes) composed of more than 10 strokes. However, 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 [4]; Rust et al. 1981, 1985 [5, 6]). Brook et al. (1982) [7], from multiple-station electric field measurements, inferred continuing currents in positive flashes in excess of 10 kA, an 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. Such large continuing currents are probably responsible for the unusually large charge transfers by positive flashes. Brook et al. (1982) [7], for one positive lightning in winter storm in Japan, inferred a charge transfer in excess of 300 C during the first 4 ms. Charge transfers during the first 2 ms estimated by Berger (1967) [8] 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) [9] for both positive and negative winter lightning in Japan. However, these latter events may well be unusual forms of lightning discharges since the grounded strike object tip was very close to or inside the cloud.

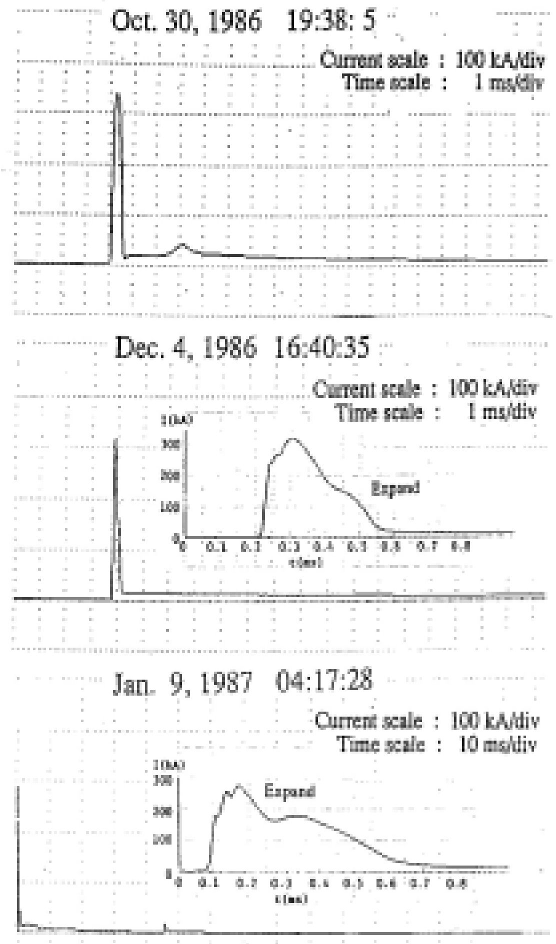

Figure 1. Directly measured currents in three positive lightning discharges in Japan. Note the very large peaks, 340, 320, and 280 kA, of the initial pulses followed by continuing currents. Transferred charges are 330, 180, and 400 C, respectively. Adapted from Goto and Narita (1995) [10].

(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 ms (Fuquay 1982) [4] or 200 ms (Rust et al. 1981) [5]. This observation suggests that a positive discharge to ground can be initiated by a branch of an extensive cloud discharge.

(4) Several researchers (e.g., Fuquay 1982 [4]; Rust 1986 [11]) reported that positive lightning discharges often involve long horizontal channels, up to tens of kilometers in extent.

(5) It appears that positive leaders can move either continuously or in a step fashion, as determined from their time-resolved optical images. 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 similar waveforms due to first strokes in negative lightning. Finally, positive leaders usually do not radiate at VHF as strongly as negative leaders.

2.2. Peak Current

A reliable distribution of positive-lightning peak currents is presently unavailable. The sample of 26 directly measured positive-lightning currents analyzed by Berger et al. (1975) [12] 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 tip and (2) discharges initiated as a result of a very long 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 tip 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 b. 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 ground. It is possible that such millisecond-scale waveforms are characteristic of tall objects, capable of generating very long upward connecting discharges. On the other hand, the distribution of positive lightning peak currents inferred from electric or magnetic fields recorded by multiple-station lightning locating systems (LLS), such as the NLDN, are contaminated by misidentified cloud-flash pulses. It is believed that the latter primarily affect the lower end of the positive-lightning peak current distribution.

From lightning locating systems' data, the median value of the positive lightning peak current is found to be greater in winter than in summer. Interestingly, Orville and Huffines (1999) [13] reported, from 1995-1997 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) [14], using data from a four-station lightning locating system in Australia, observed a tendency for positive peak current maxima (determined over 30-min time intervals) to occur in the trailing stratiform regions of mesoscale convective systems (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).

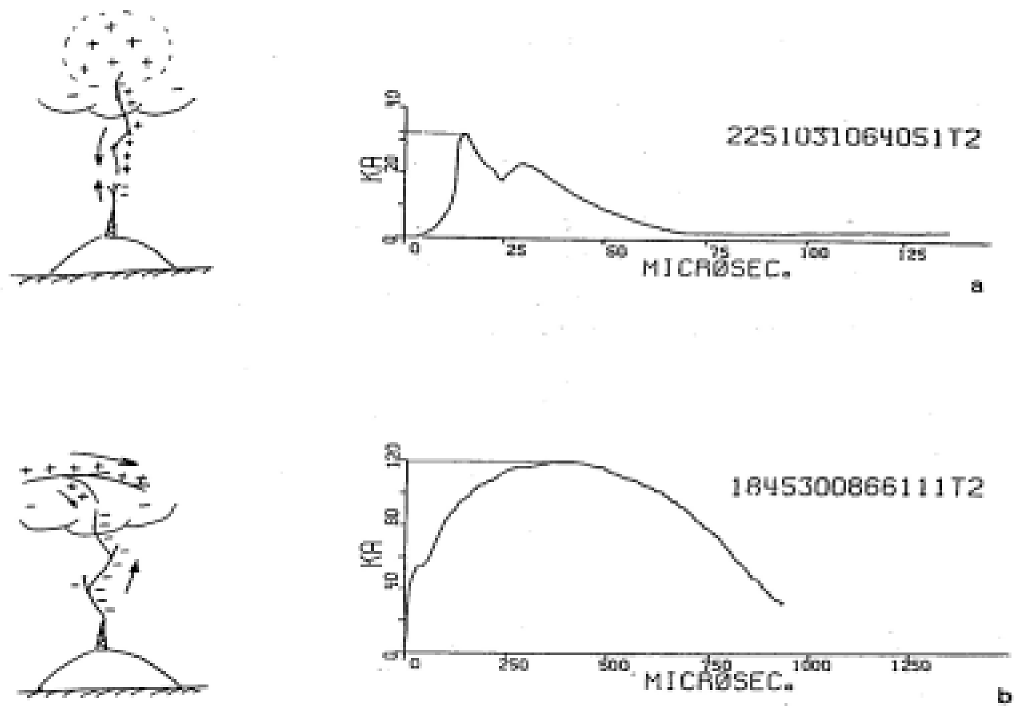

Figure 2. Examples of two types of positive lightning current waveforms observed by K. Berger: (a) "microsecond-scale" waveform (right panel), similar to those produced by downward negative return strokes, and a sketch (left panel) illustrating the lightning processes that might have led to the production of this waveform; (b) "millisecond-scale" waveform (right panel) and a sketch (left panel) illustrating the lightning processes that might have led to the production of this current waveform.

2.3. Return-Stroke Speed

Mach and Rust (1993) [15], from photoelectric measurements, reported 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 in length (for positive lightning: from 332 to 433 m; four values) and the other included values averaged over channel segments greater than 500 m in length (for positive lightning: from 569 m to 2300 m; seven values). For the "short-segment" group, Mach and Rust (1993) [15] found an average speed of 0.8×10^8 m s^{-1} for positive return strokes and 1.7×10^8 m s^{-1} for negative return strokes. Two-dimensional measurements of positive return-stroke speed were also reported by Idone et al. (1987) [16] for one positive return stroke that was part of an eight-stroke lightning flash initiated using the rocket-and-wire technique in Florida (KSC), the other seven strokes being negative, and by Nakano et al. (1987) [17] for one natural positive lightning stroke in winter in Japan. Idone et al.'s (1987) [16] measurements yielded a value about 10^8 m s^{-1} for the positive stroke and values ranging from 0.9×10^8 to 1.6×10^8 m s^{-1} for the seven negative strokes, all averaged over a channel segment of 850 m in length near ground. Nakano et al. (1987) reported a significant decrease in two-dimensional speed with increasing height over a 180-m section of the channel, from 2×10^8 m s^{-1} at 310 m above the sea level to 0.3×10^8 m s^{-1} at 490 m. Clearly, more data on positive return-stroke speed are needed.

3. BIPOLAR LIGHTNING

Lightning current waveforms exhibiting polarity reversals were first reported by McEachron (1939, 1941) [18, 19] from his studies at the Empire State Building. According to Hagenguth and Anderson (1952) [20], the number of bipolar flashes over a 10-year period of lightning studies at the Empire State Building was 11 (14 percent) out of 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 in upward flashes initiated from the Building was mostly negative. Interestingly, no flashes transferring only positive charge to ground were observed in these studies. Berger (1978) [21] reported that 72 (6 percent) of 1196 discharges observed in 1963-1973 at Mount San Salvatore were bipolar, with 68 of them being of the upward type. 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) [22] reported that 6 (6.7 percent) of 90 upward discharges from the Ostankino tower, Russia, were bipolar, all of which initially transported negative charge to ground. One bipolar discharge of a total of 118 upward flashes was reported from lightning studies on the Peissenberg tower, Germany (Fuchs et al. 1998) [23]. Many bipolar current waveforms have been observed in winter lightning studies in Japan, with the reported frequency of occurrence ranging from 5 to 33 percent. At least one bipolar lightning discharge was reported from each of the triggered-lightning experiments in France, Japan, New Mexico, Florida, and China.

There are basically three types of bipolar lightning discharges, although some events may belong to more than one category.

(1) 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 polarity reversal may occur one or more times and may involve an appreciable 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; Fig. 4a) [24]. A similar waveform is found in Fig. 19 of McEachron (1939) [18]. Hubert et al. (1984, p. 2515) [25] reported on a bipolar, millisecond-scale current waveform produced by a rocket-triggered lightning in New Mexico. The positive current component appeared to be associated with a branch of large horizontal extent below the cloud.

A reversal of polarity of continuing current from negative to positive at the end of otherwise negative rocket-triggered lightning discharge in France is seen in Fig. 2 of Waldteufel et al. (1980) [26] and in Fig. 4 of Hubert and Mouget (1981) [27]. An occurrence of positive continuing current at the end of otherwise negative flash initiated from the Peissenberg tower was reported by Fuchs (1998) [28].

(2) The second type of bipolar discharges is characterized by different polarities of the initial stage current and of the following return stroke or strokes. An example of such current waveform is shown in Fig. 23b of Berger and Vogelsanger (1966) [29] and Fig. 6a of Berger (1978) [21]. The initial stage current in this waveform, reproduced in Fig. 3, is negative (up to some hundreds of amperes with the total charge transfer of 40 C), and the return stroke current, followed by a continuing current, is positive (peak value of 27 kA with the 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. Berger (1978) [21] gives one more example of bipolar current waveform, in his Fig. 6b. Nakahori et al. (1982) [30] observed, in a lightning discharge to a 200-m smoke stack in a winter storm in Japan, a negative initial stage current with superimposed pulses up to 20 kA or so in amplitude followed by a positive return-stroke current pulse having a peak of 31 kA. Fernandez (1997) [31] reported on a positive initial stage current in triggered lightning at Camp Blanding, Florida, that was followed by leader/return stroke sequences transferring negative charge to ground.

(3) The third type of bipolar discharges involves return strokes of opposite polarity. Examples of current waveforms produced by such discharges are found in Fig. 17 of McEachron (1939) [18] and in Fig. 18 of Berger and Vogelsanger (1965) [32]. Janischewskyi et al. (1999b) [33] observed three return strokes in an upward discharge initiated from the 553-m tall Canadian National (CN) tower, whose currents were - 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 the third strokes it was 335 ms. All three strokes followed the same channel, as observed within about 535 m of the

Figure 3. Current of upward bipolar flash from Tower 1 on Mount San Salvatore (Event 6439). The current is shown as a function of time with the overall flash duration being about 550 ms. Adapted from Berger and Vogelsanger (1966) [29].

tower tip.The waveshape characteristics of all three strokes were similar. As discussed in Section 2.3, Idone et al. (1987) [16] studied a Florida rocket-triggered flash that contained eight return strokes one of which was positive and the other seven were negative. The positive stroke was the third in the flash, with the preceding and following interstroke intervals being 374 and 369 ms, respectively. Note that all the documented bipolar discharges in this category (return strokes of opposite polarity) are of the upward type.

For winter lightning in Japan, Narita et al. (1989) [34] suggested that, in a bipolar discharge, currents of both polarities follow the same channel to ground, but from different, oppositely charged regions in the cloud, as illustrated in Fig. 4. It is likely that the explanation of bipolar current waveshapes suggested by Narita et al. (1989) [34] for winter lightning also applies to summer bipolar lightning.

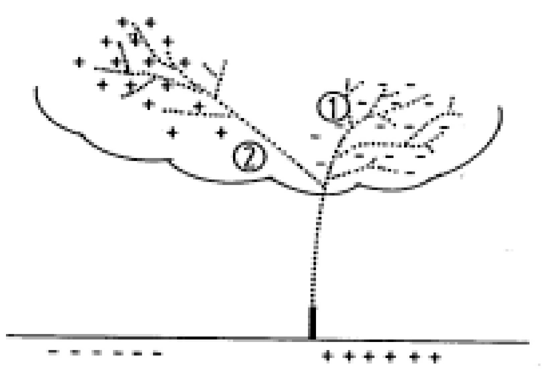

Figure 4. A possible explanation of observed bipolar lightning currents. Adapted from Narita et al. (1989) [34].

4. CONCLUDING REMARKS

There has been significant progress in studying positive lightning during the last two decades or so. However, the properties of positive lightning remain considerably less understood than those of negative lightning.

It appears that positive cloud-to-ground discharges are intimately related (to a greater degree than negative discharges) to cloud lightning discharges. Further, some cloud discharge processes are apparently capable of producing electric and magnetic field signatures resembling those characteristic of return strokes and of comparable amplitude. The polarity of these cloud-discharge pulses is probably more often the same as that expected for positive return strokes. As a result, in the absence of independent evidence of a channel to ground, it is very difficult to identify positive return-stroke waveforms with confidence.

The initiation of positive lightning using the rocket-and-wire technique may provide new insights into the discharge processes involved. The artificial initiation of a positive return stroke has not been successful so far, probably due to the tendency, discussed above, for positive lightning to occur as a single-component, as opposed to multiple-component, event. This tendency, in the case of rocket-triggered lightning, translates to a positive discharge that is composed of the initial stage only, that is, contains no return strokes. As noted above, sometimes positive initial continuous current in rocket-triggered lightning is followed by leader/return stroke sequences transferring negative charge to ground, but a positive continuous current followed by downward leader/upward return stroke sequencies transferring positive charge to ground has not yet been documented.

Bipolar lightning discharges are usually initiated by upward leaders from tall objects. It appears that positive and negative charge sources in the cloud are tapped by different upward branches of the lightning channel.

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