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Recoil leader formation and development☆

Vladislav Mazur [a,*], Lothar H. Ruhnke [b], Tom. A. Warner [c], Richard E. Orville [d]

[a] NOAA/OAR National Severe Storms Laboratory, Norman, OK 73072, USA
[b] Cooperative Institute for Mesoscale Meteorological Studies, University of Oklahoma, Norman, OK 73972, USA
[c] Institute of Atmospheric Sciences, Rapid City, SD 57702, USA
[d] Dept. of Atmospheric Sciences, Texas A&M University, College Station, TX, USA

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ABSTRACT

The existing interpretation in the lightning literature, based on field measurements, defines recoil leaders as negative leaders. However recoil leaders are floating conductors, and, based on this physical assumption, they should be defined as bipolar and bidirectional leaders. This physics-based assumption has never previously been verified experimentally. Such verification, reported in this paper, has been obtained from observations of branched upward positive leaders from a tall tower using a high-speed video system synchronized with electric and magnetic field change and luminosity measurements on the ground. The analysis of these observations clearly reveals the nature of recoil and dart leaders as bidirectional and bipolar electrodeless discharges that develop from a small region along a path of the decayed channels of a previous positive leader, or a positively charged return stroke of negative CG flashes.

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1. Introduction

One of the most challenging issues in the physics of lightning is the interpretation of the sequence of processes that takes place in a positive leader channel or in a return stoke channel of negative cloud-to-ground flashes after current there is cutoff. This sequence of processes may lead (1) to formation of recoil or dart leaders somewhere along the traces of the decayed channel of a positive leader (or a return stroke), and (2) to recoil or dart leaders traversing remnants of the leader channel toward its origin. This origin would be either a branching point or the ground, in the case of return strokes.

This phenomenon was first identified in electric field change records, and was given the name “K-changes”. K-changes were initially observed to take place during time intervals between the return strokes of negative cloud-to-ground flashes, the so-called “junction process,” but were later also observed in intracloud flashes. Ogawa and Brook [9] suggested that K-changes are negative “recoil streamers” that occur when a positive J-type leader (J is for the junction stage), propagate within the cloud, and reaches a region of concentrated negative charge. This interpretation made K-changes the equivalent of “mini return strokes”. By using the word “recoil,” the hypothesis of Ogawa and Brook [9] tied together K-changes and the channels of the positive leaders that preceded them. Numerous mentions of this similarity between K-changes and dart leaders and other so-called “subsequent leaders”, can also be found in Ref. [11]. Although the word “recoil” reflects the reality of the process, the term “streamer” misrepresents it and should be replaced by the physically-correct term “recoil leader,” as suggested by Mazur [7]. The reason is that the phenomenon is a propagating discharge made of a hot plasma channel and a zone of cold streamer filaments of limited length ahead of the tip of the channel, which together constitute the developing leader process.

From the analysis of airborne records of lightning flashes initiated by an aircraft, and lightning radiation maps of intracloud flashes obtained by an interferometer [3,4] advanced the hypothesis of Ogawa and Brook [9] by postulating (1) that negative recoil leaders (called at that time as recoil streamers) should occur and propagate along the preceding positive leader channels (a part of a bipolar and bidirectional structure of an intracloud flash), and (2) that they travel back toward their origin. The origin could be a ground structure, or a branching point of a leader. However, no direct observational evidence that would confirm the speculation in Ref. [4] about the nature of recoil leaders existed at that time.

Only with the help of high-speed video systems were we able to obtain physical evidence showing recoil leaders actually propagating along previously existing paths of positive leaders [8,10]. The

* Corresponding author. Tel.: +1 405 325 6588.
E-mail address: vlad.mazur@noaa.gov (V. Mazur).

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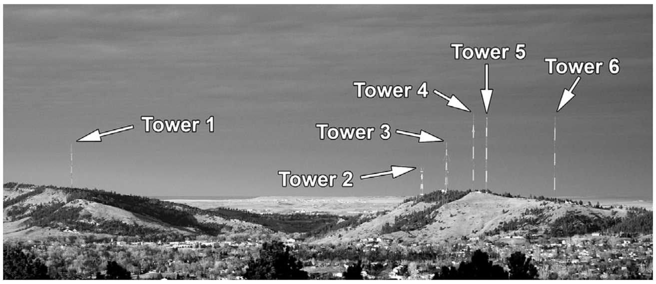

Fig. 1. View of six towers along the ridge that runs through Rapid City, SD. The heights of the tallest towers are: Tower 1(KNBN) – 163.1 m, Tower 4 (KOTA) – 184.7 m, Tower 6 (KEVN) – 190.8 m.

same observations confirmed that dart leaders are, in actuality, recoil leaders that reach the ground.

High-speed video observations of upward positive leaders also clearly show that recoil leaders and M-events associated with them occur only in branched positive leader channels after current cutoff in the branches [8]. The current records of negative upward leaders started from tall towers [1] show the absence of M-event current pulses, and thus, in negative leaders, the recoil leaders that produce them. The absence of recoil leaders in upward negative leaders also explains the well-known fact that the majority of positive CG flashes (their return strokes are analogous to upward negative leaders) do not have multiple return strokes, which are common in negative CG flashes.

The mechanism of a recoil leader's occurrence is still mysterious. Mazur and Ruhnke [5] proposed a rather crude model of recoil leader formation in positive leaders. The essence of the model is that, following the current cutoff, the channel of the positive leader continues its extension at the upper tip while cooling and losing conductivity at the lower tip (one closer to ground), and still maintains its residual net positive charge. Becoming a floating conductor in an ambient electric field, the leader obtains induced charges that distribute as a dipole in addition to the existing residual positive charge. The growth of dipole charges results in a growing negative charge along the decaying lower end of the channel. The process may lead to a negative electrical breakdown at the lower end of the conductive channel and to the formation of a recoil leader. This leader will propagate toward ground along a preferred path made of remnants of the decayed positive leader channel. Admittedly, this conceptual model did not address many details of the physical processes involved, leaving room for different physical explanations. Confirmation of this model has not yet been provided by any observations in nature. In this study, we are trying to unveil some features of recoil leader formation that could be essential for developing other physically-sound models of the recoil leader process.

2. Observational set-up

The objects of observations were upward leaders initiated from six tall TV towers located on a north-south ridge of hills, about 180 m above the surrounding terrain, in Rapid City, South Dakota (Fig. 1). All towers were within the field of view of high-speed video systems installed about 3 km southwest of the ridgeline.

Video recordings were conducted with two GPS-synchronized high-speed cameras: Phantom v7.1 (7200 ips) and Phantom v12.1 (54,000 ips), all manufactured by Vision Research. A network of four instrumented sites, all GPS-synchronized, was positioned in a close proximity to the towers [12]. Sensors installed at each instrumented site included modified whip antennas serving as

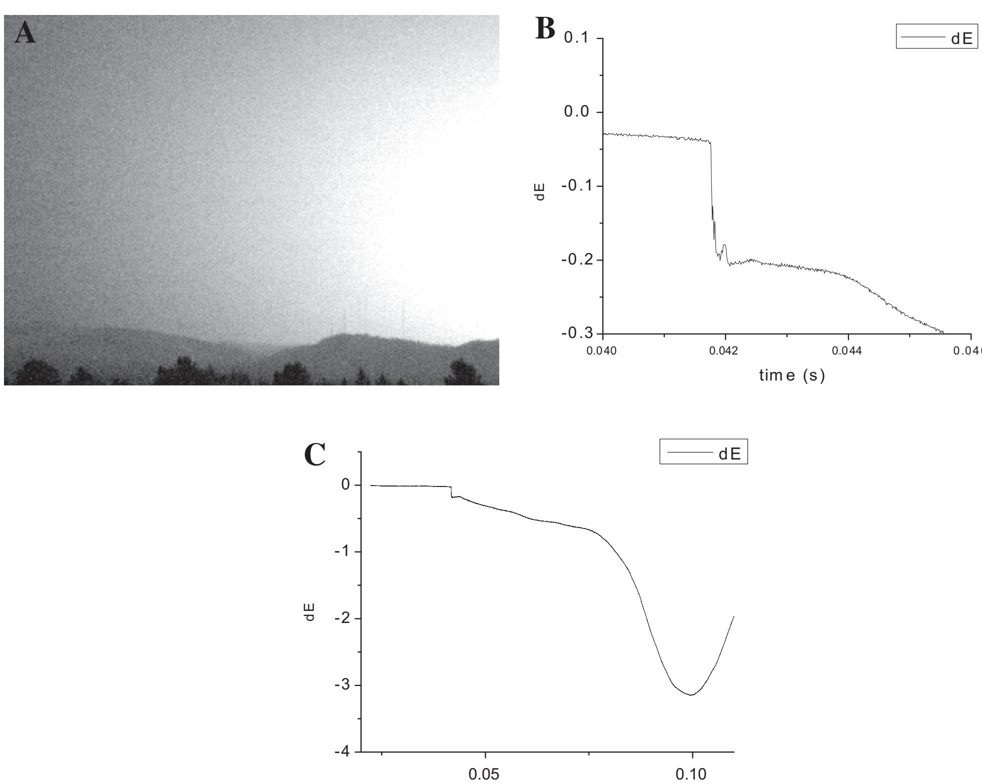

Fig. 2. (A). Burst of light during the return stroke of the +CG at 07:23:03.0,42–19 km from the tower, (B) enlarged dE record of the return stroke of this +CG flash (C) dE record of this flash shows both the return stroke and the following development of the negative upward leaders.