A negative cloud-to-ground lightning flash initiating at a high altitude and starting without classic preliminary breakdown pulses

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Abstract A special negative cloud-to-ground (-CG) flash imaged by a low frequency lightning mapping system is reported in this paper. This flash initiated at a high altitude of about 11 km. The initiation location is inferred to be the lower edge of the upper positive charge region. Both initial positive and negative leaders had downward propagations, but during the initial 500 ms the negative leader had little development. An important feature of this -CG flash is that it did not start with classic preliminary breakdown (PB) pulses; there were only a few very small and narrow (~1 μs) pulses during the initial 100 ms. The absence of PB pulses was a direct result of the inactive initial negative leader, which was caused by the high initiation altitude. We suggest that lightning flashes, including CG and intracloud flashes, initiating at high altitudes (roughly >10 km) mostly start without classic PB pulses.

Keywords: cloud-to-ground lightning, preliminary breakdown, lightning initiation.

1. Introduction

On the wideband electric field change (E-change) signature, cloud-to-ground (CG) and intracloud (IC) lightning flashes normally start with a train of characteristic bipolar pulses called preliminary breakdown (PB) pulses or initial breakdown pulses (e.g., Beasley et al., 1982). Although it has been established that the so-called initial E-change (IEC) occurs right before PB pulses (Marshall et al., 2014a, 2019; Chapman et al., 2017), IECs can only be detected within several kilometers with sensors capable of detecting "electrostatic" E-changes. As a result, IECs are not commonly detected with wideband E-change sensors, and in this study we will only focus on PB pulses. PB pulses can be classified into classic PB pulses and narrow PB pulses (Nag et al., 2009). Classic PB pulses are bipolar pulses with pulse widths of tens of μs while narrow PB pulses are mainly unipolar pulses with pulse widths on the order of 1 μs (Nag et al., 2009; Stolzenburg et al., 2014; Marshall et al., 2019). The majority of studies on PB pulses focused on classic PB pulses (e.g., Gomes et al., 1998; Marshall et al., 2014b; Smith et al., 2018). In this study we also only consider classic PB pulses, and we will call them "PB pulses" for simplicity.

The percentage of negative CG (-CG) flashes that start with PB pulses has been investigated by many studies (e.g., Baharudin et al., 2012; Gomes et al., 1998; Nag & Rakov, 2009; Stolzenburg et al., 2013). It had been speculated that the percentage was related with the latitude, with flashes at higher latitudes having a better chance of producing PB pulses (Nag & Rakov, 2009). However, Marshall et al. (2014b) suggested that all -CG flashes, including hybrid flashes, start with PB pulses. They also provided possible reasons for the non-detection of PB pulses. One reason is that some PB pulses may be hidden by the noise level due to small PB pulses or a high noise level or a large distance. Another reason is that some PB pulses may occur a long time (hundreds of milliseconds) before the first return stroke (RS) and may not be recorded if the pre-trigger time of the recording system is too short.

High-speed video observations of the PB stage in IC and -CG flashes have demonstrated that PB pulses are well corresponded with light bursts from initial negative leaders, suggesting that PB pulses may be produced by the stepping processes of initial negative leaders (Campos & Saba, 2013; Stolzenburg et al., 2013, 2014; Wilkes et al., 2016). It is widely accepted that lightning flashes start with bi-directional leaders (e.g., Mazur and Ruhnke, 1993), with positive and negative ends extending in different directions, so it is reasonable to speculate that all IC and -CG flashes start with PB pulses, which are produced by initial negative leaders.

However, in this paper we will provide the first concrete evidence that a -CG flash can start without PB pulses. We will describe a special -CG flash imaged by a low-frequency (LF) lightning mapping system. Apart from the feature that it did not start with PB pulses, this flash is also special in that it initiated at a high altitude of about 11 km and the negative leader connecting to the ground had little development during the initial 500 ms. Considering the recent observation of the so-called downward positive IC (+IC) flashes which apparently do not start with PB pulses either (Wu et al., 2019a), we will discuss when and why a lightning flash does not start with PB pulses.

2. Observation

During the summer of 2017, an LF lightning three-dimensional (3-D) mapping system called Fast Antenna Lightning Mapping Array (FALMA) was established in the central region of Japan. FALMA consisted of 12 sites of fast antennas working in the frequency band of about 500 Hz to 500 kHz. The recording system at each site can record LF lightning radiation signals continuously without any deadtime with a sampling rate of

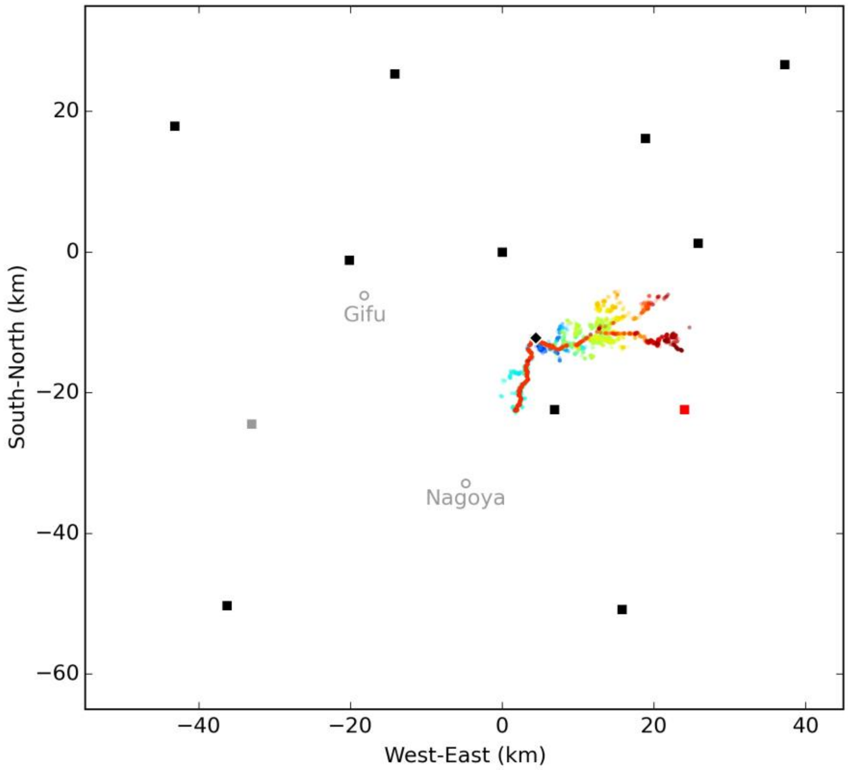

Figure 1. Sources of the -CG flash analyzed in this paper and locations of observation sites of the FALMA. The black diamond represents the initiation location of the -CG flash. Squares represent observation sites. The grey square is a site not working at the time of the flash. The red square is the site recording the waveform shown in Figures 2a and 5. The origin (0, 0) corresponds to the latitude and longitude of (35.475°N, 136.960°E).

25 MS/s and a vertical resolution of 16 bit. With the high-quality waveform data recorded at multiple sites, the system is capable of mapping lightning flashes inside the network with great detail and accuracy. Combining the high quality 3-D mapping results and E-change waveforms recorded at multiple sites, we can unambiguously identify discharge processes such as the PB, stepped leaders and RSs and make detailed studies of these processes. Locations of the 12 sites of the FALMA are shown in Figure 1. More information about FALMA can be found in Wu et al. (2018).

The atmospheric electricity sign convention is used for E-change waveforms in this paper, so a negative RS produces a pulse with positive initial polarity. The fast antennas were not calibrated, so magnitudes of E-change waveforms are shown in the digital unit.

3. Results

3.1 3-D mapping result

The special -CG flash analyzed in this paper occurred on August 18, 2017 (JST). Location of this flash relative to observation sites is shown in Figure 1. Figure 2 shows the 3-D mapping result and the E-change waveform of the flash. Altitudes of 0 to −50 °C isotherms, which were obtained by radiosonde observations by the Japan Meteorological Agency at 21:00 JST (about 27 minutes before the -CG flash) at Wajima site (37.40N, 136.90E, about 200 km from this flash) are also shown in Figure 2. The duration of this flash was about 1.6 seconds. It produced seven RSs labeled as "R1" to "R7" in Figure 2a and represented by cross signs in Figures 2b to 2e. The third and the fourth RSs had a very small time interval of 2.8 ms and cannot be differentiated in Figures 2a and 2b. These seven RSs had the same termination.

The first distinguishing feature of this flash is that it initiated at a high altitude of about 11 km, corresponding to the temperature level of about -40 °C. Initiation altitudes of -CG flashes have large variations in different storms and different regions, but they are usually well below 10 km (Caicedo et al., 2018; Karunarathna et al., 2017; Shi et al., 2019a; Wu et al., 2015). In fact, to our best knowledge, no 3-D location results of -CG flashes initiating at higher than 10 km have ever been reported. It is well understood that -CG flashes usually initiate from the lower edge of the main negative charge region. Due to the fact that the main negative charge region is usually located in the temperature range of -10 to -25 °C (Rakov and Uman, 2003, pp. 75), it is fundamentally difficult for the initiation location of -CG flashes to reach a very high altitude.

The reason for the high initiation altitude of the -CG flash in Figure 2 is that it did not initiate from the lower edge of the main negative charge region but from the lower edge of the upper positive charge region. Figure 3 shows the charge structure inferred from lightning flashes within ±5 minutes of the -CG flash in Figure 2. Note that sources of the -CG flash were not used for the determination of the charge structure. The method for the charge structure determination is similar to that commonly used for the Lightning Mapping Array (e.g., Wiens et al., 2005). The 3-D mapping results are examined for each flash and sources of positive and negative leaders are manually selected. Examples of the determination of positive and negative leaders for an IC and a -CG flash can be found in Wu et al. (2019b). Further, sources of horizontal negative leaders are assigned as positive charges and sources of horizontal positive leaders are assigned as negative charges, and results for all flashes in the designated period are put together to form the overall charge structure.

From Figure 3, we can see that the flash initiated from the lower edge of the

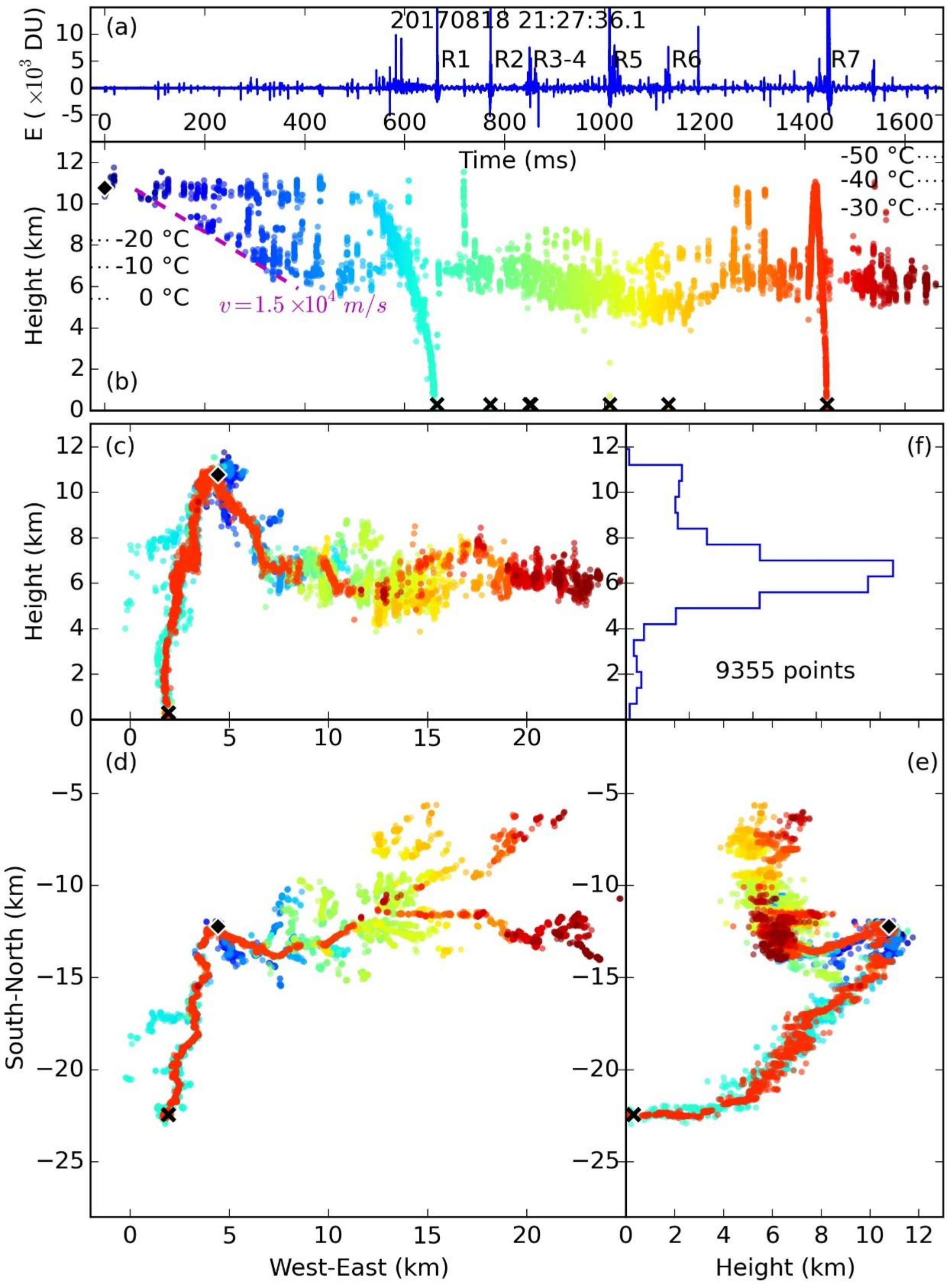

Figure 2. E-change waveform and 3-D mapping result of the -CG flash. (a) E-change waveform. (b) Height-time view. (c) Height-distance (from west to east) view. (d) Plan view. (e) Distance (from south to north)-height view. (f) Source distribution along the height. The black diamond represents the initiation location. Cross signs represent RSs. Time 0 corresponds to the time of the first source of this flash.

upper positive charge region. The negative leader mainly propagated outside of the inferred charge region, and probably because there were no negative charges below the

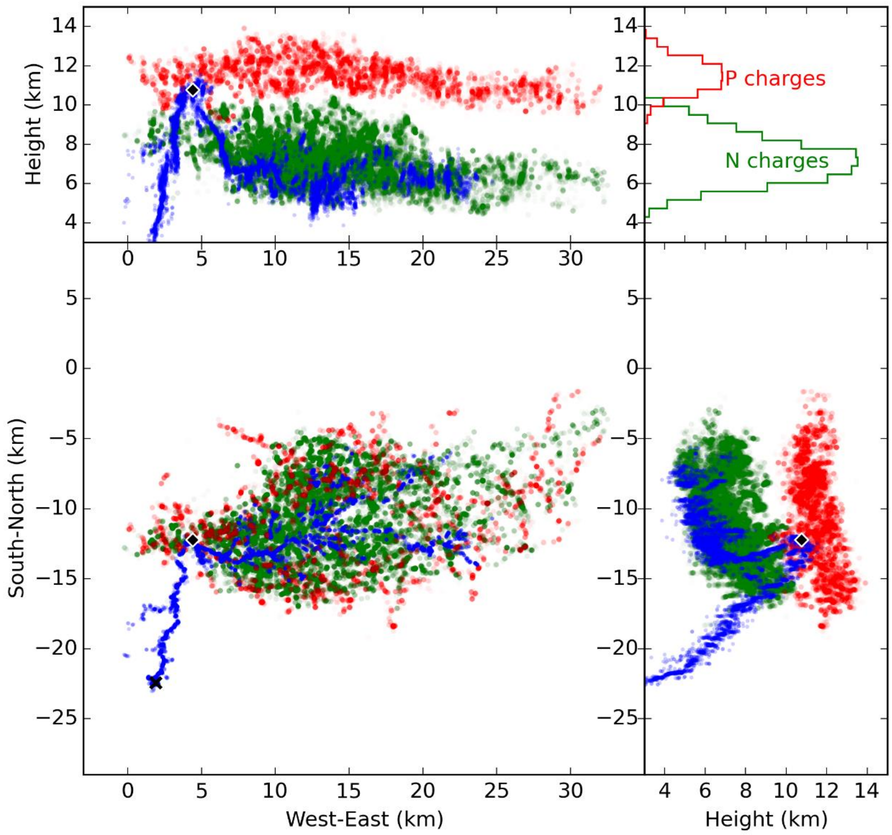

Figure 3. Inferred charge structure. Red points represent positive charges and green points represent negative charges. Blue points represent sources of the -CG flash and the black diamond represents the initiation location.

negative leader to "block" its downward development, the negative leader successfully reached the ground. The positive leader first propagated downward until it reached the lower edge of the main negative charge region, and then it propagated mainly horizontally in the negative charge region.

The channel structure of this -CG flash is also special. Normal -CG flashes usually start with downward negative leaders and horizontal or upward positive leaders. An example detected by the FALMA is given in Figure 2 in Wu et al. (2019b). However, the flash in Figure 2 consisted of initial positive and negative leaders both developing downward. Such structure for -CG flash has not been reported before. The downward velocity of the positive leader is estimated to be 1.5×10^4 m/s, typical for positive leaders in -CG and IC flashes (Wu et al., 2019b). The velocity for the negative leader, however, has large variations during its development. From Figure 2b, we can see that the negative leader started the downward progression at the time of about 500 ms. Before that time, sources of the negative leader were detected at a roughly constant altitude of about 11 km. Combined with other subplots in Figure 2, it is clear that the negative leader had little development before the time of about 500 ms.

Sources of the negative leader were extracted and plotted in Figure 4. Figure 4d shows the distance variation of the negative leader sources relative to the initiation location. Before the time of 500 ms, the distance had a maximum of only about 2.5 km, indicating that the negative leader was almost inactive during the initial 500 ms. From the time of about 550 ms, the negative leader started developing downward with a relatively small velocity of stepped leaders (e.g., Campos et al., 2014), but the velocity seems to increase with time. Two dashed lines indicating velocities of 0.70 and 1.2×10^5 m/s are plotted with the sources in Figure 4d, and the leader velocity was roughly in this range.

It should be noted that although we stated that the negative leader was "inactive" during the initial 500 ms, the possibility exists that no negative leader channels were actually formed during this period. Currently we do not have further evidence to determine exactly what the discharge processes are during the initial 500 ms. However, we can see clearly a positive leader developing downward, and based on the widely accepted theory that natural lightning flashes start with bidirectional leaders (e.g., Mazur & Ruhnke, 1993), we will simply assume that an initial negative leader also existed but was just "inactive" during the initial 500 ms.

3.2 E-change pulses during the initial 100 ms

An important feature of the -CG flash reported in this paper is that it did not start with PB pulses. E-change waveform during the initial 100 ms is shown in Figure 5. Nine pulses indicated by cross signs in Figure 5a are plotted in Figures 5b-5j to show pulse characteristics. Pulse widths are estimated and they are generally around 1 μs. In Figures 5b-5j, vertical dashed lines with 1-μs separations are also plotted so readers can directly estimate the pulse widths, and it is clear that these pulses are much narrower than PB pulses, whose pulse widths are usually on the order of tens of μs (e.g., Weidman & Krider, 1979; Marshall et al., 2014b).

There are other obvious differences between pulses in Figure 5 and PB pulses. First, PB pulses in the same pulse train usually have the same initial polarity. Specifically, PB pulses in -CG flashes usually have initial positive changes while those in normal polarity IC flashes usually have initial negative changes (atmospheric sign convention). However, pulses with both initial polarities exist in Figure 5. Second, PB pulses are usually quite strong and sometimes can be comparable to the following RS

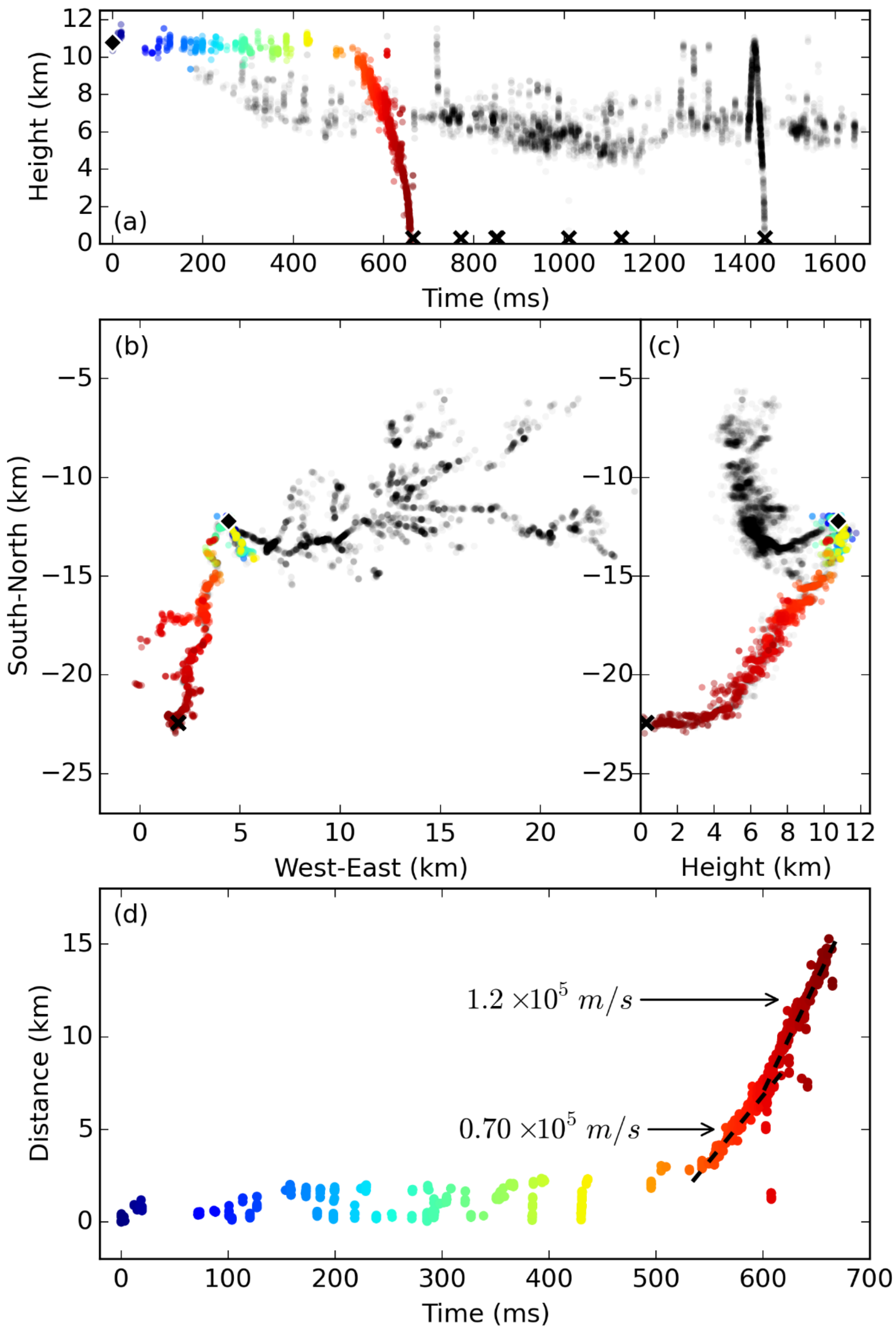

Figure 4. Sources of the negative leader (colored points) in the -CG flash (Figure 2). (a) Height-time view. (b) Plan view. (c) Distance (from south to north)-height view. (d) Distance (with respect to the initiation location)-time view.

(Rakov & Uman, 2003, pp. 119). However, pulses in Figure 5 are apparently very small. Although we do not know the absolute amplitude of these pulses and cannot compare with PB pulses reported in the literature, from Figure 2a we can see that these pulses are

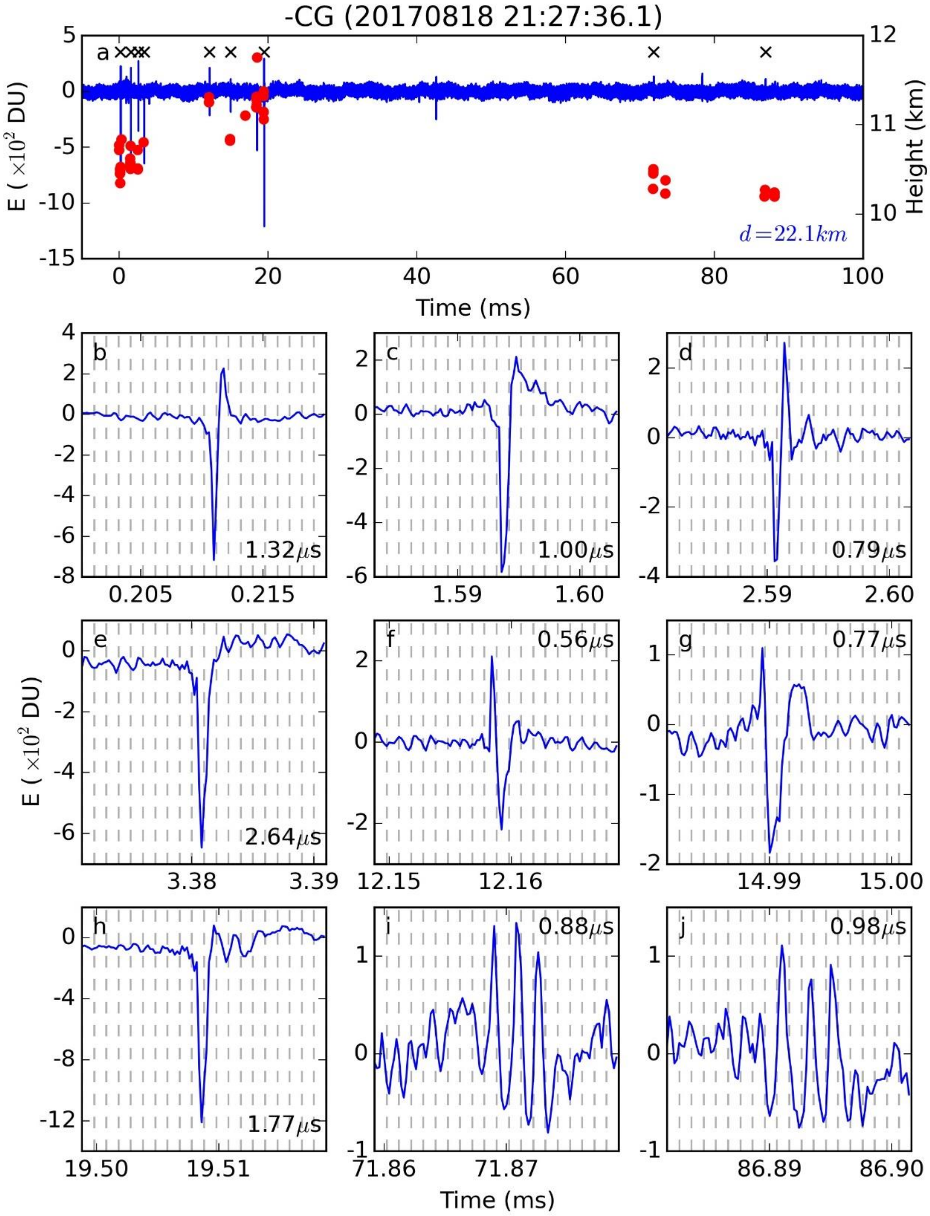

Figure 5. E-change waveform during the initial 100 ms of the -CG flash in Figure 2. Red points indicate source heights of corresponding pulses. The value of *d* represents the distance between the initiation location and the observation site. Nine pulses indicated by cross signs in Figure 5a are shown in Figures 5b-5j with a length of 20 μs. Vertical dashed lines with 1-μs separations are plotted in Figures 5b-5j.

much smaller than other pulses in the same flash. In fact, most of the pulses are so small that they can be hardly recognized in Figure 2a. Third, small pulses usually can be found superimposed on the rising portion of PB pulses (Weidman & Krider, 1979). Pulses in Figure 5 do not have such fine structure.

Based on these clear differences, we conclude that this -CG flash did not start with PB pulses, and we believe that this is the first concrete evidence that a -CG flash can start without PB pulses. It is indeed difficult to prove that -CG or IC flashes can start without PB pulses, because it is difficult to eliminate the possibility that PB pulses exist but are not detected due to various reasons (Marshall et al., 2014b). For the -CG flash reported in this paper, the possibility that some PB pulses occurred before the pulses in Figure 5 but were not detected by our system is very low for three reasons. First, this -CG flash was close to most of observation sites, and it is unlikely that PB pulses occurred but were not detected by any of the sites. As can be seen from Figure 1, the closest site to the initiation location was only about 10 km. Second, from the 3-D structure shown in Figure 2, we can see that positive and negative initial leaders start from the same initiation location, and it is difficult to imagine other negative leaders, which should be responsible for PB pulses, occurred before these initial leaders. Third, the non-detection of PB pulses is actually an expected result of the high initiation altitude, which will be further discussed in section 4.

4. Discussion

4.1 The absence of PB pulses due to the inactive negative initial leader

Wu et al. (2019a) reported a special type of IC flash called "downward +IC flash" which initiated at high altitudes (mainly above 12 km) and started with downward positive leaders and horizontal and generally inactive negative leaders. Downward +IC flashes apparently do not start with PB pulses. As an example, the E-change waveform during the initial 100 ms of the downward +IC flash in Figure 2 in Wu et al. (2019a) is shown in Figure 6. We can see that pulses at the beginning of this flash are very similar to those of the -CG flash reported in this paper (Figure 5). In both cases, the pulses are very narrow (around 1 μs) and small and contain both initial polarities.

If we look at the initial 500 ms of the -CG flash in Figure 2, its characteristics are very similar to those of downward +IC flashes. Common characteristics include high initiation altitudes, inactive initial negative leaders and downward positive leaders. The key property that resulted in the absence of PB pulses at the beginning of the -CG flash in this study and downward +IC flashes is the inactive initial negative leader. It is believed that PB pulses are produced by the stepwise propagations of initial negative leaders (e.g., Campos and Saba, 2013; Stolzenburg et al., 2013). In the case of -CG flashes, initial negative leaders propagate downward, producing a train of positive pulses, and in the case of normal polarity IC flashes, initial negative leaders propagate upward, producing a train of negative pulses. However, in the case of the special -CG flash in this study and

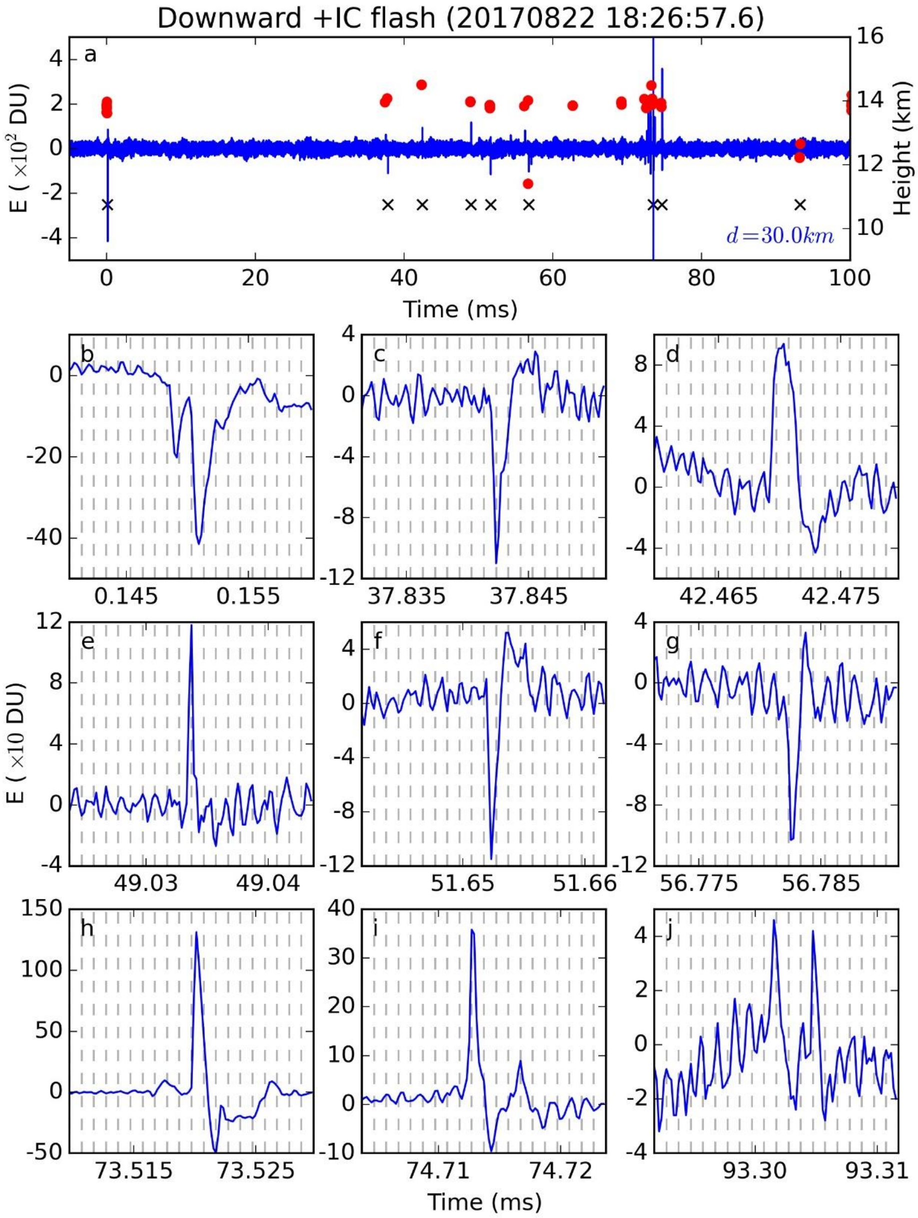

Figure 6. The same as Figure 5 but for the downward +IC flash shown in Figure 2 in Wu et al. (2019a).

downward +IC flashes, the initial negative leaders barely developed forward. It is even possible that there was actually no negative leader in the early stage. If we look at Figure 2b, we can see that sources representing the initial negative leader during the first 500 ms are seemingly part of recoil leader sources, so it is possible that no initial negative leader was formed at the beginning of this flash. As a result, no PB pulses were produced at the beginning of these flashes.

4.2 Inactive initial negative leaders at high initiation altitudes

Inactive initial negative leaders seem to occur only when initiation altitudes are high enough. The reasons behind may be the weak electric field and the low air density at high altitudes. We believe that PB pulses are produced by a negative leader propagating in a large region with strong ambient electric field as discussed by Shi et al. (2019b). As also discussed by Stolzenburg et al. (2014), initial negative leader channels may be less conductive than normal stepped leader channels, so initial negative leaders may need a large ambient electric field to form new steps and to propagate. However, the ambient electric field is likely to be relatively small at high altitudes and thus may be not large enough to support the continuous development of initial negative leaders. Moreover, it is clear that as the altitude increases, the air density decreases, resulting in longer steps of negative leaders (Edens et al., 2014; Wu et al., 2015). Assuming an initial negative leader at a high altitude produces a step at the very beginning, because the step is very long, the leader tip may not have enough potential difference with respect to the ambient potential to support the formation of new steps (da Silva and Pasko, 2015). Therefore, initial negative leaders at high altitudes are difficult to progress forward and to produce PB pulses.

We can also find evidence supporting the above argument when comparing different behaviors of initial positive and negative leaders with changing altitudes. Wu et al. (2015) demonstrated that velocities of initial negative leaders in IC flashes decrease significantly with increasing initiation altitudes; leaders initiating at 10 km can be one order of magnitude slower than those initiating at 5 km. Wu et al. (2019b) further analyzed velocities of positive leaders in IC and -CG flashes. They showed that although velocities of positive leaders in IC flashes tended to decrease with increasing altitudes, the variation was much smaller than that of initial negative leader velocities, and almost all positive leaders, including those in IC and -CG flashes, had velocities in a small range of 1 to 3×10^4 m/s. If we look at Figure 2 again, we can see that although the initial negative leader had little development during the initial 500 ms, the positive leader propagated downward with a normal velocity of 1.5×10^4 m/s. The stark difference is very likely resulted from the fundamental difference between positive and negative leaders, that is, negative leaders propagate with discrete steps while positive leaders usually propagate continuously. Therefore, the difficulty in propagating forward is a manifestation of the difficulty in forming new steps for initial negative leaders at high altitudes.

4.3 Lightning flashes not starting with PB pulses

From the above analysis, it is clear that whether a lightning flash starts with PB pulses depends on whether the initial negative leader can continuously form new steps and propagate forward, which is further related with the initiation altitude. It seems that as the initiation altitude increases, the possibility that a lightning flash does not start with PB pulses also increases. Above exactly what altitude do lightning flashes start without PB pulses is likely dependent on the specific definition of PB pulses and may also be different in different regions. However, we suggest that when initiation altitudes are higher than 10 km, lightning flashes, including both IC and CG flashes, probably do not start with PB pulses based on the following three observations. First, 3-D location results of lightning flashes initiating above 10 km are rarely reported, probably due to inactive negative leaders that usually cannot be well located. Second, Wu et al. (2015) analyzed IC flashes with initial negative leaders showing upward propagations, and initiation altitudes of these IC flashes were mainly below 10 km. Third, Wu et al. (2014) showed that narrow bipolar events higher than 10 km are generally not followed by leader processes. These results suggest that 10 km may be an appropriate altitude threshold above which initial negative leaders cannot easily form new steps and propagate forward.

However, we believe that the vast majority of lightning flashes not starting with PB pulses are IC flashes reported by Wu et al. (2019a). In fact, the -CG flash reported in this paper is the only flash identified so far that does not start with PB pulses. The rarity of such -CG flashes is simply due to the inactive initial negative leader, which is the reason for the non-production of PB pulses. The initial negative leader starts at a high altitude and has little development at the beginning, so it will have little chance to progress to the ground, and most of the time it will just develop into a downward +IC flash reported by Wu et al. (2019a). The condition that is favorable for the inactive initial negative leader to gain speed and develop to the ground at a later stage may be that the flash initiates at the edge of a charge region like the flash reported in this paper.

It should also be noted that there may be other situations unrelated to this study in which lightning flashes do not start with PB pulses. For example, if a lightning flash starts with a horizontal negative leader, the leader will probably not produce a train of bipolar pulses with the same initial polarity.

5. Conclusions

A special -CG flash imaged by the FALMA is reported in this paper. Distinguishing characteristics of the -CG flash are as follows.

(1) This -CG flash initiated at a high altitude of about 11 km, corresponding to the temperature level of about -40 °C. Initiation altitudes of –CG flashes reported in the

literature are usually well below 10 km.

(2) This -CG flash initiated from the lower edge of the upper positive charge region of a normal dipolar charge structure. Normal –CG flashes usually initiate from the lower edge of the main negative charge region.

(3) The initial negative leader had little development during the initial 500 ms. Later it progressed downward to the ground with a relatively small velocity as a negative stepped leader.

(4) This -CG flash started without any classic PB pulses. There were only a few very small and narrow (~1 μs) pulses during the initial 100 ms. It was suggested that all –CG flashes produce classic PB pulses (Marshall et al., 2014b). This is the first concrete evidence that a –CG flash can start without classic PB pulses.

These characteristics are closely related with each other. The absence of PB pulses was a direct result of the inactive initial negative leader, which was further caused by the high initiation altitude. Considering the recent observation of downward +IC flashes which share similar characteristics during the initiation stage (Wu et al., 2019a), we conclude that with increasing altitudes, the possibility of the production of PB pulses decreases due to the difficulty in forming new steps for initial negative leaders, and we suggest that lightning flashes, including IC and CG flashes, initiating at higher than 10 km most likely do not start with PB pulses.

Acknowledgement. This work was supported by the Ministry of Education, Culture, Sports, Science, and Technology of Japan (Grant 16H04315 and 18K13618).

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(Received April 25, 2020; revised June 4, 2020; accepted June 10, 2020)