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Luminosity characteristics of dart leaders and return strokes in natural lightning

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Abstract. Streak-camera photographs were obtained in daylight for 23 subsequent strokes in five Florida negative cloud-to-ground flashes. Out of the 23 return-stroke streaked images, only 11 were accompanied by leader streaked images, while all 23 leaders were identified in corresponding electric field records. Thus, 12 subsequent leaders (one of which created a new channel to ground) failed to produce luminosity above the daylight background level. The brightest three dart-leader/return-stroke sequences from two flashes have been examined for relative light intensity as a function of time and height. Dart-leader light waveforms appear as sharp pulses with 20-to-80% risetimes of about 0.5-1 μs and widths of 2-6 μs followed by a more or less constant light level (plateau). The plateau continues until it is overridden by the return-stroke light waveform, suggesting that a steady leader current flows through any channel section behind the downward moving leader tip before the return-stroke front has passed that channel section. Return-stroke light pulses near ground have 20-to-80% risetimes of about 1-2 μs and amplitudes a factor of 2 to 3 greater than those of the dart-leader light pulses. As opposed to the return-stroke light pulses that suffer appreciable degradation during the upward propagation of the return-stroke front, the dart-leader light pulses preserve their shape, and the pulse amplitude is either more or less constant or increases as the leader approaches ground. The average electric field intensity across the dart-leader front, whose length is inferred from measured light-pulse risetimes and propagation speed to be of the order of 10 m, should be at least an order of magnitude greater than the average electric field intensity across the return-stroke front, whose length is inferred to be of the order of 100 m.

1. Introduction

Jordan and Uman [1983] studied relative light intensity as a function of height and time for seven subsequent return strokes in two lightning flashes at ranges of 7.8 and 8.7 km. The observed light signals exhibited a fast rise to peak followed by a slower decrease to a relatively constant value. The amplitude of the initial light peak was found to decrease exponentially with height with a decay constant of about 0.6 to 0.8 km. The 20-to-80% risetime of the light signal was between 1 and 4 μs near ground and increased by an additional 1 to 2 μs by the time the return stroke reached the cloud base, a height between 1 and 2 km.

Jordan et al. [1995] performed a similar study for two M components following a subsequent return stroke at a range of 4.9 km. As opposed to the return stroke light pulse whose amplitude and waveshape varied markedly with height, the amplitude and waveshape of one M component light pulse was essentially invariant with height between the cloud base (about 1 km) and ground, while the other M component had a relatively constant light waveshape and had a light amplitude that varied somewhat with height. The two M component light pulses, both occurring within about 0.6 ms of the return stroke pulse, exhibited a more or less symmetrical waveshape with a risetime and falltime of the order of many tens of microseconds. A "two-wave" mechanism for the lightning M component that predicts the observed salient features of the light profiles of this lightning process as well as the observed electric and magnetic fields has been proposed by *Rakov et al.* [1995].

In this paper, which can be considered an extension of the work of *Jordan and Uman* [1983] and *Jordan et al.* [1995], we examine relative light intensity as a function of time and height for three dart-leader/return-stroke sequences. This is the first detailed analysis of the luminosity profiles due to natural-lightning dart leaders.

2. Data

Correlated high-speed photographic and wideband electric field data were obtained for nine subsequent strokes in two negative cloud-to-ground lightning flashes during the summer of 1979 near Tampa, Florida [see *Master et al.*, 1984], and for 14 subsequent strokes in three similar flashes during the

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summer of 1982 in Gainesville, Florida [see *Ganesh et al.*, 1984]. In both experiments, high-speed photographic records were obtained using a Beckman and Whitley 351 streak camera capable of a film writing rate of 0.05 mm/μs. The time resolution of the streak camera was approximately 0.5 μs. The streak photographs were digitized using an Optronics Photomation microdensitometer [*Jordan*, 1990]. All light intensity profiles presented in this study are given in relative light units, while the microdensitometer directly measures "specular" film density. Film calibration from which the specular film density could be related to the incident relative light intensity in relative light units was performed by V. P. Idone of SUNYA. The film showed little sensitivity below 10 relative light units, but the relation between the specular film density and the relative light intensity was approximately linear from 10 to 1000 relative light units. Seven out of nine return strokes in the two Tampa flashes have been previously analyzed by *Jordan and Uman* [1983].

Distances to the lightning channels were in the range from 5 to 9 km, as determined from a combination of multiple-station TV direction-finding and thunder-ranging in 1979 and were estimated from thunder-ranging in 1982. All experiments were performed in daylight. The total number of subsequent strokes with optically detectable leaders was 11 (10 dart leaders and one dart-stepped leader) with five of them, including the dart-stepped leader, being very faint (less than 1 relative light unit), occurring in five flashes that had a total of 23 subsequent strokes. Twelve subsequent leaders (one of which created a new channel to ground) produced electric field signatures but failed to produce luminosity above the daylight background level. Eleven optically detected leaders were previously analyzed by *Jordan et al.* [1992] for the propagation speed versus following return-stroke initial electric field peak and previous interstroke interval, with the propagation speeds being in the range from 5 to 24 m/μs. The brightest three dart-leader/return-stroke sequences, occurring in two flashes, are used here for the analysis of luminosity as a function of time and height. Characteristics of those three are given in Table 1.

3. Results

Streak-camera images and the corresponding relative light intensity waveforms at different heights along the channel (for the entire visible channel and for the bottom 480 m) for three dart leader/return stroke sequences are presented in Figures 1, 2, and 3.

As seen in Figures 1b, 1c, 2b, 2c, 3b, and 3c, the dart-leader light waveforms appear as sharp pulses with 20-to-80% risetimes of 0.5-1 μs and widths of 2-6 μs. The widths were measured between the point of initial deflection of the dart-leader light pulse from background and the point where the light pulse tail becomes indistinguishable from the following more or less constant light level (plateau). The plateau continues until it is overridden by the return-stroke light waveform, suggesting that a steady leader current flows through each channel section behind the downward moving leader tip before, and perhaps for some time after, the return-stroke front has passed that channel section. There is a tendency, although weak, for the dart-leader light plateau to be higher as the leader tip approaches ground. Return strokes exhibit wider light waveforms than dart leaders with 20-to-80% risetimes near ground of about 1-2 μs and with appreciably slower decay. The return-stroke light pulse amplitudes near ground are a factor of 2-3 greater than those of the dart leaders (see Figures 1c, 2c, and 3c). There is a significant difference between return strokes and dart leaders in terms of the variation of luminosity along the channel: the 20-to-80% risetime of the return-stroke light pulses increases from 1.5 to 4.0 μs (mean values), while the pulse peak decays as the return-stroke front propagates from ground to the cloud base at about 1.4 km, to 25-30% of the initial value in two out of three cases (see Figures 1b and 3b) and to about 70% of the initial value in the third case (see Figure 2b). On the other hand, the risetime of the dart-leader light pulses is essentially constant with height, and the pulse peak is either more or less constant or increases as the leader front approaches ground. Note that (1) events shown in Figures 2 and 3 occurred in the same channel, (2) the return stroke in Figure 2, which exhibits relatively little luminosity decay with height, has the lowest luminosity peak of the three strokes at the bottom of the channel and the lowest electric field peak normalized to 100 km (5.9 V/m compared to 6.8 V/m and 6.5 V/m for the return strokes in Figures 1 and 3, respectively, that show a stronger luminosity decay with height), and (3) the lower luminosity attenuation return stroke in Figure 2 is preceded by an apparently more energetic dart leader (compare Figure 2a to Figures 1a and 3a).

4. Discussion

In the following, we first discuss the relative magnitudes of the light pulses associated with dart leaders and the corresponding return strokes. Then we discuss the characteristics of the dart-leader and return-stroke waves as inferred from the luminosity profiles.

4.1. Relative light intensity of dart leaders and return strokes

Guo and Krider [1985], using an all-azimuth, 20° vertical field-of-view optical system coupled to a silicon photodiode

Table 1. Characteristics of Three Dart-Leader/Return-Stroke Sequences Presented in Figures 1, 2, and 3

Storm	Time	Distance, km	Stroke Order	E_p, V/m	Previous Interstroke Interval, ms	Leader Duration, μs	Leader Speed, m/μs
79208	2246:45 UT	8.8	3	6.8	30	220	17
82222	1445:35 EDT	5.3	2	5.9	44	150	16
			3	6.5	31	360	18

E_p is the return-stroke initial electric field peak normalized to 100 km.

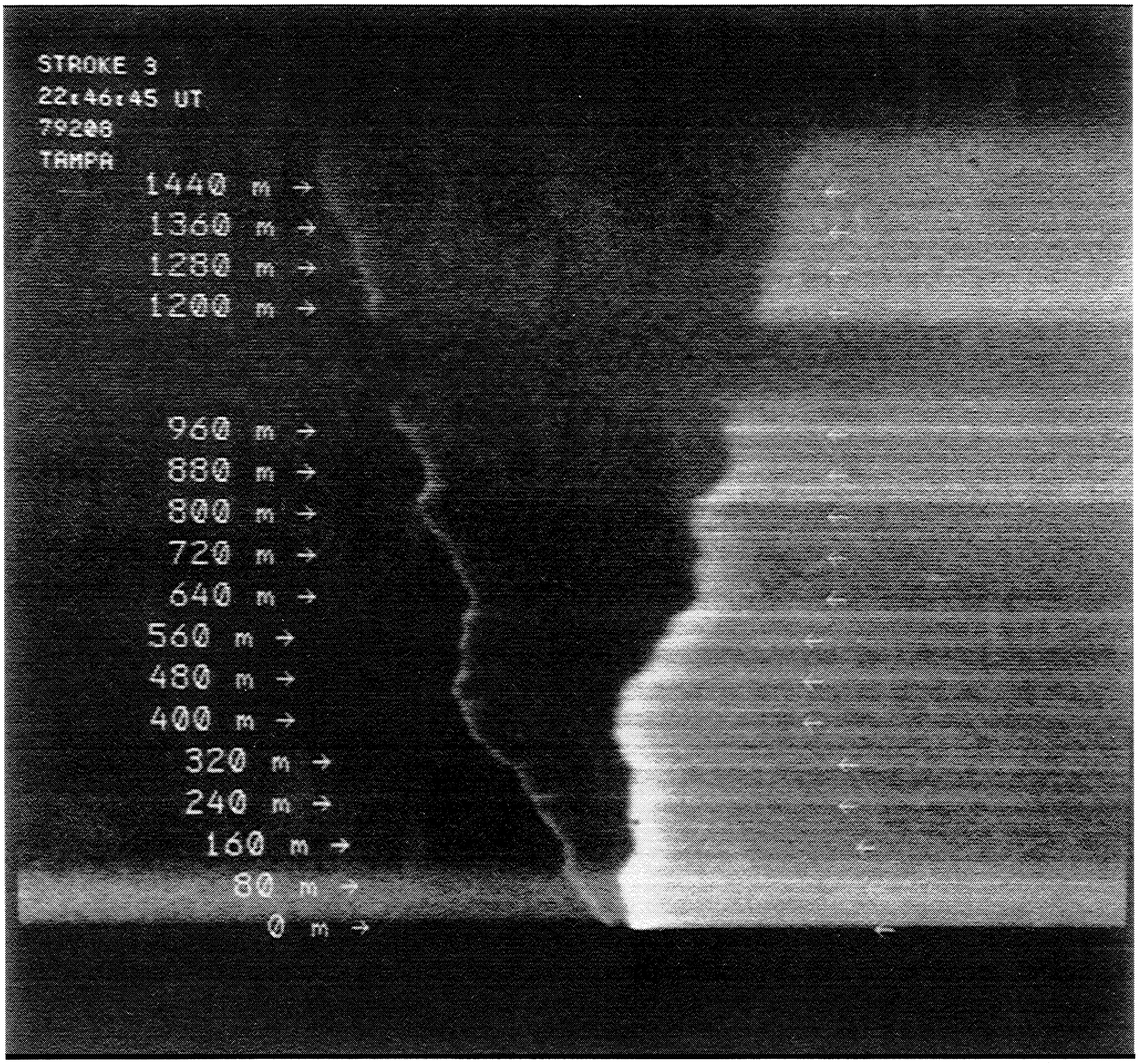

Figure 1a. Streak photograph of stroke 3 in a flash that occurred near Tampa, Florida, at 2246:45 UT on July 27, 1979. Negatively sloped image on the left is due to dart leader, and positively sloped, brighter image on the right is due to return stroke. The zero level here and in the following figures corresponds to the lower end of the visible channel.

(0.4- to 1.1-μm spectral bandwidth), found that 39 of 726 multiple-stroke flashes (about 5%) observed at the NASA Kennedy Space Center in Florida had one or more dart leaders whose peak light output per unit length was comparable to that of the following return stroke. On the other hand, *Idone and Orville* [1985] reported from their streak-photographic study of 22 strokes in two triggered lightning flashes (artificially initiated using the rocket-and-wire technique) that the ratio of maximum light output from a dart leader to the following return stroke varied from 0.02 to 0.23, with a mean of 0.1. In one example of dart-leader/return-stroke luminosity profiles given by *Wang et al.* [1995, Figure 3] the ratio of leader to return stroke light peaks is less than 0.08. Further, *Orville* [1975], from spectroscopic measurements, found dart leaders to be about a factor of 8-9 less intense in their peak radiation than the return stroke, both being viewed in a 13-m channel section. In the three dart-leader/return-stroke sequences analyzed in this paper, the ratio of leader to return-stroke luminosity peaks is about 0.3 to 0.5, as observed within the bottom 480 m of the channel (see Figures 1c, 2c, and 3c). It is likely that our daylight sample is biased toward brighter dart leaders and a lesser difference between the luminosity of leaders and return strokes. Evidence for this latter view is found in the work by *Idone and Orville* [1985], who inferred dart-leader peak currents in 22 triggered-lightning strokes using two different optical techniques: the ratio of the inferred dart-leader current to measured return-stroke current varied from 0.03 to 0.3, with the largest ratios being associated with the largest return-stroke currents and relative light intensities. Thus the three dart-leader/return-stroke sequences analyzed here are probably of

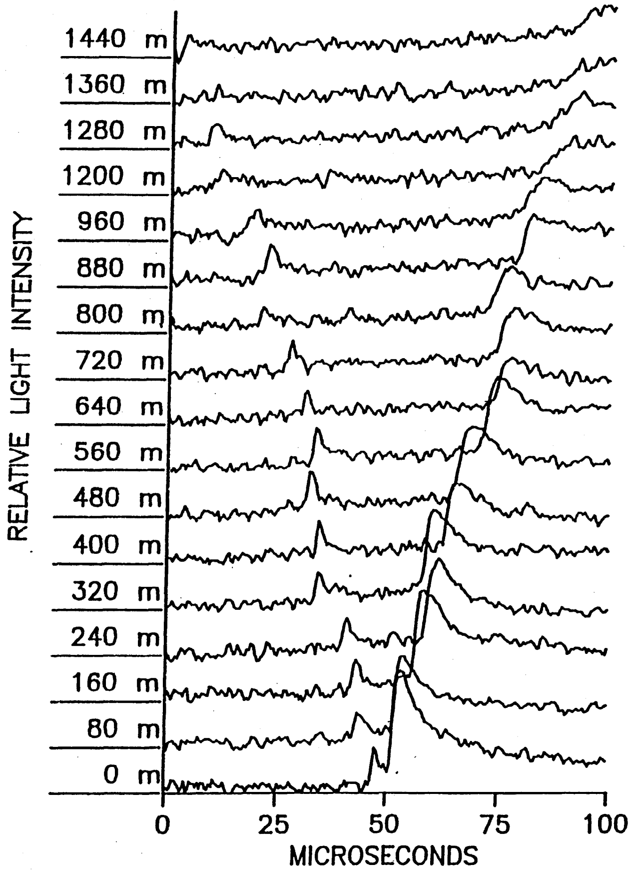

Figure 1b. Luminosity versus time at different heights above ground corresponding to the streak photograph in Figure 1a.

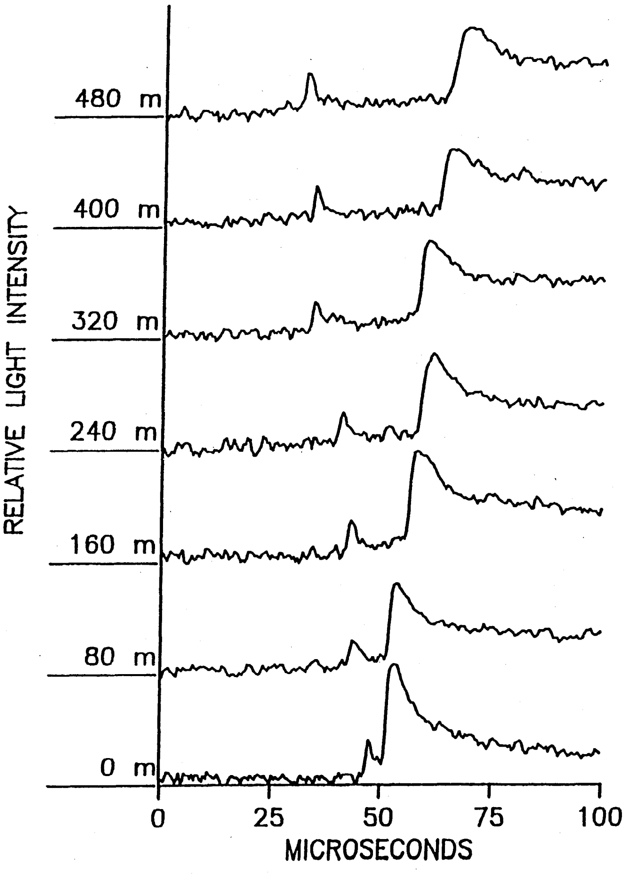

Figure 1c. Same as Figure 1b, but for the bottom 480 m of the channel only.

higher than average intensity, consistent with the fact that distance-normalized (to 100 km) subsequent return-stroke initial electric field peaks (related to return-stroke current peaks) for these three events, 6.8 V/m, 5.9 V/m, and 6.5 V/m, are more than a factor of 2 greater than the typical value of 2.7 V/m [*Rakov et al.*, 1994] for subsequent strokes following a previously formed channel.

4.2. Characteristics of the dart-leader wave

Assuming that the dart-leader current wave propagates at a constant speed v_{DL} down the essentially vertical channel and preserves its amplitude and shape, the following relation between the length Δz of the front of a spatial current wave and the risetime Δt of the corresponding temporal wave applies [e.g., *Uman*, 1987]:

$$\Delta z = v_{DL} \, \Delta t \tag{1}$$

Our observed 20-to-80% risetime of the dart-leader light pulses is about 0.5-1 μs. *Wang et al.* [1995, Table 2] reported risetime values (apparently 10-to-90%) ranging from 1.2 to 1.8 μs for seven dart leaders terminating on the 553 m high tower in Toronto, and *Cooray et al.* [1989] reported a mean zero-to-peak value of 2.9 μs and 20-to-80% value of 1.5 μs, measured at 200 to 300 m above the channel base, for 15 dart leaders in two triggered lightning flashes in New Mexico. *Cooray et al.* [1989] reported that the risetime of optical dart-leader pulses does not change significantly within the bottom 800 m or so of the channel, consistent with our data. The measured propagation speeds for subsequent leaders in this study (11 values) are in the range from about 5 to 24 m/μs [see *Jordan et al.*, 1992, Table 1] (7 to 23 m/μs in Wang et al.'s data). Assuming that the front durations for current and voltage waves are of the same order of magnitude as the front durations of the light pulses and using v_{DL} = 15 m/μs, we estimate that the front length for dart leaders is about 7.5-15 m. Such a relatively short (compared to kilometers for the lightning M component [*Rakov et al.*, 1995, Figure 3a] and hundreds of meters for the return stroke, as discussed below) front and its associated high electric field are apparently necessary to facilitate electrical breakdown (via electron impact ionization; that is, via collisions of electrons accelerated in the front electric field with atoms, ions, and molecules) in the warm air at the leader front. In order to estimate crudely the potential difference V across the dart-leader front within the bottom kilometer or so, we assume that the potential V of the channel behind the front is constant and determined by the average line charge density ρ on the lower channel and by the average capacitance per unit length C of the lower channel, $V = \rho/C$. Assuming ρ = 60 μC/m [*Rubinstein et al.*, 1995] and C = 4 pF/m [*Rakov et al.*, 1995], we obtain V = 15 MV. We further assume that the voltage drop due to current that might flow along the lightning channel ahead of the leader front is negligible compared to the potential V. Indeed, for a channel having temperature 3000°K, radius 2 cm and carrying a current less than 0.1 A [*McCann*, 1944], this voltage drop at 1 km above ground is expected to be less than 1 MV, decreasing with decreasing height. For the 15-MV potential difference across the 7.5-15 m front the average electric field intensity would be (1-2)x10^6 V/m or 10-20 kV/cm, more than sufficient for the breakdown of the warm, low-density air composing the pre-dart-leader channel [*Uman and Voshall*, 1968]. The air

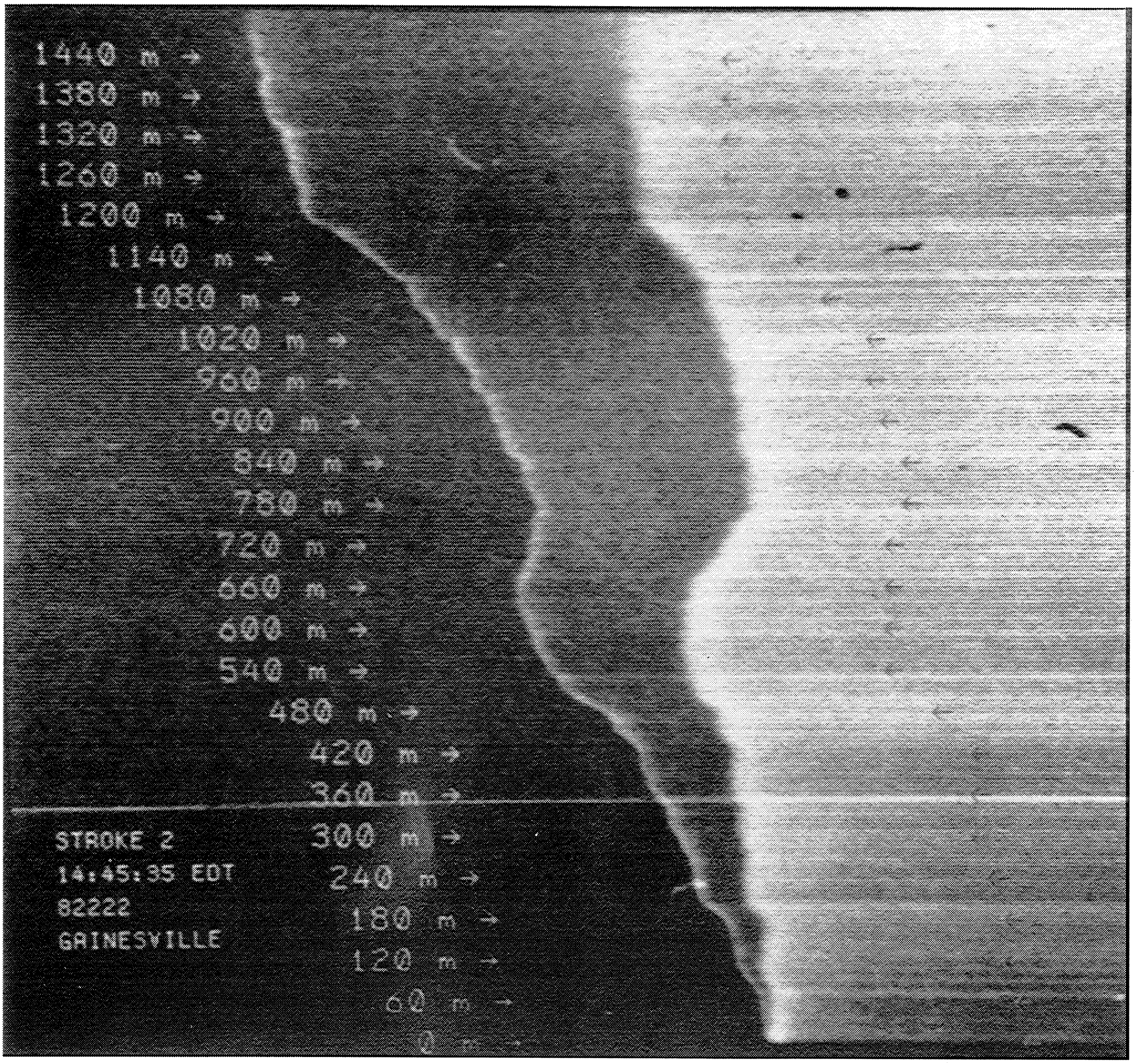

Figure 2a. Streak photograph of stroke 2 in a flash that occurred in Gainesville, Florida, at 1445:35 EDT on August 10, 1982. See also comments in caption of Figure 1a.

breakdown field at standard pressure and temperature is about $3x10^6$ V/m or 30 kV/cm and varies inversely with temperature at constant pressure. In an earlier estimate of dart-leader wavefront length, *Uman* [1969] inferred from theoretical considerations that this length is less than a meter in extent, an order of magnitude smaller value than given above. *Uman's* [1969] estimate of the dart-leader wavefront length is probably incorrect, since it would require, according to equation (1), the risetime of the corresponding temporal wave to be less than 70 ns, apparently inconsistent with the observed risetimes of the leader light pulses. It is likely that the propagation speed of the dart-leader front is lower than the speed of the portion of the dart-leader wave behind the front because this trailing portion of the dart-leader wave propagates in a region of increased electric conductivity left behind by the processes at the moving front. As a result, charge piles up at the leader tip, maintaining the sharper front needed for sustained local breakdown, which in turn, facilitates further leader propagation. One can view the lack of degradation of the dart-leader wavefront as being due to the dart-leader current's being generated at the downward moving front and propagating upward, rather than propagating downward from the cloud charge source, a model also discussed by *Bazelyan* [1995], *Cooray* [1996], and *Thottappillil et al.* [1997].

If the luminosity, instead of being related to the current as discussed above, were related to the power dissipated per unit length of the channel, the front duration of the light pulses would be shorter than that of the corresponding current waves, and the total width of the light pulses of 2-6 μs might be a better basis for estimation of the front length for the spatial current and voltage waves. In the latter case, the front length would be 30 to 90 m, if the same value of v_{DL} = 15 m/μs were used. Assuming an average value of 60 m, we obtain an electric field intensity across the dart-leader front of 2.5 x 10^5 V/m or 2.5 kV/cm, which still might be sufficient for electron-impact breakdown in the pre-dart-leader channel. *Orville and Idone* [1982] give a "dart leader length", a characteristic that is similar to the dart-leader front length which we just derived

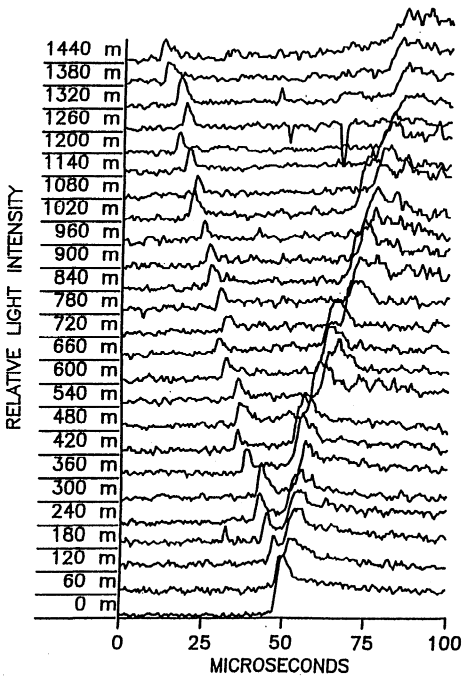

Figure 2b. Luminosity versus time at different heights above ground corresponding to the streak photograph in Figure 2a.

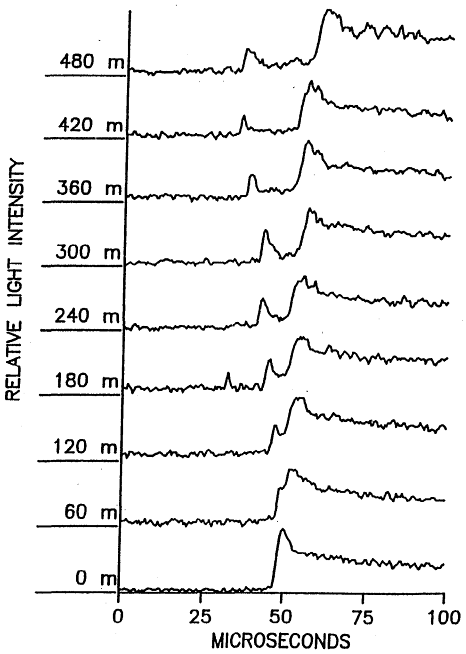

Figure 2c. Same as Figure 2b, but for the bottom 480 m of the channel only.

based on the total width of light pulses. They obtained the "dart-leader length" by multiplying the total width of the dart-leader track on their streak photographs by the measured dart-leader speed. The average dart-leader length was reported by Orville and Idone to be 34 m with a range of 7-75 m (to be compared with our range of 30-90 m). Similar measurements of *Schonland and Collens* [1934] yielded an average of 54 m with a range of 25 to 112 m (as given by *Orville and Idone* [1982]), and *Schonland* [1956] reported a typical value of 40 m.

4.3. Characteristics of the return-stroke wave

In a way similar to that used above for dart leaders, that is, from equation (1) with v_{DL} replaced by the typical return-stroke front speed of 150 m/μs [e.g., *Uman*, 1987] and assuming Δt = 1-2 μs (the 20-to-80% risetime of return-stroke light pulses near ground; see above), we can estimate the length of the front of the return-stroke spatial wave near ground to be about 150-300 m, at least an order of magnitude greater than the 7.5-15 m obtained for the dart-leader wave. If the return-stroke front is characterized by approximately the same electric potential difference as the leader front, 15 MV (leader potential ahead of the return-stroke front and near zero potential behind the front), the average electric field intensity across the return-stroke front will be 5 x 10^4-10^5 V/m or 0.5-1 kV/cm. At such relatively low fields, further ionization at the return-stroke front is only possible because of the relatively high temperature, 20,000°K or more [*Orville*, 1975], and the correspondingly low particle density of the dart-leader channel into which the return-stroke front propagates.

It is worth noting that there is little variation of the light-pulse peak within the bottom 400-500 m or so (see Figures 1c, 2c, and 3c) for the three return strokes whose luminosity profiles are considered here, perhaps due to relatively short (a few tens of microseconds or less) time interval between the leader and return-stroke waves. The decrease of the light-pulse peak does occur (see section 3 above) but predominantly in the higher channel sections. Assuming the exponential decay height of 0.6-0.8 km determined by *Jordan and Uman* [1983], we estimate a luminosity peak decrease to 45-55% of the original value at 480 m, while *Schonland* [1956] reported that the decrease of subsequent, as opposed to first, return-stroke luminosity with height is "not very marked." More time-resolved optical records are needed to deduce the typical (statistically reliable) variation of return-stroke luminosity with height.

5. Summary

The first detailed characterization of the luminosity profiles due to the natural-lightning dart leader is presented. Dart-leader light waveforms appear as sharp pulses with 20-to-80% risetimes of about 0.5-1 μs and widths of 2-6 μs followed by a more or less constant light level (plateau). The plateau continues until it is overridden by the return-stroke light waveform, suggesting that a steady leader current flows through any channel section behind the downward moving leader tip before, and perhaps for some time after, the return-stroke front has passed that channel section. Return-stroke light waveforms near ground exhibit 20-to-80% risetimes of about 1-2 μs, appreciably longer than the dart-leader light waveforms. The amplitudes of the return-stroke light pulses near ground are a factor of 2 to 3 greater than those of the dart-leader light pulses, a relatively low ratio, which is possibly indicative of a bias toward the higher-intensity events. There is a significant difference between return strokes and dart leaders in terms of the variation of luminosity along the channel: the 20-to-80% risetime of the return-stroke light pulses increases and the pulse peak decays as the return-stroke front propagates from ground to the cloud base at about 1.4 km, whereas the risetime of the dart-leader light pulses is essentially constant with height, and the pulse peak is either more or less constant or increases as the leader front approaches ground. The average electric field intensity across a dart-leader front having a length of the order of 10 m is inferred to be at least an order of magnitude higher, about 10-20 kV/cm, than the average electric field intensity, about 0.5-1 kV/cm, across the return-stroke front having a length of the order of 100 m.

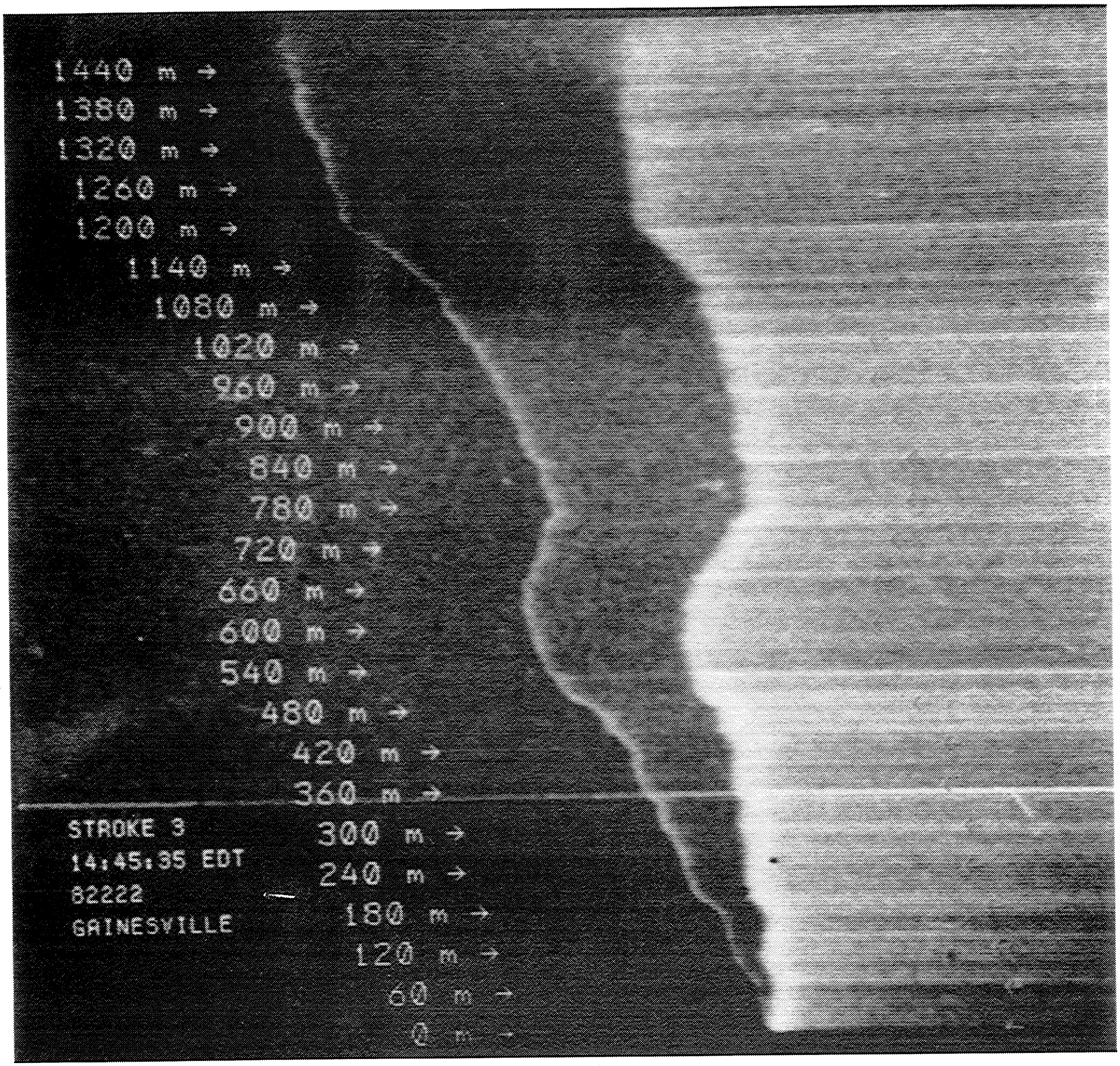

Figure 3a. Streak photograph of stroke 3 in the flash whose stroke 2 is presented in Figure 2. See also comments in caption of Figure 1a.

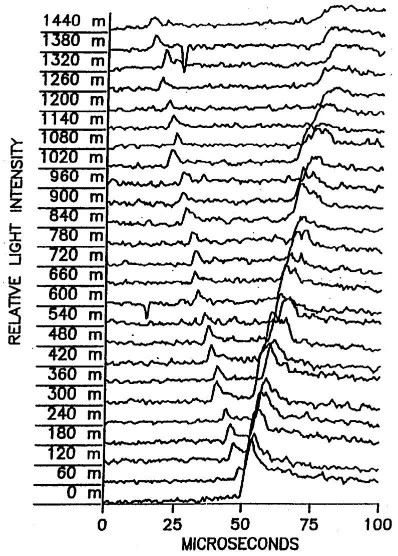

Figure 3b. Luminosity versus time at different heights above ground corresponding to the streak photograph in Figure 3a.

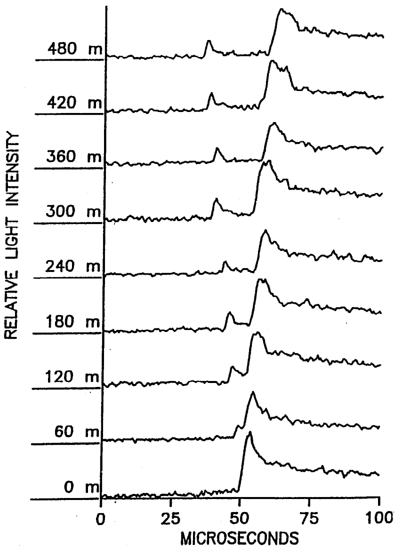

Figure 3c. Same as Figure 3b, but for the bottom 480 m of the channel only.

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