Transition in Optical and Radio Features during the Initial Leader Development of Intracloud Lightning

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Abstract

How the successively upward, isolated source-dominated propagation of the intracloud (IC) lightning transitions into highly branched, sideways propagation remains an intriguing question. Because the initial IC leader development is usually obscured by thunderclouds, there are few reported optical observations of the initiation and early propagation of IC lightning (Stolzenburg et al., 2021). Here, we analyze and detail the observations of this transition during initial IC leader development with data from optical instruments (Atmosphere-Space Interactions Monitor on the International Space Station), LF magnetic sensors, and VHF interferometry. This transition stage is initially defined by characteristics of the VHF interferometry source maps. By comparing multiple measurements for the same flashes, we find that this transition stage is also defined by repeatable (but different) features in the LF power density and optical waveforms. We find that the ratio of 337 nm (blue)/777.4 nm (red) optical radiance is above unity prior to the transition but is almost always below unity after the transition. The variance in this optical ratio suggests that the dominant illuminating process changes from isolated streamer activities (blue) to thermal channel excitations (red) through the transition. Although the decrease of the optical ratio after the transition could result from the extension of the hot leader channel, we find that the blue radiance drops through the transition, while the red radiance remains almost invariant. Furthermore, the optical radiance reaches the maximum when the transition starts and the LF power density sharply decreases after the transition, suggesting the transition may occur when the leader gradually propagates outside of the high E-field region.

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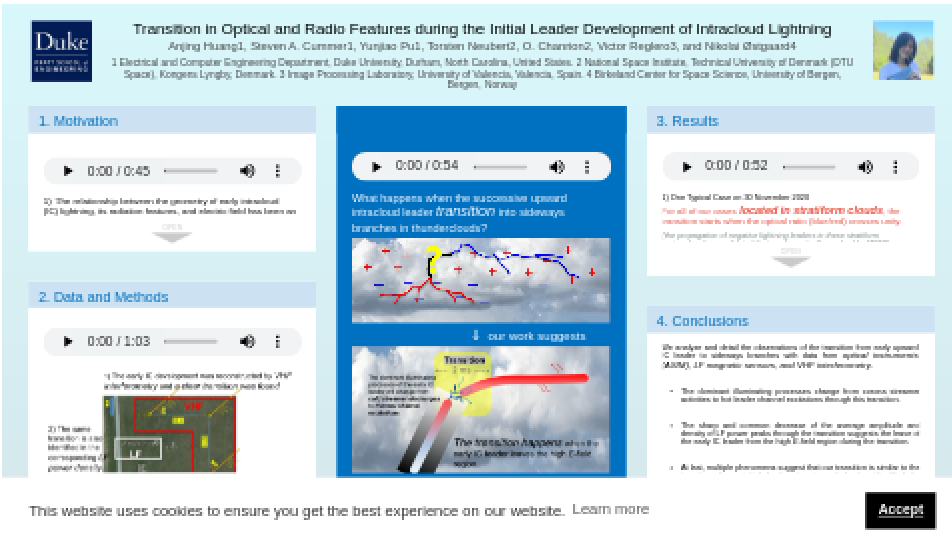

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PRESENTED AT:

1. MOTIVATION

1) The relationship between the geometry of early intracloud (IC) lightning, its radiation features, and electric field has been an open question long ago (*Vonnegut,* 1983; *Coleman et al.,*2003)

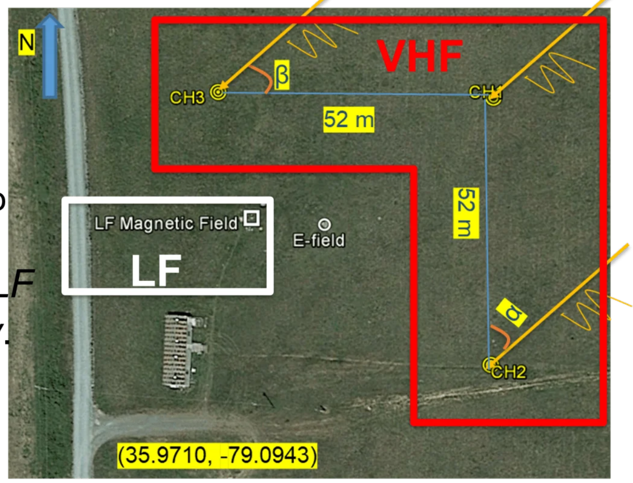
2) *Rare early IC lightning development within clouds* was captured by ground-based photometric instruments.

3) Owing to the recent operations of space-borne equipment such as the *Atmosphere-Space Interactions Monitor (ASIM)* on the International Space Station (ISS), we have a chance to investigate the optical radiance of different IC lightning processes from a top view with less opacity of the cloud compared to the ground-based observations.

2. DATA AND METHODS

1) The early IC development was reconstructed by *VHF interferometry* and *a clear transition was found*

2) The same transition is also identified in the corresponding *LF power density*.



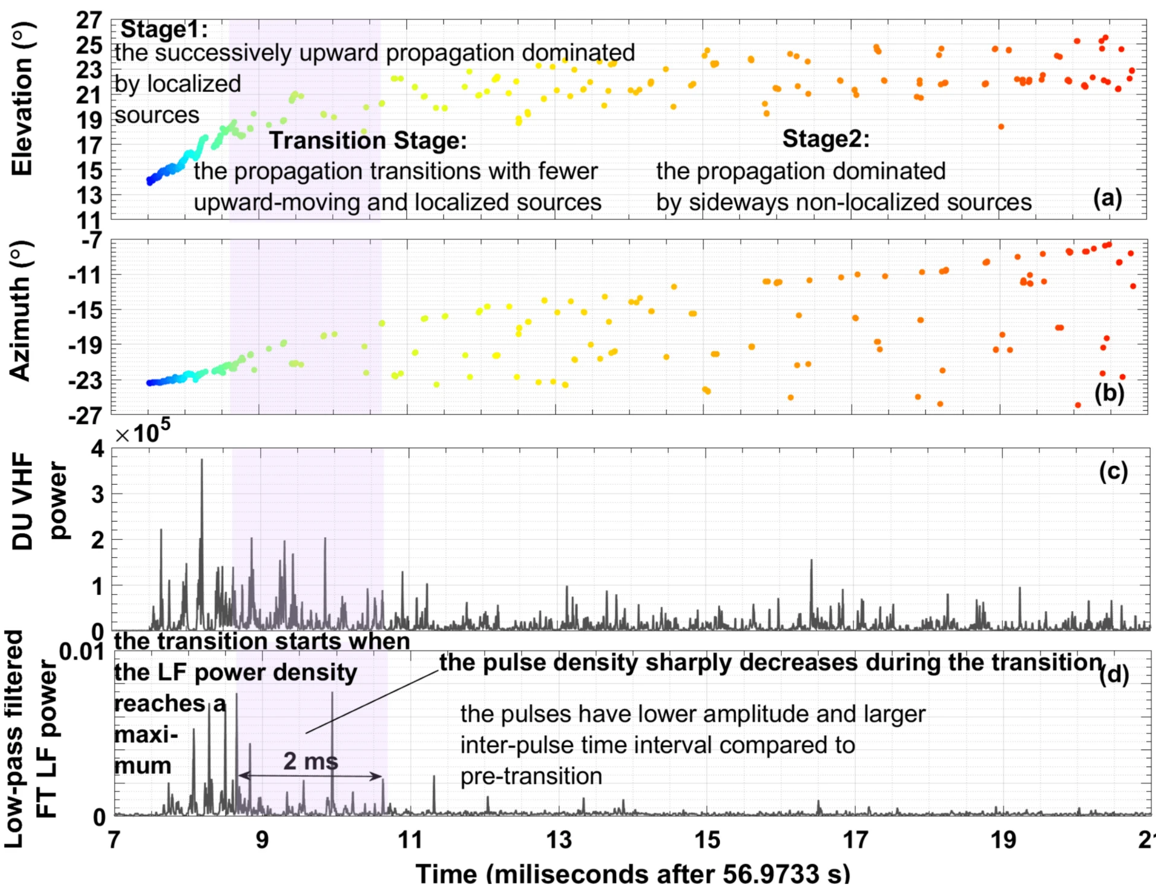
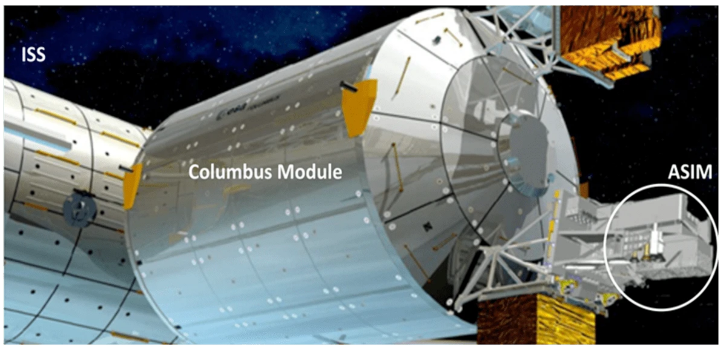


Figure 1. The purple rectangle marks the transition stage. Stage1 and Stage2 are periods prior to and after the transition stage. (a) and (b) are VHF mapping results from Duke University (DU; 35.971°N, −79.094°E). (c) and (d) are the power of DU VHF and Florida Institute of Technology (FT; 28.062°N, −80.624°E) LF signals.

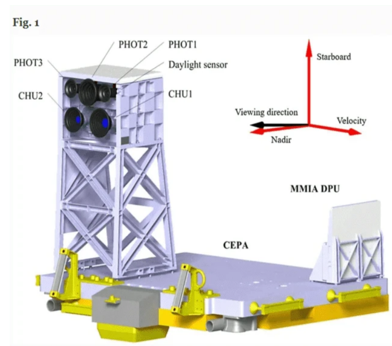
The FT LF sensor is 890 km away from the DU VHF interferometry system. *This distance is similar to the distances (typically in the range of 700 km to 1000 km) between the ASIM reported locations of flashes and the nearest LF sensors where we can capture the early development of IC flashes.*

The power is calculated as the square of the measured signals and averaged over 10 μs. Especially, the LF power in (d) passes a band-pass filter with 50 kHz and 300 kHz cut-off frequency.

3) This transition is also defined by repeatable (but different) features in the *optical waveforms (from* Atmosphere-Space Interactions Monitor on the International Space Station, *ASIM)*.



From Birkeland Centre for Space Science



Chanrion et al. (2015)

ASIM is equipped with photometers and cameras in selected bands, i.e., 337.0 nm (blue) and 777.4 nm (red).

- *777.4 nm radiance → current* from fast developing and highly conducting hot leader channel
- *337 nm* radiance → from non-thermal discharges (i.e., *streamers and coronas*) isolated or at the front tip of hot channel leaders
- If no structures of leader channels form, the *777.4* nm optical radiance was indicated to become *negligible* due to the existence of streamers alone.

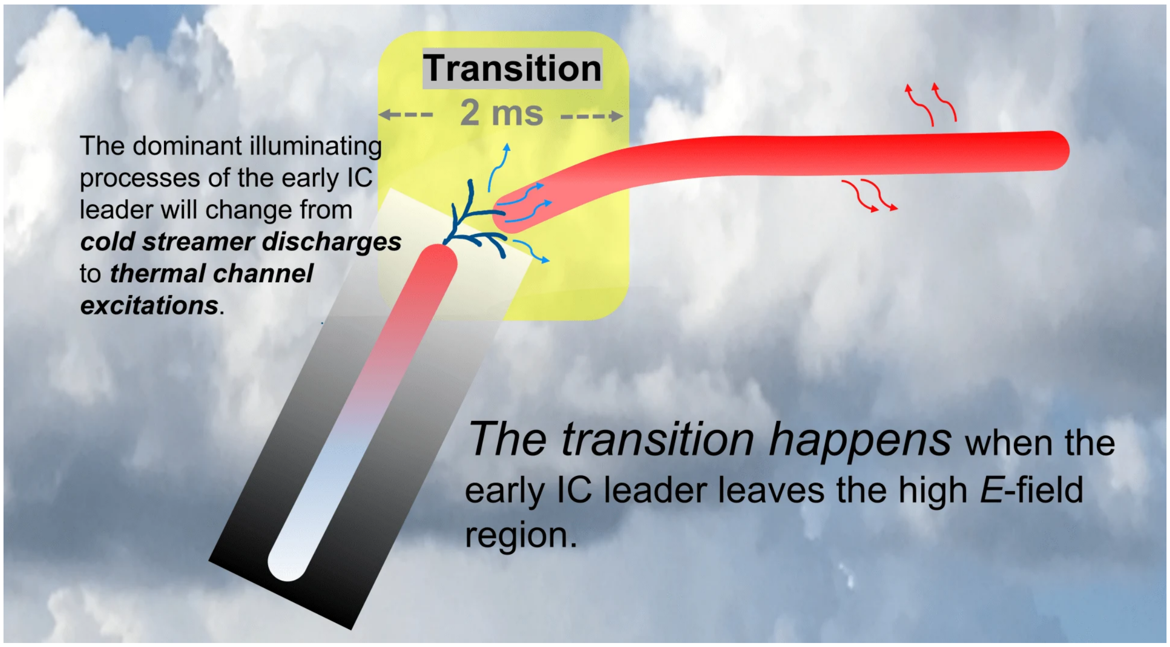
(*Soler et al*., 2020; *Montanyà et al*., 2021)

What happens when the successive upward intracloud leader *transition* into sideways

branches in thunderclouds?

[VIDEO] https://res.cloudinary.com/amuze-interactive/image/upload/f_auto,q_auto/v1638773119/agu-fm2021/9d-77-2e-42-96-a2-0a-47-6a-fc-a8-36-73-2a-39-d7/image/ezgif.com-gif-maker_qqfj4a.mp4

⇓ our work suggests



This transition has been clearly identified in observations from *VHF interferometry, LF magnetic field sensors, and optical instruments.*

3. RESULTS

1) One Typical Case on 30 November 2020

For all of our cases ***located in stratiform clouds***, the transition starts when the optical ratio (blue/red) crosses unity.

(the propagation of negative lightning leaders in these stratiform regions has been validated that can be optically resolved by MMIA)

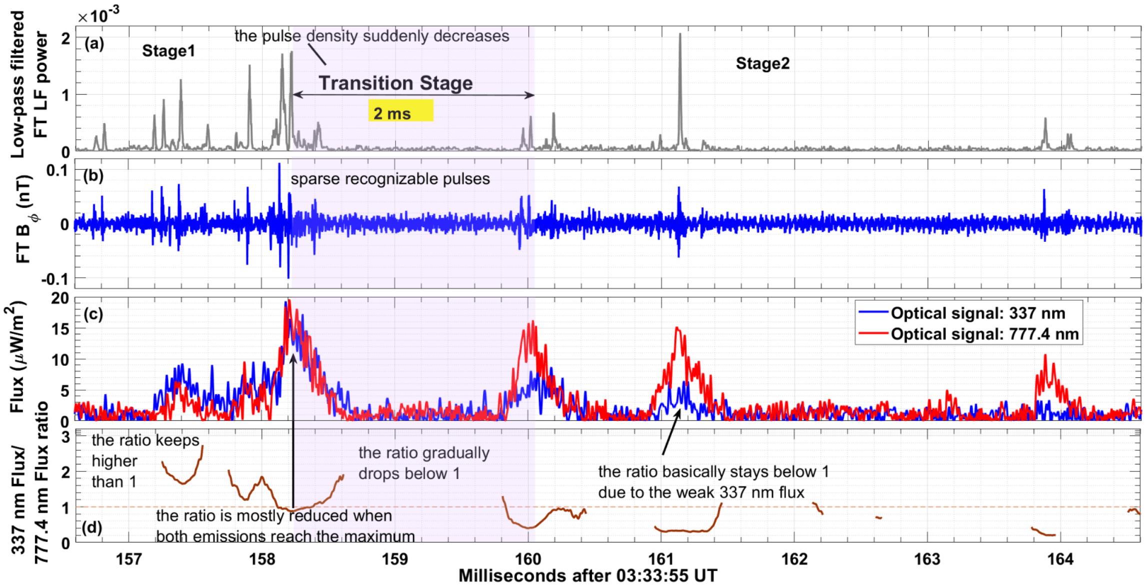


Figure 2. The early development of this flash was fortunately located in the stratiform region of the thundercloud according to the ASIM camera frames and NLDN records. The purple rectangle marks the transition based on the definition of the transition in Figure 1.

- the ratio of 337 nm/777.4 nm radiance stays *greater than unity in Stage one*
- the optical ratio declines to unity and *stays lower than unity in Stage two.*
- Although the decrease of the optical ratio after stage one could result from the extension of hot leader channels, Figure 2c shows that the blue radiance remarkably declines through the transition, while the red radiance remains almost invariant.
- Therefore, we could confidently suggest that the *dominant illuminating processes for this case have a physical transition from cold corona discharges to excitations by thermal leader channels.*

2) Overall results for 30 ASIM-detected IC flashes

For all of our cases (including those that are not located in stratiform clouds), the transitions start around the time when the radiance in both bands reaches the maximum and the ***optical ratio (blue/red) is mostly reduced***.

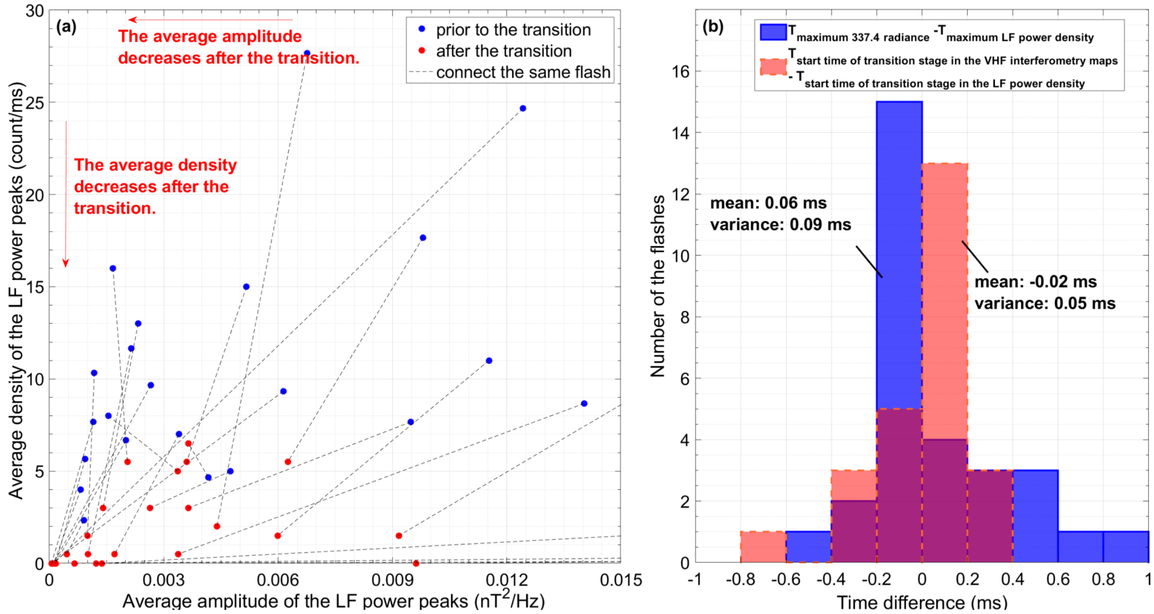


Figure 3. The overall results from 30 IC flashes present the common features of the transition. (a) The relationship between average amplitude and average density of the LF power peaks before and after the transition of 30 IC cases. (b) Blue histogram: differences between the time when maximum 337 nm radiance and maximum LF power density. Red histogram: time differences between the start of the transition identified from VHF interferometric results and corresponding LF power waveforms.

Sparse recognizable LF power peaks were identified in the transition stage → ***the energy in the total vertical E-field is going to be exhausted in the transition*** and the remaining energy no longer supports considerable impulsive charge transfers.

The transition starts after the largest IBP when the optical radiance reaches maximums and the blue/red ratio coincidently declines to unity for the typical cases, suggesting that our transition is similar to the transition from initial leader to stepped leader identified by *Stolzenburg et al.* (2020).

4. CONCLUSIONS

We analyze and detail the observations of the transition from early upward IC leader to sideways branches with data from *optical instruments (ASIM), LF magnetic sensors, and VHF interferometry*.

- The dominant illuminating processes change from corona streamer activities to hot leader channel excitations through this transition.
- The sharp and common decrease of the average amplitude and density of LF power peaks through the transition suggests the leave of the early IC leader from the high *E*-field region during the transition.
- At last, multiple phenomena suggest that our transition is similar to the transition from initial leader to stepped leader identified by *Stolzenburg et al.* (2020).
- Therefore, our conclusions support the conclusions of cloud-to-ground strokes that the high conductivity channel is not fully formed for the initial leader, and thus the initial leader is physically different from the stepped leader.

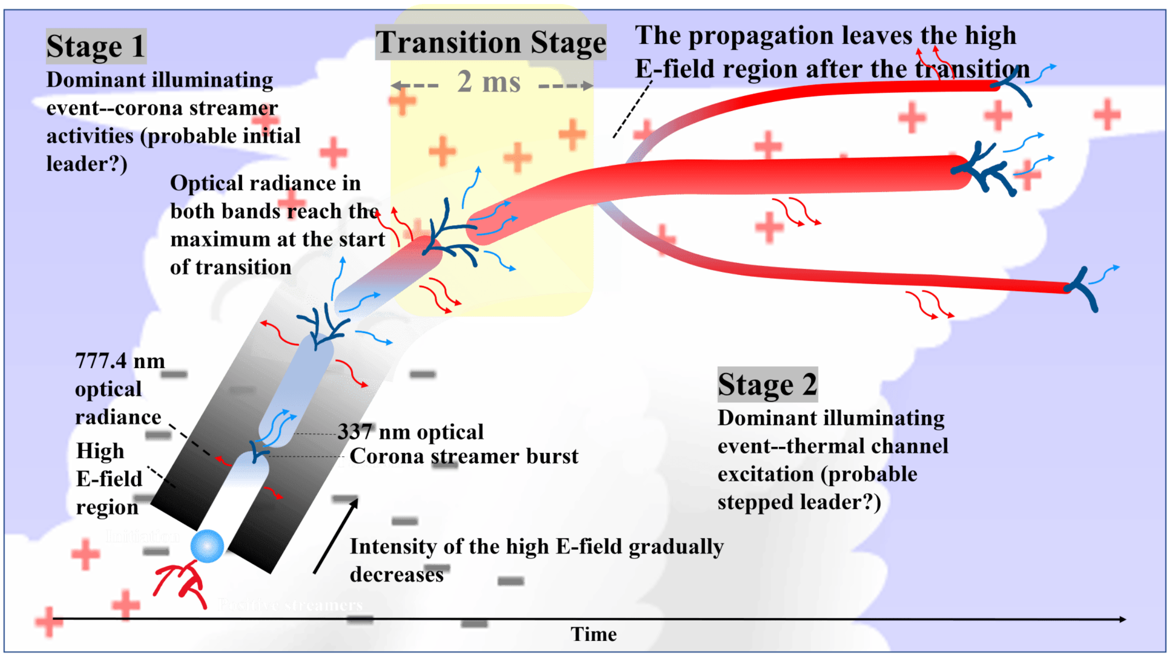


Figure 4. A summarized diagram of the early development of IC flashes in three stages. The length of the transition stage is defined as 2 ms and is marked by a yellow rectangle. The IC leaders are plotted from white to blue to red, suggesting the channels are developing from dielectric condition to mature stage. The initial, upward development of the leader is intermittent to exhibit the stepped feature. The background geometry behind the leaders plotted from black to white indicates the decrease of the high *E*-field intensity with the development of IC leader.

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