High-speed video observations of positive ground flashes produced by intracloud lightning

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[1] High-speed video recordings of two lightning flashes confirm that positive cloud-to-ground (CG) strokes can be produced by extensive horizontal intracloud (IC) discharges within and near the cloud base. These recordings constitute the first observations of CG leaders emanating from IC discharges of either polarity. In one case, the discharge began with a negative leader that propagated horizontally, went upward and produced an IC discharge. After the beginning of the IC discharge, a positive leader emanated from the lowest portion of the IC discharge, and initiated a positive return stroke. In the other case, the IC discharge began with a positive leader and then initiated a downward-propagating positive leader that contained recoil processes and produced a bright return stroke followed by a long continuing luminosity. These observations help to understand the complex genesis of positive CG flashes, why IC lightning commonly precedes them and why extensive horizontal channels are often involved.
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1. Introduction

[2] Electric field records have shown that positive lightning flashes to ground are often preceded by significant intracloud (IC) discharge activity lasting, on average, more than 100 ms [*Fuquay*, 1982] or 200 ms [*Rust et al.*, 1981]. Optical measurements also show that positive discharges to ground often involve long, horizontal channels, up to tens of kilometers in length [e.g., *Fuquay*, 1982; *Kong et al.*, 2008; *Saba et al.*, 2008]. It is now generally accepted that one cause of the red sprites (and other transient luminous events) that occur at high altitudes are horizontally extensive flashes that transfer large amounts of positive charge to ground [*Boccippio et al.*, 1995; *Rodger*, 1999; *Moudry et al.*, 2003; *Pasko*, 2007; *Lyons et al.*, 2008; *Mika and Haldoupis*, 2008]. According to *Valdivia et al.* [1997] the electromagnetic pulses from the IC portion of a positive cloud-to-ground +CG lightning may cause the nucleation of sprites and according to *Yashunin et al.* [2007] M components have the potential to initiate transient luminous events during the continuing current stage and explain their delay from the parent lightning.

[3] Another characteristic of positive flashes to ground is that multiple strokes (i.e., strokes subsequent to the first) are very infrequent and usually do not follow the same path to ground as the first stroke. For example, all the subsequent strokes in multiple-stroke positive flashes observed in Japan (M. Ishii et al., Termination of multiple-stroke flashes observed by electromagnetic field, paper presented at the 24th International Conference on Lightning Protection, Staffordshire University, Birmingham, U. K., 1998) and in Brazil (M. M. F. Saba et al., High-speed video observations of positive lightning, paper presented at IX International Symposium on Lightning Protection, Institute of Electrotechnology and Energy, Foz do Iguaçú, Brazil, 2007) created new ground terminations.

[4] Based on the above facts, *Rakov and Uman* [2003] have suggested that if the cloud conditions are right, a positive discharge to ground can be initiated by a branch of, or otherwise produced by, an extensive IC discharge. Here, we will describe video observations of two (+CG) flashes, one in Brazil and one in the U.S., that confirm this hypothesis and show the close relationship between IC and +CG discharges.

2. Instrumentation

[5] A RedLake MotionScope 8000S high-speed digital video camera (1000 frames per second) was used to record images of cloud-to-ground flashes in Southern Brazil between December 2006 and March 2007. During August 2007, the same camera, together with a Photron PCI-512 high-speed digital camera (4000 frames per second) was used to record several flashes in Tucson, Arizona. The high-speed video images were GPS time-stamped and stored in the cameras until a signal was received from an external source, and the trigger point could be set to determine how many video frames were read out before the event of interest. Each trigger pulse was initiated manually by an operator when a flash was observed within the camera field-of-view. For more details on the operation and accuracy of high-speed cameras for lightning observations, see *Saba et al.* [2006].

[6] In order to determine the stroke location, polarity, and an estimate of the peak current, we used data from two Vaisala lightning location systems, BrasilDat in Brazil and the NLDN in the United States. More information on the characteristics of these networks is given by O. Pinto et al. (Recent upgrades to the Brazilian Integrated Lightning Detection Network, paper presented at 19th International Lightning Detection Conference, Vaisala, Tucson, Arizona, 2006) and *Cummins et al.* [1998], respectively. The matching of strokes between cameras and networks was done

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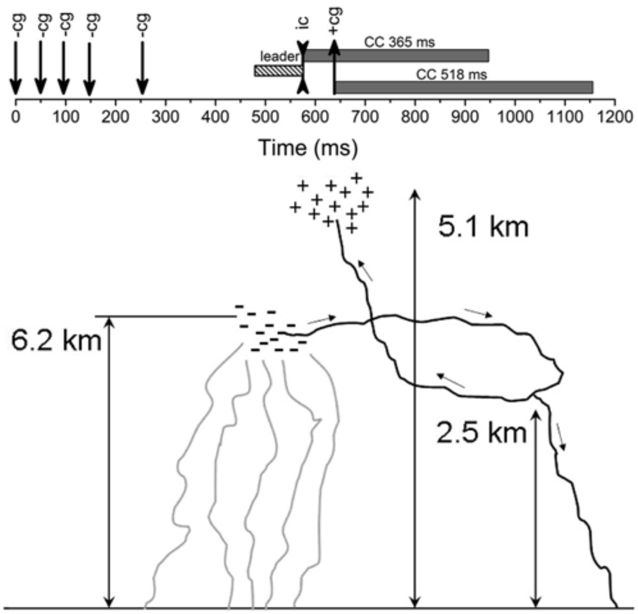

Figure 1. Timeline and a schematic representation of the sequence of events that were recorded on video for Case 1. The +CG struck 13 km from the camera and had an estimated peak current of +21 kA.

using GPS time-synchronization (to an accuracy better than 1 millisecond).

3. Observations

[7] A total of 39 +CG flashes were recorded in both campaigns (28 in Southern Brazil and 11 in Tucson, AZ). IC discharge activity was nearly always recorded before and after the +CG flashes, and in the two cases that will be described here, IC channels were clearly visible at or near the cloud base with characteristics that indicated they initiated positive downward leaders and +CG strokes (as reported by the lightning locating networks) followed by long continuing current. The luminosity produced by the continuing current was recorded by the camera in both flashes and will be referred in this work as continuing luminosity (CL).

3.1. Case 1: Southern Brazil

[8] Figure 1 shows a sketch and timeline of the first event that was a bipolar CG flash in Southern Brazil (14:58 UT, March 26, 2007). According to BrasilDAT, the positive CG stroke struck ground at a distance of 13 km from the camera and had an estimated peak current of +21 kA. The overall discharge began with a sequence of five negative cloud-to-ground (−CG) strokes (see Table 1), each of which appeared to have a different ground termination and no continuing luminosity (CL). 222 ms after the last negative stroke, a new negative leader emanated from the same region of the cloud and propagated horizontally and to the right in the camera field-of-view. After crawling along the cloud base to the left (between the heights of 2.5 and 4.0 km) and then going upward toward higher parts of the cloud (Figure 2a), this leader initiated a very bright IC discharge that was followed by a CL that lasted for 365 ms (Figure 2b). The CL contained several intensifications of luminosity that were similar to M-components in CG flashes [*Campos et al.*, 2007, 2009]. 58 ms after the beginning of the IC discharge, a new leader emanated from the lowest portion of the IC channel (Figure 2c) and created a positive stroke to ground and a new ground termination (Figure 2d). Both the IC and the +CG channels remained luminous for hundreds of milliseconds (Figure 2e), but the latter lasted longer and had several M-components (more details on the M-components in this and other positive flashes and the methodology used to analyze them are given by *Campos et al.* [2007, 2009]).

[9] The height of the positive charge center in Case 1 could be estimated by adding the height of the leader before it left the camera field-of-view to an estimate of the distance it traveled during the next three video frames (i.e., before the initiation of the IC discharge). The latter distance was estimated by multiplying the average vertical speed (Table 2) by the duration of the last three video frames (3 ms). The horizontal distance from the camera to the negative charge center was assumed to be the average range of the −CG strokes, and the horizontal distance to the positive center was assumed to be the range of the +CG stroke. Because of the different distances, the negative charge center appears to be below the positive center in Figure 1.

[10] It should be noted that all images are two-dimensional projection of the channel. Therefore, all heights inferred in this case and in the case described below are rough estimates. However, a good agreement was obtained between these rough estimates and the information given by radiosondes for the heights of the −10 to −25 °C temperature levels where the negative charge centers are usually located [*Rakov and Uman*, 2003].

3.2. Case 2: Arizona

[11] Case 2 occurred during a large, monsoon thunderstorm in Southeastern Arizona, (14:58 UT, July 31, 2007), and a sketch and timeline of the development of this flash is shown in Figure 3. According to the NLDN data, this +CG stroke struck ground 6.4 km from the camera and had an estimated peak current of +23 kA. The horizontal distance to both charge centers depicted in Figure 3 was assumed to be the range of the +CG stroke, and the height of the charge centers was estimated using the same method employed in Case 1.

[12] The flash started with a leader that propagated horizontally to the left in the camera field-of-view. After crawling along the cloud base (between the heights of 2.2 and 2.7 km), and then going upward into higher parts of the

Table 1. Some Characteristics of the Discharges in Case 1

Time (ms)	Discharge Type	Estimated Peak Current (kA)	Preceding Time Interval (ms)	Distance From the Camera (km)
0	−CG	−30	–	19
49	−CG	−17	49	24
94	−CG	−20	45	24
147	−CG	–	53	–
254	−CG	−12	107	33
578	IC	-	324	–
636	+CG	+21	58 after IC; 382 after last −CG	13

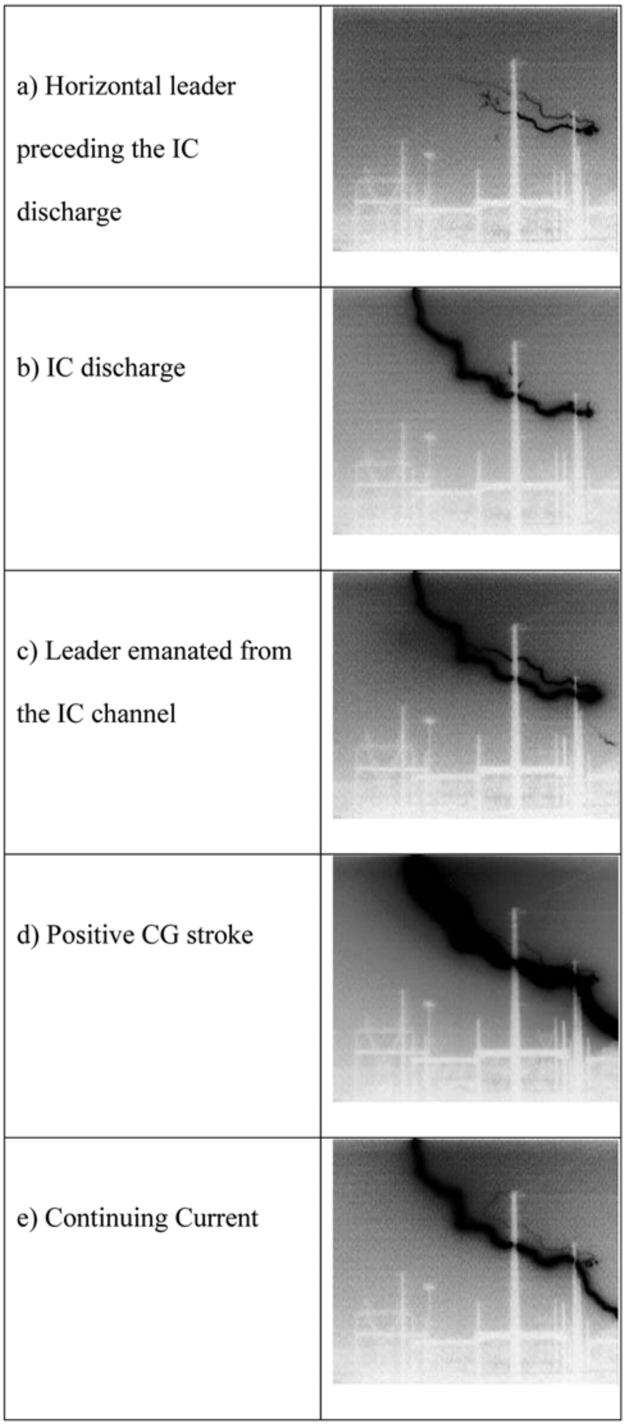

Figure 2. Selected negative images for the flash recorded in Brazil (Case 1).

cloud (Figure 4a), it initiated an IC discharge (Figure 4b). During the last 22 ms of leader development (that lasted a total of 149 ms), several recoil leaders (RLs) were observed that indicated this leader had positive polarity [*Saba et al.*, 2008]. After the IC discharge, several new leader channels emanated from its region and propagated toward ground (Figure 4c). One of these leaders initiated a very bright positive stroke that followed the right-hand portion of the IC channel into the cloud (Figure 4d). A long CL followed this single stroke for 216 ms (Figure 4e) and contained several M-components. Contrary to the first case (discussed above), the IC channel disappeared immediately after the beginning of the +CG stroke, but several RLs retraced the left portion of the IC channel (that disappeared after the return stroke) and other previously-formed leader paths.

Table 2. Distance Traveled and Average Speed of the Leaders

	IC		+ CG	
Leader	Case 1 Negative leader	Case 2 Positive leader	Case 1 Positive leader	Case 2 Positive leader
Distance traveled (km)	8.9	8.3	2.5	2.7
Average Speed (ms^{-1})	0.9×10^5	0.6×10^5	1.6×10^5	1.6×10^5

3.3. Leader Characteristics

[13] The horizontal leader that initiated the IC discharge in Case 1 was much more branched and bright than the initial IC leader in Case 2. This suggests that the IC leader in Case 1 was of opposite polarity to the leader in Case 2 (i.e., negative in Case 1 and positive in Case 2). The durations of the leader propagation were 99 ms in Case 1 and 147 ms in Case 2. No significant increase in speed was observed during the horizontal propagation in both cases. Table 2 presents the duration and average speed of each IC leader and the corresponding CG leader for each case.

[14] The speeds of both positive leaders increased as they approached the ground (more details are given by *Saba et*

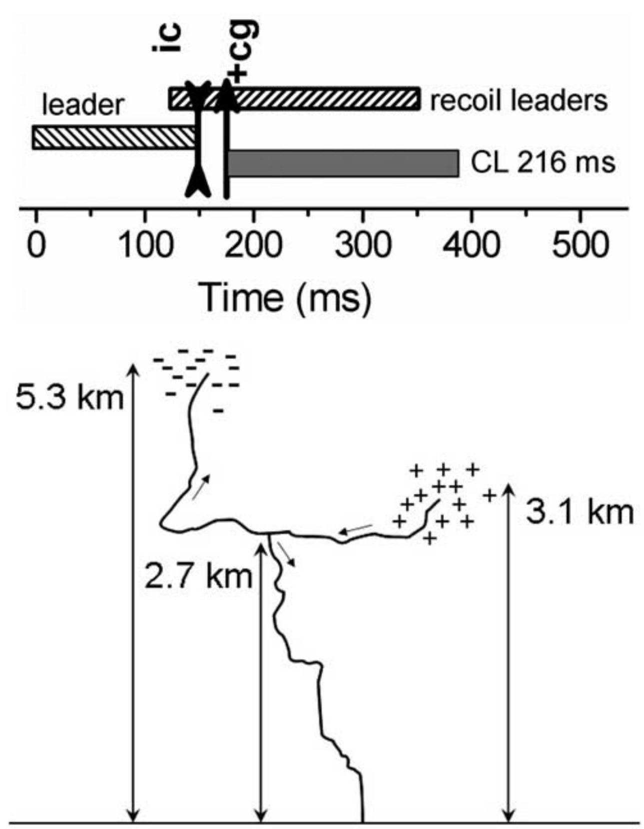

Figure 3. Timeline and schematic representation of the sequence of events that were recorded on video for Case 2. The +CG struck 6.4 km from the camera and had an estimated peak current of +23 kA.

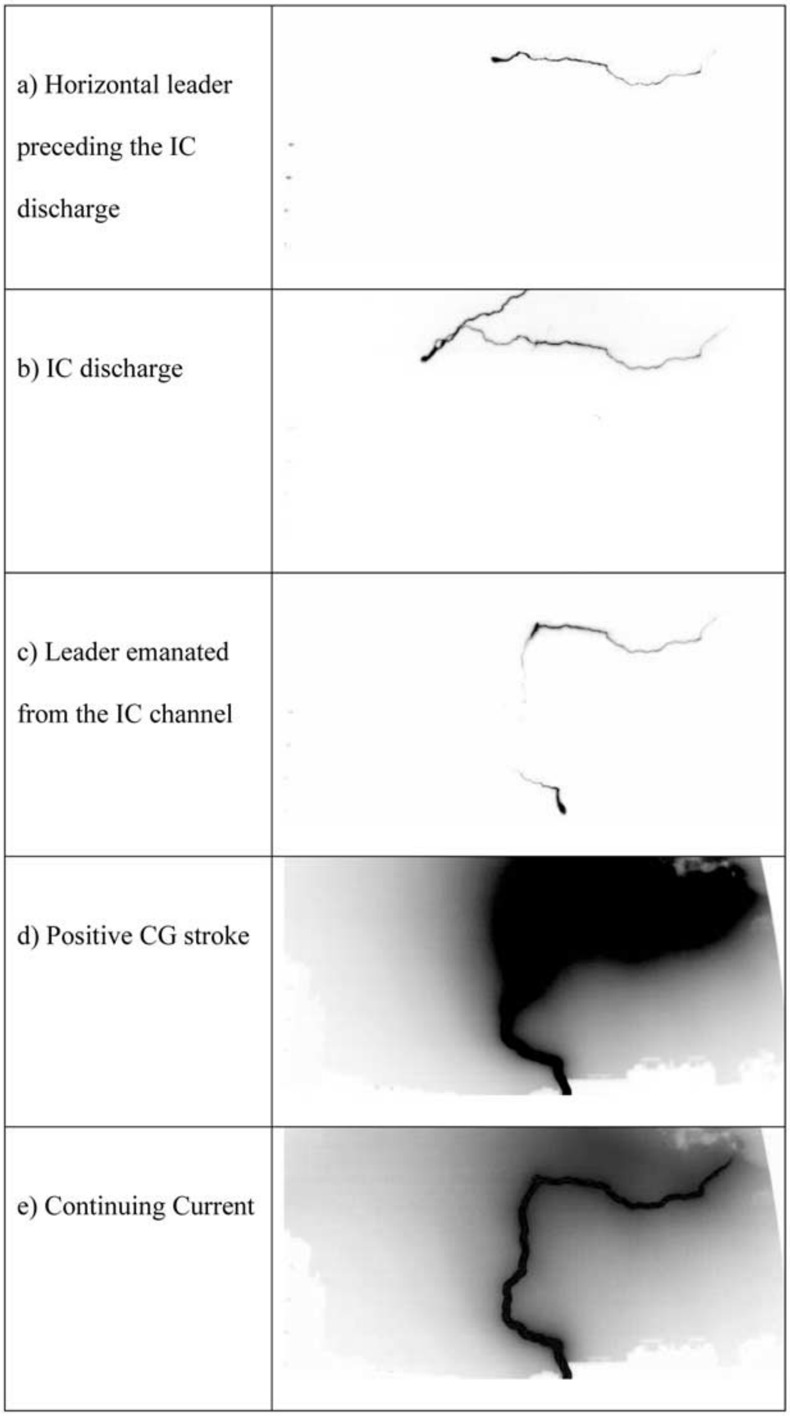

Figure 4. Selected negative images for the flash recorded in Arizona (Case 2).

al. [2008]). More measurements of positive and negative leaders are found in the works by *Saba et al.* [2008, also presented paper, 2007] and *Kong et al.* [2008], and there is a good agreement between the values presented in those papers and the values presented here.

4. Conclusion and Discussion

[15] Although both flashes produced positive CG strokes and were initiated by leaders emanating from IC discharges that were at or close to the cloud base, in Case 1 the IC flash was initiated by a negative leader and in Case 2 it was initiated by a positive leader. In addition to the leader characteristics mentioned in section 3.3, the polarities of the IC leaders were inferred from the facts listed below:

[16] 1. Case 1 the IC leader began in the same region of the cloud that produced negative CG strokes. The channel of the positive stroke was connected to the ending region of the IC leader, which indicates that the IC leader was a negative process propagating toward a positively charged region.

[17] 2. Case 2 the IC leader produced several RLs during its development. This behavior was observed by *Saba et al.* [2008] during the propagation of positive leaders towards ground, and it has never been observed during the development of negative leaders. Also, the channel of the positive stroke was connected to the starting region of the IC leader which indicates that this was a positively charged region.

[18] In Case 1, both the IC and the +CG channels coexisted for a long time (approximately 300 ms), whereas in the Case 2 they did not coexist at all. This may be because in Case 1 a very intense CL was present in the IC channel before the initiation of the +CG, whereas in Case 2 there was only an extremely faint luminosity in the IC channel. The intense CL in Case 1 indicates that there was likely intense ionization and a large charge transfer, and this may have helped the IC and +CG channels to coexist after the +CG stroke.

[19] At present, our knowledge about the physics of positive lightning is not as good as that for negative lightning, and many questions remain about the genesis of positive discharges. Here, we have documented that +CG flashes can be initiated by IC leaders of either polarity, and this behavior may help us to understand why extensive intracloud lightning commonly precedes positive CG flashes.

[20] The association of extensive intracloud discharges with positive flashes suggests that positive discharges cannot always be modeled as the neutralization of simple, vertically stacked monopoles [*Rakov*, 2003]. Moreover, this complex structure can be helpful to studies on sprite morphology [*Mika and Haldoupis*, 2008] and to studies on why sprites are more common above some particular kind of storms [*Lyons et al.*, 2008].

[21] On the account of the large charge transfers involved, positive CG strokes are of primary importance in protection against lightning. Positive flashes are also a major concern for lightning detection and location systems because their complex waveforms are sometimes rejected or attributed to intracloud flashes. A better knowledge of the positive flash initiation and development may help in identifying the electric and magnetic field waveforms that are produced by positive CG flashes.

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