Phenomenology of Intracloud Lightning

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ABSTRACT: The purpose of this study is to clarify and examine the characteristics of intracloud (IC) lightning leaders. IC leaders have been previously characterized in the literature, though the processes which produce detectable optical emission are not well understood. To further explore IC leaders, particularly the energetics, we incorporate VLF measurements from the Huntsville Alabama Marx Meter Array (HAMMA), VHF measurements from the North Alabama Lightning Mapping Array (NALMA) and optical measurements from the Lightning Imaging Sensor (LIS).

The relationships emerging between electric fields, radiation field pulses, and optical emissions are used to outline energetic characteristics of IC leaders and define the active portion of the IC lightning flash spatiotemporally. We characterize IC leader pulses in terms of previous studies, expanding in terms of the above instrumentation's ability to highlight the 4D nature of lightning. Thus allowing the consideration that each radiation field pulse may not have equal probability of producing detectable optical emission.

INTRODUCTION

This study examines the characteristics of intracloud (IC) lightning leaders in terms of optical emission and active stages in the IC leader. IC leaders have been nominally defined in the literature, and the optical emission during this process is not well understood. Historically, there has been debate about the most active portion of the leader; *Bils et al.* [1988] found the beginning of the electric field record to be the most active portion of IC lightning (consisting of significant microsecond scale pulse activity). Before this, *Kitagawa and Brook* [1960] identified the most active portion of the electric field change as occurring after an initial portion, similar to that of *Bils et al.* [1988], consisting of large amplitude pulses.

Understanding the spatiotemporal evolution of an IC leader can expand on the current understanding of the active portion of an IC leader; thus in this study we incorporate ground based electric field measurements with time of arrival (TOA) source locations, and space based observations of optical emission from the Lightning Imaging Sensor (LIS). Measurements from these instruments in this study not only allows the characterization of the active (potentially more energetic) portion of the leader, but addresses the question of what produces light on the pulse electric field change level.

Previously, the radiation field from electric field records has been discussed in terms of peak pulse amplitude, width, length of waveform and ratio of initial half cycle amplitude to overshoot (e.g., *Krider et al.* [1975]; *Shao and Krehbiel* [1996]; *Villanueva et al.* [1994]; *Weidman and Krider* [1979]). This study seeks to build on these characterizations with the inclusion of optical emission

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using group level data from LIS. Exploiting the relationship between the electric field change and LIS group level data with the intention of identifying pulse characteristics specific to those pulses in the electric field change record which produce detectable optical emission. It is important to note that each radiation field pulse may not have an equal probability of producing detectable optical emission.

Instrumentation

HAMMA

The Huntsville Alabama Marx Meter Array (HAMMA) is a ground based array of 7 electric field change meters, centered in Huntsville, AL with baselines of typically $\sim$15km. HAMMA samples the changes in the electric field in the very low frequency (VLF) to low frequency (LF) regime (1 Hz to 400 kHz) [*Bitzer et al.*, 2013] and simultaneously captures the electrostatic, induction and radiation components of the electric field resulting from a lightning flash.

To fully realize the processes producing light, and those which do not produce light, it is imperative to utilize the full electric field wave form and electric field measurements as the electric field is ultimately responsible for optical emission. In this sense, HAMMA is critical as it allows many diverse components of an IC leader to be studied and is presently used in LIS validation [*Bitzer*, 2011]; thus it is well suited for utilizing electric field waveforms representing multiple electric field components.

Electric field change data will be used from thunderstorms occurring in 2010-2013.

NALMA

The North Alabama Lightning Mapping Array (NALMA) is a multisensor network with thirteen stations in the Huntsville, AL region. NALMA operates in the Very High Frequency (VHF) regime (76-82 MHz) [*Goodman et al.*, 2004]. NALMA sensors measure the time of arrival (TOA) of VHF radiation produced by lightning, the time of peak power within 80μs windows is recorded and retrieved. From this the spacetime location of the VHF source may be reconstructed using TOA techniques [*Koshak et al.*, 2004]. The 4D (time, x, y, z) path of lightning processes and source power are used in conjunction with HAMMA sources to further understand the processes which emit optically.

LIS

LIS, a spaceborne lightning imaging sensor on a NASA developed low earth-orbiting platform (Tropical Rainfall Measuring Mission (TRMM)), which provides radiance, time, and location of lightning events. LIS is a staring imager with an approximate field of view of 600x600km and detects the change in brightness, due to the lightning event, relative to the background brightness [*Christian et al.*, 1999].

The platform carrying LIS has an orbital inclination of 35^o, thus the ground-based sensor networks in Huntsville, AL are within LIS domain. LIS data chosen for this study will consist of multiple overpasses in 2010 and 2011 in dates and areas co-located with HAMMA and NALMA electric field records.

This study focuses on characterizations on the electric field pulse and the LIS group level - the latter is defined as adjacent illuminated pixels during a single frame. Each pixel illuminated above a relative background brightness in a single frame is referred to as an event. Groups may be further clustered in to lightning flashes, but are not are not considered in this study [**?**].

Methods

The relationship between electric field changes and optical emission in lightning is an important aspect in understanding thunderstorm dynamics and cloud electrification, which in turn is critical to advancing weather forecasting techniques. This study seeks to address this knowledge gap, specifically, to characterize radiation field pulses capable of producing detectable optical emission. Initially, 20 IC lightning leaders have been chosen and analyzed on a microsecond scale electric field pulse level, one such IC leader is given in Figure 1. From this the active stage of an IC leader may be characterized not only by the amplitude and variation in the electric field change record, but by their spatiotemporal-temporal characteristics, namely that the active portion of the IC leaders coincides with vertical displacement and optical emission.

Each IC leader occurred on October, 25th 2010 during various stages in a thunderstorm life cycle and during a LIS overpass. Within each of these leaders, pulses are characterized in terms of width, amplitude, polarity and the optical emission resulting from the electric field change. At this time the clarification of optically complex processes is shown to potentially disseminate between pulses which do and do not produce light, based on their physical characteristics including width, amplitude and multiplicity of peaks (Figure 2). These attributes of radiation field pulses allow a deeper understanding of pulse activity and actively discharging processes in IC leaders.

Results

Previously the active portion of IC lightning has been classified solely on the electric field record. In light of the 4D description of an IC leader available in this study the optically active portion of the leader (temporally) occurs after the IC leader began ascent within the cloud (referred to as the vertical extent of the leader). This optically active portion of the leader coincides with an increase in VLF/LF pulse activity and both HAMMA and NALMA sources show an increase in height (as seen in Figure 1), which is thought to be a negative leader ascending from the negative charge layer in a cloud to the upper positive charge layer. Differentiation between radiation field pulses which (1) do and (2) do not produce detectable optical emission is addressed initially by evaluating 14 pulses that correspond (spatially and temporally) to a LIS group and 100 pulses which do not correspond (spatially or temporally) with a LIS group or event. The preliminary analysis is given in Tables 1 and 2. In terms of previously reported pulse characteristics, the characteristics of both types of HAMMA pulses are given (those which do and do not produce detectable optical emission) in Table 3. It is important to note the characteristics given in Tables 1 and 2 indicate that not all radiation field pulses are equal.

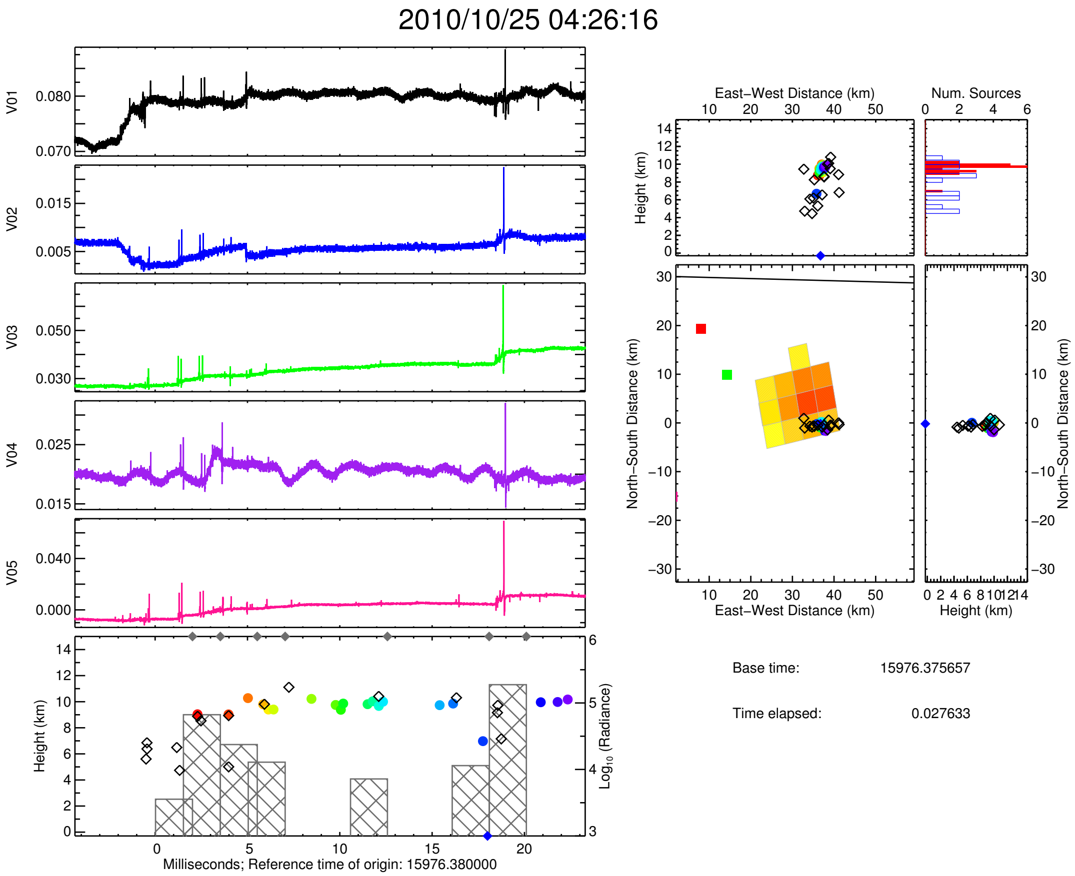

Figure 1: An IC lightning leader, occurring on October 25th, 2010 at 04:26:16 UTC, as viewed in HUDAT [*Bitzer*, 2011]. On the left the 5 electric field waveforms corresponding to a different HAMMA sensor. The bottom left plot is a zt plot of the leader as mapped by NALMA (circles colored with time), HAMMA (hollow diamonds) and LIS (grey hatched rectangles). On the right is a combination of the spatial representation of the leader, and graph source location with height (upper right). The yellow/red squares in the lower left box represents LIS event pixels and groups. The red and green squares in this same frame are the sensors corresponding to the red and green waveforms on the left.

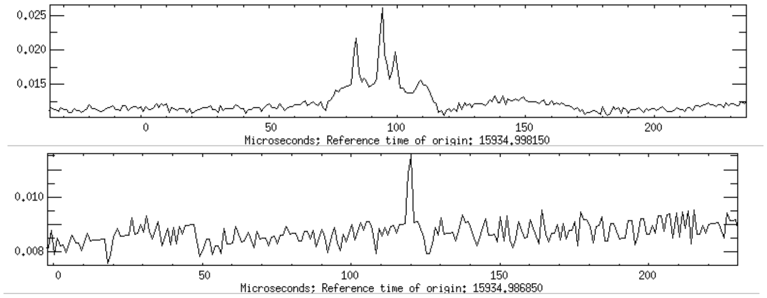

Figure 2: An IC lightning pulse associated with a LIS group (top) and without a LIS group (bottom). The pulses are from a leader on Oct 25th, 2010 at 04:25:41 UTC, detected by HAMMA sensor 1.

Parameter	**Range**	**Standard Deviation**	**Median**
Rise time (μs)	[2,35]	11.19	16
Width (μs)	[5,70]	17.36	30
Amplitude (V/m)	[0.095, 1.78]	0.53	0.843

Table 1: Initial characterization of radiation field pulses in IC leaders which correspond to a LIS group, indicating detectable optical emission (14 pulses analyzed). The Amplitude is the electric field change normalized to 100 km and the minimum and maximum are reported as range.

Parameter	**Range**	**Standard Deviation**	**Median**
Rise time (μs)	[1,12]	2.12	3
Width (μs)	[2,16]	3.07	5
Amplitude (V/m)	[0.053, 1.58]	0.26	0.147

Table 2: Initial characterization of radiation field pulses in IC leaders that occur within the LIS field-of-view and **do not** correspond to a LIS group or event (100 pulses analyzed). The Amplitude is the electric field change normalized to 100 km and the minimum and maximum are reported as range.

Parameter	HAMMA	*Sharma et al.* [2005]	*Villanueva et al.* [1994]	*Bils et al.* [1988]	*Le Vine* [1980]
Amplitude (V/m)	[0.053, 1.78]	0.16-23.59	n/a	n/a	n/a
Rise time (μs)	[1, 35]	0.03-7.59	n/a	n/a	8.37
Width (μs)	[2, 70]	0.12-18.01	26	9.3	7.33

Table 3: The characteristics of all pulses (114 considered) compared to those in representative studies. The minimum and maximum (range) are reported for HAMMA pulses.

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