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Characteristics of a bipolar cloud-to-ground lightning flash containing a positive stroke followed by three negative strokes

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ABSTRACT

Using time-correlated high-speed video images at 3200 frames per second, broadband electric field change data and low-frequency magnetic fields, a natural bipolar cloud-to-ground (CG) lightning flash with one first positive stroke followed by three subsequent negative strokes is analyzed. All of these four strokes transferred electric charge to the ground through the same lower channel with a time interval of 328 ms between the positive stroke and the first negative stroke. The flash onset was followed by several positive leaders that extended below the cloud base, one of which descended to culminate in a positive stroke with a continuing current. Another positive leader extended horizontally to a distant negative cloud region and induced several recoil leaders that intermittently retrograded along the leader channel. Eventually, three recoil leaders successively traversed along the path of positive stroke to produce respective negative strokes, resulting in the polarity reversal of charge transferred to the ground. The average two-dimensional (2-D) speed of the positive leader was 1.1×10^5 m/s, while for the 3 negative leaders was 6.7×10^6 m/s. The zero-crossing time and rise time of the radiation field waveform for the 3 negative strokes are smaller than the typical negative subsequent strokes, making them hard to be recognized as return strokes by the CG lightning location network.

1. Introduction

The reversal in the polarity of charge transferred to the ground has been observed for a small percentage (about 6%) of total cloud-to-ground (CG) lightning flashes (Gorin and Shkilev, 1984). As for upward lightning, this ratio could be much higher (roughly 20%) for winter thunderstorms in Japan (Goto and Narita, 1995). In these flashes, usually termed as bipolar flashes, both positive and negative charges are lowered to the ground, through the identical lower part of a lightning channel near the ground.

The reported observations of bipolar flashes are mostly associated with upward lightning that usually starts with an upward leader from the top of elevated objects (e.g., Hubert et al., 1984; Zhou et al., 2011), and the cases involving an initial downward leader are relatively infrequent. Jerauld et al. (2009) reported a natural downward bipolar flash containing two stroke locations with electric and magnetic field measurements. Fleenor et al. (2009) presented four bipolar flashes occurring in the Central Great Plains by using video recording system records and the National Lightning Detection Network (NLDN) Database. Nag and Rakov (2012) examined two bipolar flashes only with electric field data, whereas there were no available GPS time and NLDN records for the first bipolar flash and the positive stroke of the second bipolar flash may be an intra-cloud lightning discharge based on the NLDN report. Recently, Chen et al. (2015) documented a downward bipolar lightning flash that contained one first positive stroke with a peak current of 142 kA and five subsequent negative strokes hitting on a 90 m tall structure.

It is commonly observed that the bipolar flashes with an initial downward leader occur as a combination of positive CG and negative CG flashes with their respective features. That is, these bipolar CG flashes often contain a first stroke of positive polarity with a continuing current, as well as several subsequent negative strokes; the interval between the positive stroke and the first negative stroke is often longer than 100 ms (e.g., Saba et al., 2013). The reversal in the polarity of strokes reflects the change in the polarity of descending leaders prior to the return stroke. Saba et al. (2013) attributed the negative leader preceding the negative stroke to the recoil leader that retrogrades along the path of the positive leader during the early development of

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flashes. The analyses of Saraiva et al. (2014) based on the three-dimensional (3-D) lightning mapping observation of a bipolar flash confirmed this scenario; in addition. They also reported one case of bipolar flash where the recoil leader might branch to create a new lightning path to reach the ground, leading to bipolar flashes with multiple channels.

The bipolar flashes in which the strokes deposit sequentially electric charge of negative and positive polarities to the ground through the identical channel are very rare, and more observations are desired to formulate a general formation mechanism of polarity reversal in CG lightning strokes. In this paper, we report the analyses of a natural bipolar lightning flash observed by a high-speed camera during the summer campaign in 2014 at the Shandong Artificially Triggering Lightning Experiment (SHATLE) (Qie et al., 2011). This flash contained one positive stroke followed by three negative strokes that all deposited charge to the ground through the same channel below the cloud. Comprehensive measurements, including broadband electric field (E-field) change, magnetic field, surface electrostatic field, and radar reflectivity, are used to investigate the physical process of this bipolar CG flash and examine the waveform characteristics of negative strokes which have rarely been reported previously.

2. Observations and measurements

The bipolar CG flash reported here was captured at 12:31 UTC (Beijing time 20:31) on July 14, 2014. This flash was observed from the main observation site (37.8284°N, 118.1150°E) of SHATLE at a frame rate of 3200 frames per second (fps) with a Phantom M310 video camera equipped with a F1.4 Nikon lens with a focal length of 28 mm; the image resolution is 1280 × 800 pixels. The simultaneous measurements were obtained at the same location through a slow E-field change antenna, a fast E-field change antenna (Jiang et al., 2013; Qie et al., 2014), and a low-frequency (LF) magnetic sensor (two perpendicular loop antennas) (Lu et al., 2013, 2014). The parameters of instruments that contribute to the analysis of this flash are listed in Table 1. All the measurements were synchronized through a GPS receiver with timing accuracy better than 100 ns, which makes it possible to compare the visual development of the flash with recorded electromagnetic signals. The physical sign convention is adopted for the polarity of the electric field, i.e., positive E corresponds to negative charge overhead. With this definition, a negative CG stroke that lowers a negative charge to the ground will produce negative surface E-field change; for an assumed cylindrical coordinate system with the negative CG stroke located at the origin, a positive azimuthal magnetic field is measured at the location of the magnetic sensor, namely counterclockwise.

Radar reflectivity data were obtained from a meteorological radar located in Jinan (36.80°N, 116.78°E, 160 km from the stroke), Shandong Province. The weather balloon sounding data from Zhangqiu station (36.70°N, 117.55°E), about 135 km from the stroke location, at 12:00 UTC on July 14, 2014 were used to infer the environmental temperature profile of the thunderstorm.

3. Analysis of flash development

3.1. General characteristics and waveform parameters of the strokes

The electric and magnetic field measurements for the bipolar flash are shown in Fig. 1. The slow (black curve) and fast E-field change data (blue curve) consistently indicate that this flash contained one positive stroke and three subsequent negative strokes (as indicated in the figure) over an overall duration of about 817 ms. The pre-stroke in-cloud activity lasted about 120 ms after the flash onset that was visible on all the measurements, which is typical for first positive strokes (Rust et al., 1981; Fuquay, 1982; Kong et al., 2008, 2015). As indicated by the luminosity data (red curve) based on high-speed images, the positive stroke was followed by a long continuing current of ~80 ms; the small variations superposed on the sustained brightening of the lighting channel indicate the occurrence of *M*-components, as suggested by the corresponding small deflections in electric and magnetic fields. During a subsequent time interval of ~220 ms prior to the first negative stroke, seven *K*-processes occurred with clear electric and magnetic variations. The 328 ms interval between the positive stroke and the first negative stroke was relatively long in comparison with other observations of bipolar flashes; the inter-stroke interval between three negative CG strokes was 104.4 ms and 111.2 ms, respectively. The third (last) negative stroke was also followed by a relatively short continuing current of about 20 ms.

The positive stroke was located by the Lightning Location System (LLS) of the State Grid Corporation of China. The LLS covers most parts of China and locates CG lightning using a similar principle as the U.S. NLDN. The location error of the LLS for CG lightning is <1000 m in our observation area of Shandong Province (Chen et al., 2008). We compared the location result by LLS with the position of a rocket-triggered lightning in SHATLE and found the location error is less than 800 m. The LLS-reported peak current of the positive return stroke for this bipolar flash is 68.4 kA, and is located about 14.3 km northwest of the observation site. This location appears to be reasonable as the E-field variation before the positive stroke and suggests that this stroke occurred far from the so-called “reversal distance” (roughly 7–9 km) regarding the polarity of electric field change caused by a descending lightning leader prior to the return stroke (Beasley et al., 1982).

It is interesting to note that the following 3 negative return strokes were not located by the LLS, and they were misclassified as intra-cloud lightning flashes, similar to the case analyzed by Nag and Rakov (2012). In order to conjecture the cause of the misclassification, we analyzed the parameters of microsecond-scale electric field waveforms produced by the three negative return strokes and compared them with previously reported characteristic values of both positive and negative return strokes, as shown in Table 2. It can be seen that the initial electric field peak normalized to 100 km (geometric mean) of three negative return strokes was close to the value (geometric mean) of those subsequent negative return strokes reported in Florida, but was 4.6 times smaller than the counterpart (arithmetic mean) for positive return strokes and 3.3 times smaller than that for the positive stroke in the same flash. Note that the arithmetic mean zero-crossing time of three negative strokes in this bipolar flash was almost 8 times smaller than the statistical result of negative subsequent return strokes, which may be the partial reason for misclassification of these negative strokes by the LLS. Shorter zero-to-peak rise time and 10%–90% peak rise time of the three negative return strokes indicated that they could produce a stronger radiation electromagnetic field than normal negative strokes with a similar electric field peak. In addition, the rest parameters of three negative strokes, listed in Table 2, were much smaller than those of referenced negative and positive return strokes. It should be noted that because the zero-to-peak rise time of the second negative return stroke was only 0.4 μs, the last three parameters for this return stroke could not be determined through the fast E-field waveform. Compared with normal negative strokes, the shorter and smaller waveform characteristics of negative strokes in the bipolar CG flash indicated that charges with opposite polarities flowed along the same channel, in the order of firstly positive and then negative, would have different physical processes, such as the change of channel conductivity and the residual positive charge's effect on the following negative charge.

In order to better understand the return stroke processes, we show the fast electric field waveforms over a 100 μs interval for all the four

Table 1
Parameters of instruments that acquired data for the analysis.

Instrument	3-dB bandwidth	Sampling rate	Time constant
Slow E-field change antenna	~10 Hz–1 MHz	5 MHz	0.22 s
Fast E-field change antenna	1 kHz–2 MHz	5 MHz	0.1 ms
Low-frequency magnetic field	3–300 kHz	1 MHz	N.A.