Observation and properties of a sub-cloud bidirectional leader

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ABSTRACT: In this paper we–present the evolution of a bidirectional leader which appeared in 'virgin' air. In the observations we did not find any delay between the onsets of the two leader ends. The positive leader end presented a single channel, brighter and slower than the negative end. On the other side, the negative end was branched, less bright and twice as fast as the positive end. The attachment of one of the negative channels with a pre-existing intra-cloud channel showed that the polarity reversal point in the bidirectional leader remained fixed. Recoil leaders appeared along old negative channels of the bidirectional leader. Recoil activity started after the first branching of the positive leader. The discussion is aimed at improving current bidirectional leader models.

INTRODUCTION

The bidirectional leader model proposed by Kasemir [1960] has been used to explain overall processes occurring in the development of lightning flashes (e.g. Mazur and Ruhnke, 1993 and 1998). The basis of bidirectional leader theory is that negative and positive leaders are two ends of a "tree" that extend simultaneously. In intracloud flashes both leader ends move into charge regions of opposite polarity. In this development, the leaders maintain their potential by balancing positive and negative charges along the leader channel ("zero net charge"). In Mazur and Ruhnke [1993] and Behnke et al. [2005], the authors maintain that the potential of the channel will be adjusted in order to maintain zero net charge induced on the channel by the cloud potential. The use of cloud potential allows modeling the behavior of a simple lightning flash by comparing the potential of the leader to the potential profile of the cloud. The leader will continue to propagate if the potential difference between leader tip and surrounding cloud charge is sufficiently large (Kasemir, 1960; Mazur and Ruhnke, 1993; Bazelyan and Raizer, 2000).

The bidirectional leader model served as a basis for some advanced models of lightning flashes (Mansell et al., 2002; Riousset et al., 2007 and 2010). The models did not take into account any asymmetry between negative and positive leaders. Observational studies have shown almost an order of magnitude difference in propagation speed between negative leaders ($1\text{-}2 \cdot 10^5$ m s^{-1}) and positive leaders ($2\text{-}3 \cdot 10^4$ m s^{-1}) (e.g. Mazur and Ruhnke, 1998; Porctor et al., 1988; Shao et al., 1996). But there are reports of much faster positive leaders (Saba et al., 2008; Biagi et al., 2011; Yoshida et al., 2010). The negative leader propagation speed is a result of stepping process (Rakov and Uman, 2003, section 4.4.6) whereas positive leaders are often said to propagate continuously with few branches. However, in Biagi et al. [2011] observations are presented of positive leaders exhibiting shorter steps of 0.4-2 meters at intervals of 17-30 microseconds. Another important characteristic of lightning leaders is their branching. The models presented by Lalande and Mazur [2012] suggest that branching occurs when the potential difference between the leader tip and its environment exceeds a certain threshold.

Recently van der Velde and Montanyà [2013] presented some characteristics of leader development by means of the Lightning Mapping Array. In that work, the effect of the potential of the leader on its propagation is treated considering the asymmetry between polarities. Additionally the authors suggested that retrograde leaders (recoil leaders) would reduce the leader potential.

The occurrence of bidirectional leaders has been confirmed from the detections of VHF mapping systems and in lightning triggered by aircraft and rockets (Mazur, 1989; Laroche et al., 1991; Lalande et al., 1998; Rakov and Uman, 2003, p. 322.) However no clear high-speed video observations have been presented and analyzed. In this paper we present and discuss a high-speed video observation of a bidirectional leader. The event clearly showed the initiation and the propagation of both positive and negative ends.

DATA

High-speed video images were recorded by a Vision Research Phantom v7.3 video camera with a 28 mm/2.8 lens. The frame rate was ~11000 frames per second with an exposure of ~90 µs and a resolution of 576 x 480 pixels with 14 bits of information per pixel.

The area of interest is covered by a VHF interferometer network (114-117 MHz) of four sensors operated by the Meteorological Service of Catalonia (Montanyà et al. [2007]). Although no lightning data are presented in this paper, the IC detections from this network were used to estimate the distance of the event from the observation location.

OBSERVATIONS

During the 2012 campaign in the Ebro Valley Laboratory (northeastern part of Spain), on the 9th of September 2012 an unusual storm was observed to produce a significant amount of positive cloud-to-ground (+CG) lightning flashes. In that episode all the CG events recorded with a high-speed video camera corresponded to positive polarity. In one recording, a bidirectional leader serendipitously appeared beneath the cloud base as part of an already ongoing lightning. Figure 1 displays a selected frame of the bidirectional leader during its development.

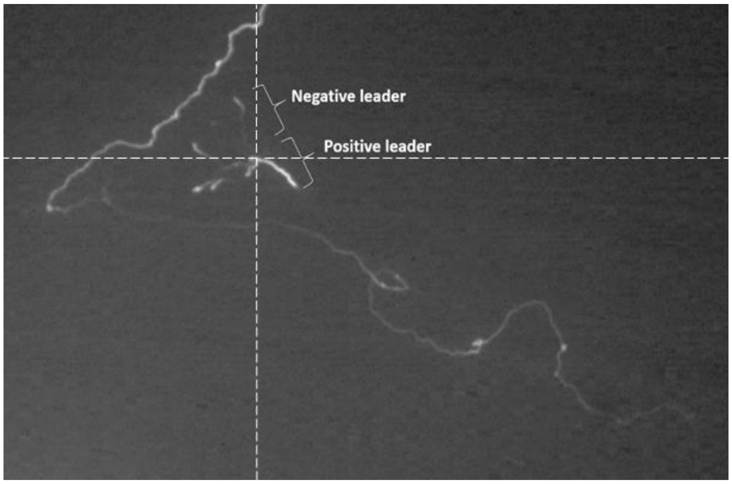

Figure 1. Video Frame of the observed bidirectional-leader during an intra-cloud flash.

The event in figure 1 emerged from the intersection of the two perpendicular dashed lines. From a single bright dot two ends of a leader began to propagate in opposite directions. The positive end progressed to the right, whereas the negative end headed to the left of the image. The leader propagated for ~6 ms from the first detection in the video. During this time the positive end progressed brightly and unbranched whereas the channels of the negative end flickered and branched. Then the bidirectional leader showed the 'tree' shape shown in figure 1 and schematicized in figure 2a. As will be discussed in the next section, the polarity of each leader end will be determined from its propagation speed and branching.

The leader progressed bidirectionally until 6.08 ms when one branch of the negative end attached to the pre-existing channel in the left of the field of view. The pre-existing channel is assumed to be positive. When the attachment occurred (figure 2b), the connecting negative channel brightened just until the point where the bidirectional leader was born (figure 2c). We assume that the intense increase of brightness is related to intense charge neutralization (or transfer) since the negative channel attached to a positive channel. Then, the fact that the brightness arrived precisely at the location where the leader was born (or where the positive leader end started) indicates that after this current episode the negative channel became positive.

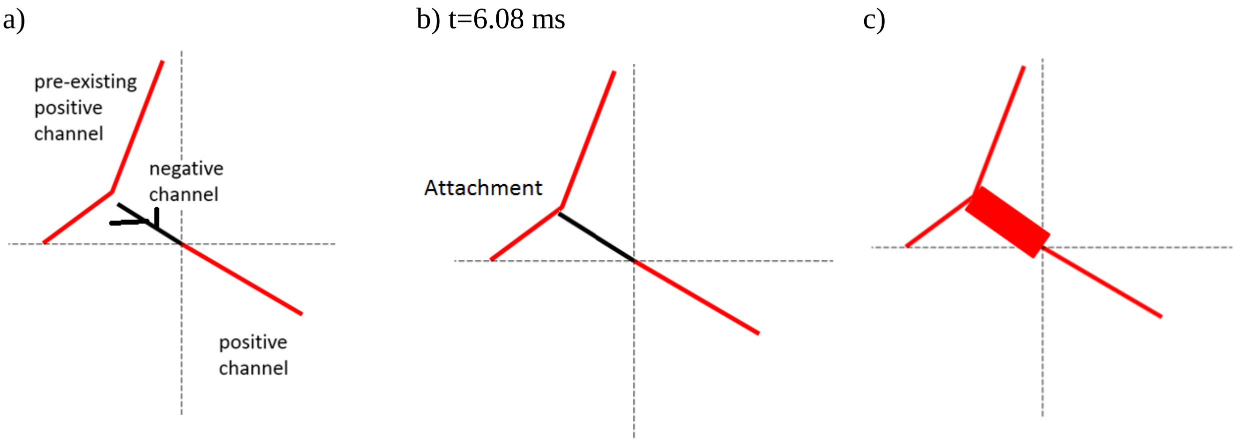

Figure 2. Sequence representing the attachment of the negative end of the bidirectional leader to the pre-existing positive channel. The intersection of the dashed lines corresponds to the location where the bidirectional leader initiated.

After the attachment process, the positive leader end continued advancing as part of a branch attached to the pre-existing channel. At about t=17 ms the leader branched and recoil activity began at the location where the bidirectional leader initiated (intersection of the two perpendicular dashed lines in figures 1 and 2). Recoils were observed along channels corresponding to the old negative 'tree' of the bidirectional leader.

DISCUSSION

a) Initiation of the bidirectional leader

The event serendipitously appeared in the image. It was first distinguishable with a single dot (pixel of the image). From that dot, both leader ends began simultaneously, so no delay was observed. Reports of artificially triggered lightning by rockets and aircraft indicated that positive leaders started 3-6 ms before the negative leader (Mazur, 1989; Laroche et al., 1991; Lalande et al., 1998; Rakov and Uman, 2003, p. 322.). In our observation we did not find any delay.

b) Leader speeds

Speeds of the leaders are presented in figure 3. Both leaders exhibited their maximum speeds and luminosity at the initiation. Leaders quickly decreased in both ends. Asymmetry in leader speeds was observed. The negative leader was almost twice as fast as the positive leader.

c) Branching

The assumed negative end was branched whereas the positive end maintained a single channel until a late stage when recoil activity appeared. For the first two milliseconds the negative end branched with a rate of 3.5 branches per millisecond.

d) Luminosity

As was pointed out before (e.g. Mazur et al. [1998] and by Montanyà et al. [2012]), the tips of both leaders were brighter than the rest of the channels. The channel of the unbranched positive end of the bidirectional leader was brighter all the time compared with the channels of the branched negative end. This may indicate that more current was flowing in the positive channel than in an individual channel of the negative end. In the negative end, for most of the time only the tips of the channels were visible. We assume that there is a strong relation between luminosity and current flowing in a leader (e.g. Chen et al 1999). If so, even if the positive leader end was slower, it carried more current due to the branching of the negative end.

e) Evolution of the point where polarity reverses

Thanks to the observation of the attachment of the negative end with a pre-existing channel (figure 2) we observed that the charge neutralization (or transfer) occurred until the location where the bidirectional leader initiated (intersection of the two dashed lines in figures 1 and 2). That fact suggests that the location of the point where the polarity of charge along the leader reverses remained fixed. In such a case, the asymmetry of the leader speeds in this bidirectional event did not force a shift of the sign reversal point. But contrary to this observation, in the model of Williams and Heckman [2012] that point was displaced with time due to the asymmetry of leader speeds.

CONCLUSIONS

In this paper we have presented and discussed the evolution of a bidirectional leader which appeared in 'virgin' air. This observation allowed investigating some properties of a bidirectional leader that can be useful to improve models. In the observations we did not find delay between the onsets of both leaders. The positive leader end presented a single channel, brighter and slower, whereas the negative end was branched, less bright and twice faster. The attachment of one of the channels of the negative end with a pre-existing channel allowed us to determine that the location of the leader where polarity reverses did not shift and was not influenced by the asymmetry of leader speeds. After the attachment the leader continued progressing. Recoil leaders appeared along old negative channels of the bidirectional leader. Recoil activity started after the initial branching of the positive leader.

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