Resolution of the sprite polarity paradox: The role of halos

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[1] This study revisits the sprite polarity paradox, first manifest by observations that exceptional cloud-to-ground flashes with negative polarity generally did not produce detectable sprites. The paradox is here resolved by the Transient Luminous Event (TLE) known as the halo, which on account of its inferior brightness (0.3 MR versus 1.5 MR) and substantially shorter duration (1 ms versus 10–100 ms) in comparison with the sprite, is not readily detectable in ground-based video cameras with standard field duration (16.7–20 ms). Observations with improved temporal resolution (ISUAL (Imager of Sprites and Upper Atmospheric Lightnings) from space and PIPER (Photometric Imager of Precipitated Electron Radiation) observations from the ground) provide evidence that flashes with negative polarity dominate the global halo population, and that the halo numbers are more than sufficient to account for the previously missing TLEs. The evidence for lightning polarity-dependent TLEs (sprites, positive and halos, negative) is attributable to the well established but incompletely understood contrast in the behavior of negative and positive lightning flashes to ground.

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1. Introduction

[2] *Wilson* [1925] first suggested that dielectric breakdown in the mesosphere might accompany superlative lightning flashes in the troposphere. The transient luminous events (TLEs) resulting from this quasi-electrostatic process are now recognized as sprites [*Sentman and Wescott*, 1993; *Lyons*, 1994]. Wilson's prediction for sprite initiation is independent of the polarity of the parent lightning, so the observations that the great majority of sprites are caused by ground flashes (CGs) with positive polarity presented a paradox [*Williams*, 2001; *Williams et al.*, 2007]. Negative ground flashes typically outnumber positive ones by 10 to 1, but of the tens of thousands of field observations of sprites, only a few sprites have been unambiguously linked with negative ground flashes [*Barrington-Leigh and Inan*, 1999; *Taylor et al.*, 2008; *Lyons et al.*, 2010].

[3] The main physical criterion for sprite initiation following *Wilson* [1925] is the vertical charge moment change of the parent lightning flash. One possible explanation for the pronounced polarity asymmetry is simply that supercritical positive charge moments are abundant whereas like quantities with negative polarity are not. Measurements of lightning charge moments worldwide [*Williams et al.*, 2007] with Schumann resonance methods, and region-by-region [*Cummer and Lyons*, 2004, 2005; *Lyons et al.*, 2009], do show a dominance of supercritical events with positive polarity, yet a substantial fraction (roughly 10%) of all supercritical charge moments show negative polarity. *Williams et al.* [2007] identified the dramatic contrast between the relative numbers of negative sprites one expects and the number observed in numerous ground-based video camera observations as the sprite polarity paradox.

[4] The halo, a category of TLE (Transient Luminous Event) distinct from sprite [*Barrington-Leigh*, 2000; *Barrington-Leigh et al.*, 2001], was tentatively suggested as the resolution of this paradox [*Williams et al.*, 2007], by providing a TLE response to supercritical charge moments of negative polarity. Earlier suggestions that halos might play this role came with the initial discovery of the phenomenon by *Barrington-Leigh et al.* [2001] with their two key findings: (1) "occurrence of sprite halos … is not unusual in association with –CGs" [*Barrington-Leigh et al.*, 2001, p. 1750] and (2) "many of these events may be invisible when integrated on 17-ms video field…" [*Barrington-Leigh et al.*, 2001, p. 1749]. *Bering et al.* [2002b], *Bering et al.*

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[2004a, 2004b] and *Bhusal et al.* [2004] subsequently linked halos with negative CGs in optical observations from stratospheric balloons. Yet in contrast, more recent observations since the publication of *Williams et al.* [2007] using ground-based video cameras with standard frame-rate in the European sprites campaign report an abundance of sprites, but no halos [*Neubert et al.*, 2008].

[5] New observations from space with the ISUAL satellite [*Hsu et al.*, 2008], with a view of TLEs in the Earth's limb, and observations from the ground with a sensitive photometer array [*Newsome and Inan*, 2010] with exceptional time resolution (80 μs), together provide a valuable new perspective on the sprite polarity paradox. The percentages of electrostatically induced TLEs (sprites and halos) in the halo category show considerably greater consistency with the bipolar distributions of vertical charge moment than the earlier ground-based TLE observations. This study is concerned with a closer look at the characteristics of the lightning flashes responsible for halos, and the polarity asymmetry between positive and negative ground flashes that can account for polarity-dependent TLE forms. The new observations are interpreted in comparison with recent theoretical developments on halo formation [*Hiraki and Fukunishi*, 2006; *Adachi et al.*, 2008; *Luque and Ebert*, 2009; *Hiraki*, 2010]. In the latter work of *Hiraki* [2010], the halo phenomenon is treated as a phase transition.

[6] This paper is organized into sections that treat various observations chosen to understand the apparent paradox and its resolution. Section 2 is concerned with ISUAL satellite observations and the global capture of halo events that are the targets for the ELF observations in section 3. Simultaneous ground-based observations of halos with standard frame-rate camera and high-speed photometer (PIPER) are the subject for section 4. Distinct differences in the behavior of positive and negative lightning flashes are documented in section 5 on the basis of millisecond-resolution video camera observations. An extensive discussion section (section 5) is followed by conclusions (section 6).

2. Halo Observations With the ISUAL Satellite

[7] FORMOSAT-2 (FS-2) is the first satellite that features a payload mission to survey the transient luminous events (TLEs) in the upper atmosphere. The ISUAL (Imager of Sprites and Upper Atmospheric Lightnings) payload on FORMOSAT-2 consists of three sensor packages including an intensified CCD imager (Imager), a spectrophotometer (SP) and a dual-band array photometer (AP). For the TLE events reported in this paper, the imager data were recorded through the 623–750 nm $1PN_2$ filter and with an image frame integration time of 14 / 29 ms. The ISUAL SP consists of six band pass–filtered PMTs that cover the major emission bands of molecular nitrogen. The band pass selections are SP1 (150–290 nm; FUV; N_2 LBH band), SP2 (centered at 337 nm with a bandwidth 5.6 nm; for $2PN_2$ (0–0)), SP3 (centered at 391.4 nm with a bandwidth 4.2 nm; for $1NN_2$+ (0–0)), SP4 (608.9–753.4 nm; for $1PN_2$ band), SP5 (centered at 777.4 nm; for lightning OI emission) and SP6 (228.2–410.2 nm; for $2PN_2$ band). The ISUAL AP includes a blue (370–450 nm) and a red (530–650 nm) arrays; each has 16 vertically stacked PMTs that provide temporal and spatial variations of emissions along the vertical direction.

[8] The ISUAL imager, SP and AP are all co-aligned at the center of their views. The ISUAL imager and SP have the same field-of-view (FOV) of 20 deg (horizontal) $\times$ 5 deg (vertical). Each channel of AP has a FOV of 22.6 $\times$ 0.23 degree. The FOV of combined 16 channels in each AP module is 22 deg (H) $\times$ 3.6 deg (V). On trigger, the ISUAL imager snaps six frames of images (1 frame before the trigger and 5 frames after), SP samples at a constant rate of 10 kHz for 205 ms and the AP samples at a rate of 20 kHz for the first 20 ms then slows down to 2 kHz for a total length of 240 ms.

[9] The FORMOSAT-2 satellite was launched in May 2004. In the first five-year survey, more than 10,000 TLEs (sprites, halos, elves, gigantic jet and blue jets) were recorded by ISUAL. Elves are found to be the most abundant type ($\sim$80%) of TLEs, whereas sprites and halos only contribute $\sim$20% [*Su et al.*, 2005; *Chen et al.*, 2008; *Hsu et al.*, 2008].

[10] The ISUAL is designed for limb view geometry [*Chern et al.*, 2003; *Mende et al.*, 2005]. Another advantage to limb view for ISUAL instruments is the edge-on view of TLEs. For the sideway view of pancake-like halos and donut-shaped elves, the integrated emission across the optical path length of the TLE events is longer than other viewing angles of TLE events. The enhanced brightness of these edge-on TLE events increases the ISUAL detection for TLE events, especially for the nearly transparent space environment.

[11] From 2004 to 2007, ISUAL recorded a total of 214 halos. Their geographical locations, their brightnesses, and the optical behavior of their parent lightning flashes, all products of the ISUAL satellite, are an important contribution to the present study.

[12] Recently, a strong correlation was found between the 777.4-nm brightness and vertical current moment waveform for sprite-producing lightning [*Adachi et al.*, 2009]. This finding enables us to derive lightning current/charge moment change through optical measurements. Here we report the time-resolved (with 100 μs resolution) optical behavior of lightning that is verified in ISUAL observations to produce pure haloes, pure sprites, or a combination of a halo and sprite (a 'sprite halo'), respectively. We analyzed 85 events observed by ISUAL during the period from July 2004 to November 2005. The results are shown in Figure 1. Out of 85 events, 24 events were pure halos (shown in blue), 22 events were pure sprites (shown in green), and 39 events were combinations of the two ('halo-sprites', shown in red). These events were selected using the condition that the peak lightning emission intensity was higher than the background noise by at least a factor of 3. Detailed characteristics in each classification were reported by *Adachi et al.* [2008]. Figure 1 shows composited lightning optical waveforms, color-coded for each of three TLE categories. Here, we set t = 0 at the beginning of each event when the signal first exceeds three standard deviations of the background noise. For quantitative comparisons, the absolute luminosity was derived by correcting the atmospheric transmittance with the MODTRAN-4 model [*Anderson et al.*, 2000], applying the instrumental functions, and normalizing to a source-observer

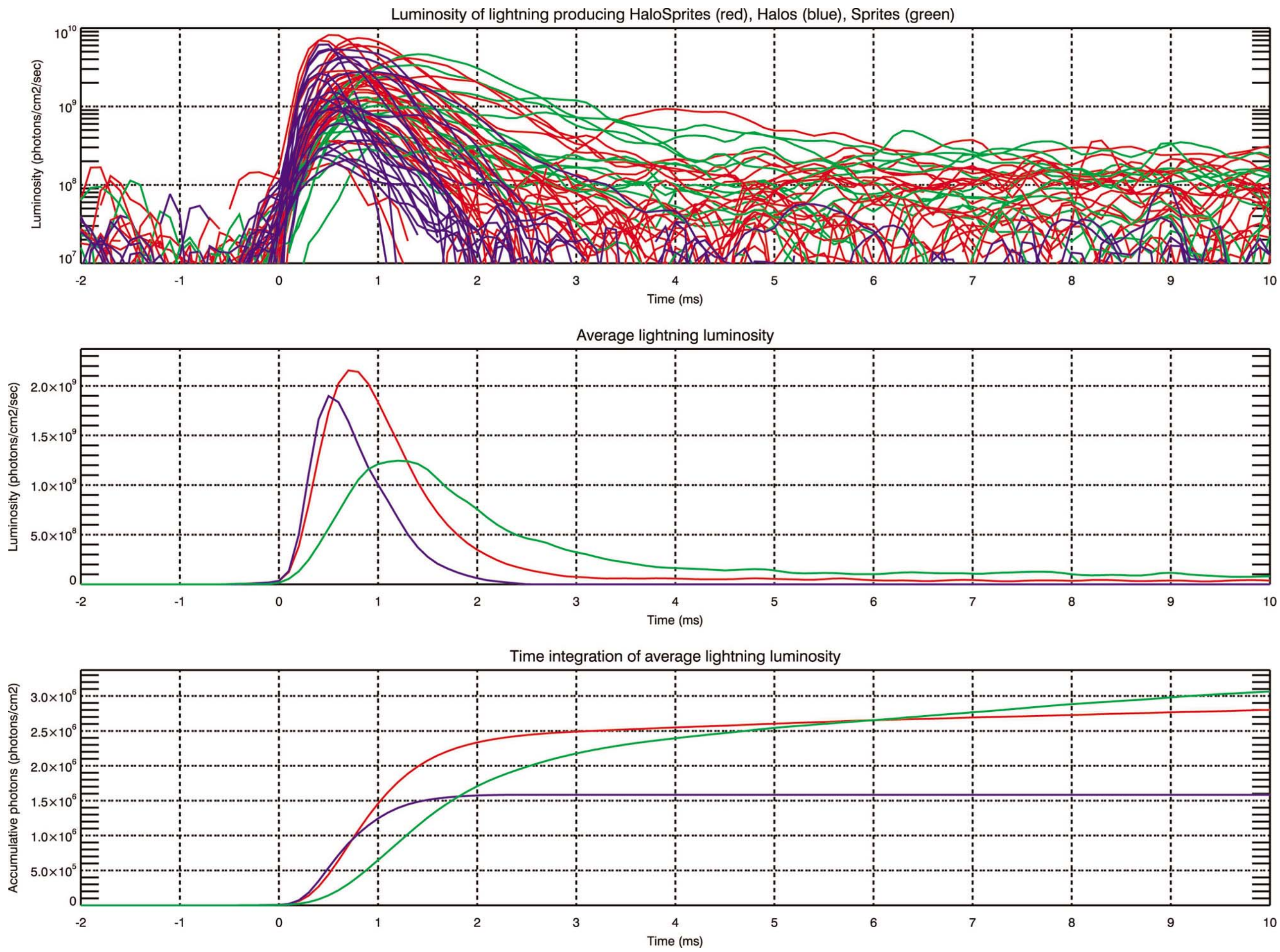

Figure 1. Waveforms of optical emission from parent lightnings for halo (blue), sprite (green), and sprite halo (red), as recorded on the ISUAL satellite.

distance of 3000 km. Also note here that we reduced instrumental noise using an effective filter with 0.4 ms Hamming window.

[13] Strictly speaking, the optical emission observed by ISUAL is scattered light originated from both cloud-to-ground and intracloud components of lightning. *Adachi et al.* [2009] showed a few outlying cases which indicated possible significant contributions of intracloud lightning components. However, because they also found that those events had a distinctive feature of two bright cores of lightning in the ISUAL imagery, we excluded such events from our analysis in the present study. Therefore, considering the fact that most ordinary lightning events had extremely good correlation between optical intensity and vertical current moment [*Adachi et al.*, 2009], we conclude that the results in Figure 1 are reliable indicators of the current/charge moment behavior of cloud-to-ground lightning.

[14] Despite the possibility that the parent lightning return stroke durations are broadened by multiple scattering in intervening cloud, a clear ordering of behavior is apparent. The shortest lightning waveform in Figure 1 is associated with the halo, the longest with the sprite, and the intermediate situation with the sprite halo. This finding is consistent with later results to be shown in this study, and with published results [*Hiraki and Fukunishi*, 2006; *Adachi et al.*, 2008] that lightning forcing for halos is more impulsive than for sprites.

3. ELF Global Observations of Halo-Producing Lightning From Nagycenk Observatory, Hungary

[15] The polarity and charge moment change of a lightning flash can be determined by analyzing its radio wave emission in the ELF (Extremely Low Frequency, 3 Hz – 3 kHz) band. Since the attenuation of EM waves is small in the Earth-ionosphere cavity at lower ELF frequencies [*Burke and Jones*, 1992], signals from powerful lightning discharges can be detected globally even from a single ELF observation station [*Huang et al.*, 1999; *Hobara et al.*, 2006; *Williams et al.*, 2010]. The polarity of the source discharge can be found by the direction of the field jump in the vertical electric component at the onset of the event. The charge moment change (CMC) during the lightning flash is estimated from the current moment spectrum of the source. The current moment spectrum is deduced by comparing the measured electric or magnetic field spectrum of the emission to the expected spectrum of a unit current impulse placed in the location of the source. The spectrum of a unit current

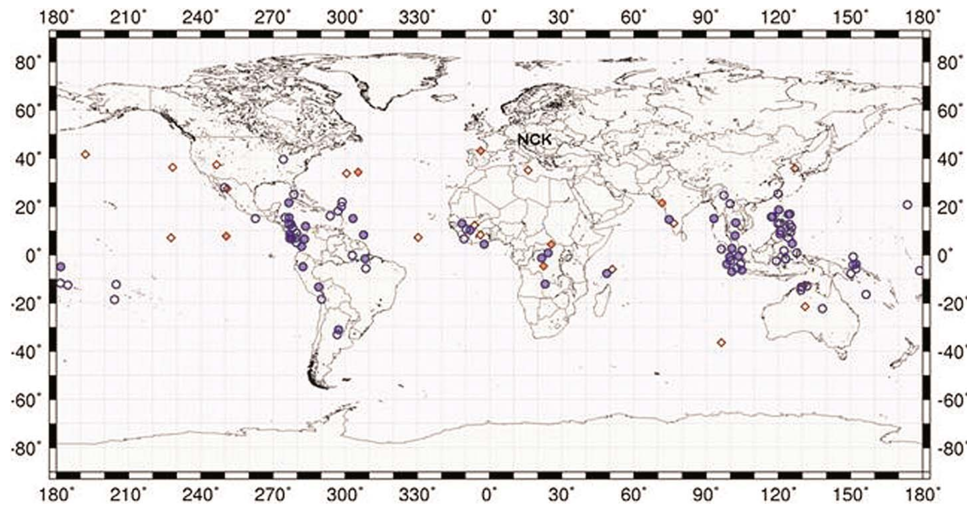

Figure 2. Global map of halo events observed by the ISUAL satellite and whose parent lightning flashes have been identified in Nagycenk ELF observations at Nagycenk Observatory (Hungary), and organized by polarity of the parent lightning. Red symbols represent positive events and blue symbols negative events. Shaded symbols correspond to cases for which the CMC of the source lightning flash could be estimated.

impulse is calculated utilizing the cavity propagation models of *Wait* [1964] and *Ishaq and Jones* [1977]. Details of the method of deducing the CMC estimation can be found in work by *Huang et al.* [1999].

[16] Time series of the vertical electric field and the horizontal magnetic field recorded at Nagycenk Observatory, Hungary (NCK; 47.62°N, 16.72°E, 513.8 Hz sampling rate, 5–30 Hz passband [*Sátori et al.*, 1996; *Sátori*, 2007]) have been searched for ELF transients corresponding to185 'pure' halos (with no evidence of sprite streamers) detected by the ISUAL satellite between 2004 and 2007. ELF transients in 121 cases could be found unambiguously by matching the onset times with the observation time of the halo. The polarity of the parent flash was positive in 23 cases and negative in 98 cases. The dominance of negative polarity is consistent with earlier studies with ISUAL observations by *Frey et al.* [2007]. A global map showing the locations of these events and the symbol-coded polarity of the parent lightning flash is shown in Figure 2. The tendency for events to cluster in the three major tropical zones (Americas, Africa and Maritime Continent) is readily apparent, though when examined more closely, the majority of these events are over water.

[17] Generally the ELF signal amplitudes from these events were comparable with the level of background noise. This is why stable CMC estimation was possible for only 46 events: for 7 positives and for 39 negatives. The histogram of CMC values is shown in Figure 3. CMCs have been evaluated by fitting an exponential current model to the current moment spectrum deduced from the vertical electric field component in which the noise level was lower. CMCs deduced from time series which were recorded under locally different (daytime/nighttime) ionospheric conditions, differ by ~20% [*Ádám et al.*, 2009, p. 289]. CMCs deduced from ELF signals recorded at nighttime at NCK have been scaled up by a factor of 1.2 to be consistent with values from daytime records, because the model for the impulse response of the Earth-ionosphere cavity assumes daytime conditions. Figure 4 shows the ISUAL-measured brightness versus the ELF-measured CMC for all events. Despite considerable scatter, a general tendency for brightness to increase with CMC is apparent.

4. Ground-Based Observations of Halos

[18] Halo detections with conventional frame-rate video cameras (with 16.7 ms resolution) is an infrequent phenomenon relative to sprites (see Table 2), but the available observations have shown an overwhelming prevalence of parent lightning with positive polarity. For example, unpublished observations in 2006 by M. Taylor and D. Pautet from Brazil with particularly sensitive cameras have shown 21 halos and at Yucca Ridge in Ft. Collins, Colorado 38 haloes, and all were linked with positive flashes identified by the National Lightning Detection Network (NLDN)

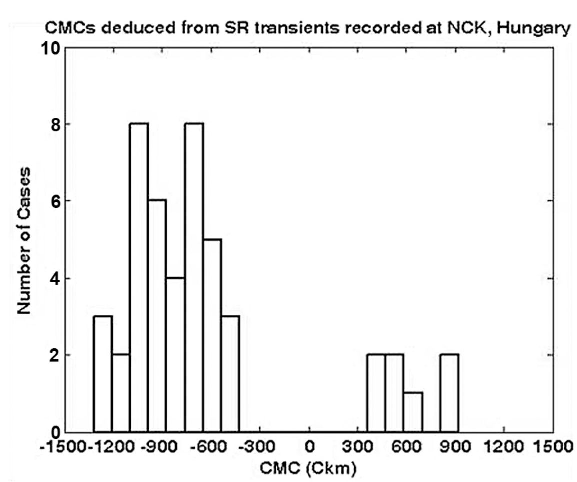

Figure 3. Histogram of ELF-measured charge moments for halo events identified by the ISUAL satellite.

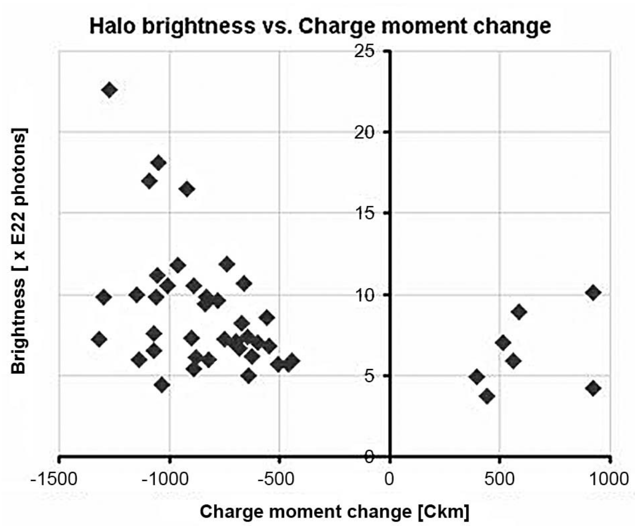

Figure 4. Halo brightness versus charge moment change for the parent lightning, for all halo events identified in ELF observations at Nagycenk Observatory in Hungary.

Table 1. Summary of Findings With High-Speed Photometer (PIPER) for Four Storms Over Land[a]

Event Counts or Ratios	Description
166 events	halo events detected with PIPER
74 events	with CG flashes with positive polarity
92 events	with CG flashes with negative polarity
27/74	‘positive’ halos detected with standard frame-rate video camera
1/92	‘negative halos’ detected with standard frame-rate video camera
20/74	‘positive halos’ accompanied by sprites (as sprite halos)
0/92	‘negative halos’ accompanied by sprites (as sprite halos)

[a]All halo events were accompanied by elves in high-speed photometer observations.

[*Bailey*, 2010, chapter 5]. In later observations in Argentina, 61 haloes were observed with only 6 of these caused by lightning with negative polarity. Other observations with standard frame rate camera in central Europe [*Bór et al.*, 2009] have revealed four halos in 2007 and twelve sprite halos, all provoked by lightning with positive polarity. None of these findings is consistent with the idea that halos provide resolution to the sprite polarity paradox because the dominant polarity of the parent lightning is positive rather than negative, and have served to motivate further inquiry into land-based observations.

[19] Stanford University has recently deployed a high-speed photometer array called PIPER (Photometer Imager of Precipitated Electron Radiation) at Langmuir Laboratory (near Socorro, New Mexico) for observations of TLEs [*Newsome and Inan*, 2010]. The temporal resolution of this device is ~80 microseconds, and so superior to the resolution of conventional frame-rate cameras by a factor of 200. But by good fortune, a conventional frame rate CCD camera was operated alongside PIPER during four storms over the continental U.S. (July 24, July 29, July 30, and August 2, 2008). In these PIPER observations, the TLEs elves, halos and sprites were readily distinguished. In all observations of halos in the present study, an elve appeared initially and was used to trigger the recording of the subsequent events—halo and sprite.

[20] Halos caused by CGs with both positive and negative polarity have been detected in these four storms. The results are summarized in Table 1. The polarity, peak current and stroke multiplicity for these flashes have been extracted from the flash data archive of the NLDN. In searching for physically connected events, we used the criterion that the halo time agrees within 1 ms of the NLDN return stroke time. With this criterion, NLDN flashes were found for 38% of the ‘negative’ halos and 60% of the positive halos. All but two of the positive flashes showed single-stroke behavior (consistent with strong tendency for positive flashes to have one stroke only [*Saba et al.*, 2010; *Williams and Heckman*, 2011]), whereas more than half of the negative events showed multiple strokes. In all cases with multiple strokes, the NLDN data showed that the halo was produced by the first return stroke of the flash, in keeping with other observations that the first stroke in a multistroke flash usually exhibits the largest peak current [*Rakov and Uman*, 1990].

[21] The detectability of the halo has much to do with the brightness of this phenomenon. Figure 5 shows PIPER-measured halo brightness versus the peak current from the NLDN for the parent lightning, for both positive and negative events. Despite considerable variability in these measurements, some of which is attributable to variations in the optical path between halo source and sensor, a tendency is apparent for brightness to increase with peak return stroke current. The other notable feature in Figure 5 is the strong tendency for superior brightness for the ‘positive’ halos, with six positive events brighter than all the negative events. (Note that the brightness scale in Figure 5 is logarithmic.)

[22] The optical duration of a halo is also an important consideration in their detectability, particularly in the case of

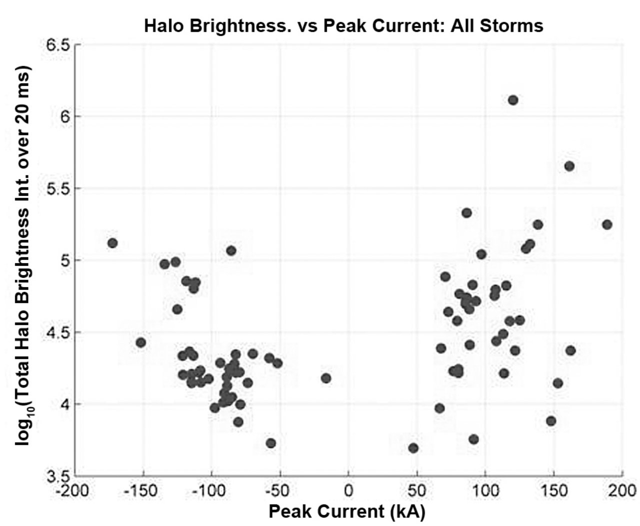

Figure 5. Halo brightness (from PIPER observations) versus peak current of the parent lightning (from the National Lightning Detection Network).

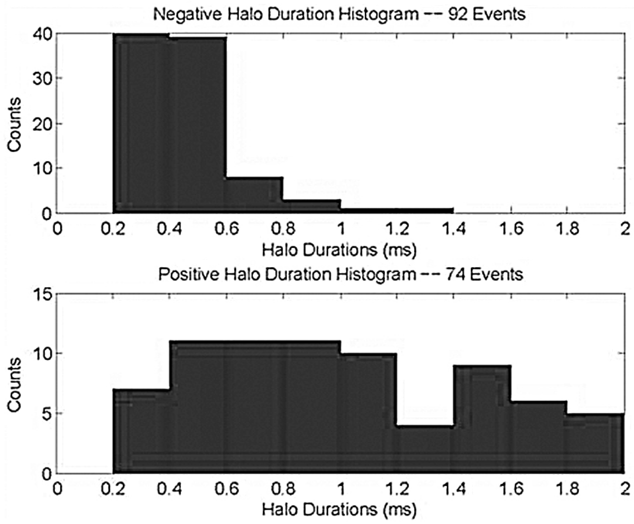

Figure 6. Histograms of halo duration for parent lightning flashes of (top) negative and (bottom) positive polarity, as measured with the high-speed photometer, PIPER.

the conventional frame-rate cameras. PIPER is well suited to documenting halo durations. Comparisons for both polarities in histogram form are shown in Figure 6. The mean duration for halos caused by positive lightning (1.0 ms) exceeds the mean negative value (0.46 ms) by a factor of two, thereby contributing to easier detection of events with positive polarity. The majority of durations of all events are less than 1 ms, and so substantially less than the time scales for the usual lightning continuing current [*Rakov and Uman*, 2003; *Ballarotti et al.*, 2005], but at the same time somewhat longer than typical durations for lightning return stroke currents [*Rakov and Uman*, 2003].

[23] Observed halo durations are plotted against peak return stroke current in Figure 7 for the same collection of events as in Figures 5 and 6. No obvious relationship between duration and peak current is evident for 'negative' halos. For positive events, the duration appears to vary inversely with the peak current, particularly in the lower range for peak current.

[24] Regarding the detections with the conventional frame-rate camera in this experiment (Table 1), only one of 92 halo events caused by negative polarity lightning was identified. In marked contrast, 27 of 74 'positive' halos were detected. This finding is consistent with the summary of earlier results by other investigators in the beginning of this section.

5. Polarity Asymmetry in Parent Lightning for TLEs

[25] Polarity asymmetry in cloud-to ground lightning is well recognized [*Williams*, 2006], but its implications for the polarity asymmetry of TLEs deserves further scrutiny. Evidence in the ELF that energetic negative flashes exhibit shorter durations than positive ones was shown by *Williams et al.* [2007]. That comparison was more qualitative than quantitative however, because the bandwidth used for these Schumann resonance observations is only ~100 Hz, and so the millisecond resolution of interest in the present context is not accessible.

[26] Further insights have been achieved by gathering events from the U.S. and its immediate vicinity whose vertical charge moments have been determined by Schumann resonance methods [*Huang et al.*, 1999; *Hobara et al.*, 2006] and whose peak currents have been measured by the NLDN (with substantially greater high frequency bandwidth). These results are shown in Figure 8: The tendency for larger peak current and simultaneously smaller charge moment for the negative flashes more likely to produce halos than sprites is readily apparent.

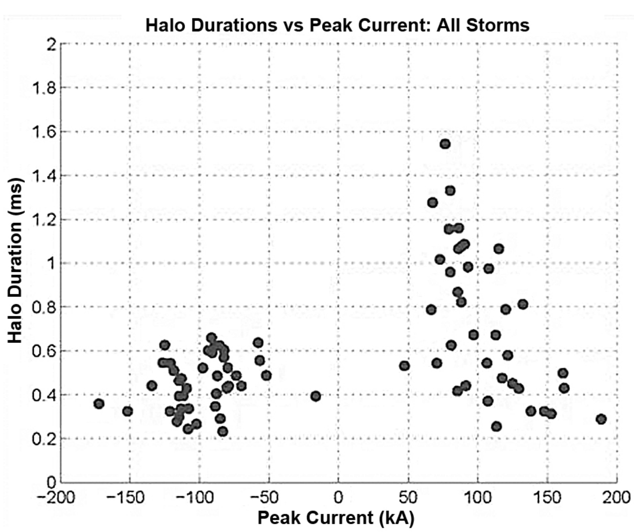

Figure 7. Halo duration (from PIPER observations) versus peak current of the parent lightning (from the National Lightning Detection Network).

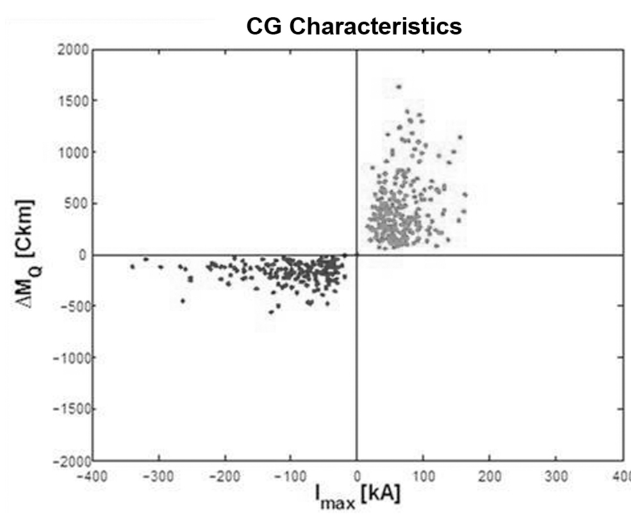

Figure 8. Lightning charge moments (from ELF measurements) versus lightning peak currents (from the National Lightning Detection Network), for a collection of large and energetic events over the USA. Negative (positive) values of I_{max} are associated with negative (positive) CGs.

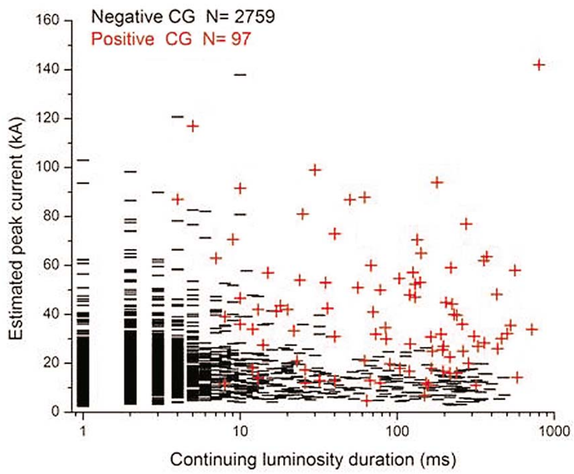

Figure 9. Peak lightning current (from the Brazil Lightning Detection Network) versus the duration of the continuing current (from simultaneous video camera measurements with millisecond resolution), for a large collection of ground flashes. The prevalence of short duration continuing current is far more common for flashes with negative polarity.

[27] Video cameras are now available with millisecond image times that are well suited for observations of continuing current durations in cloud-to-ground lightning [*Saba et al.*, 2006, 2010]. This capability serves to extend the dynamic range on time scales, and again, a dramatic contrast in behavior between positive and negative ground flashes is apparent, as shown in Figure 9. The prevalence of very short continuing current (<10 ms) with simultaneously large peak return stroke current (>100 kA) is far more likely in negative flashes than positive ones, and 'negative' halos are clearly more prevalent (over both land and sea) than 'positive' ones [*Frey et al.*, 2007; *Adachi et al.*, 2008; this study]. The evidence from PIPER observations shown in Table 1 for halos to be accompanied by sprites for an appreciable number of events with positive polarity, and not with negative polarity, is consistent with the existence of continuing current in the positive case and negligible continuing current in the negative case.

[28] What is the physically based explanation for the polarity asymmetries evident in Figures 8 and 9? This remains an open question. One hypothesis is suggested by *Williams* [2006] and is further substantiated by *Williams and Heckman* [2011]. In essence, lightning leaders with negative polarity (prevalent in CG lightning with positive polarity) are faster and carry more continuing current than their positive counterparts. The stability analysis for arcs [*Heckman*, 1992; *Williams*, 2006] shows that current cutoff and shorter discrete strokes are far more likely when the continuing (interstroke) current is smaller, as expected for positive leaders in negative polarity CG lightning.

6. Discussion

[29] The resolution of the sprite polarity paradox documented initially by *Williams et al.* [2007] has served as the main goal of this study. In pursuing that goal, a larger number of issues have arisen, all of which deserve some discussion, and follow in turn. We hasten to add one notable shortcoming of this study at the outset: the use of non-overlapping data sets. Observations are drawn from ground-based and space-based observations, from conventional frame-rate cameras and from faster optical systems. We found this integration of methods necessary to resolve various puzzlements in the earlier results, but unfortunately, we do not have observations of all kinds on the same halo events. The interpretation in this discussion should bear this shortcoming in mind.

6.1. Mathematical Framework

[30] The lightning polarity dependence of halos remains a fundamental consideration in this study. Though the improved temporal resolution available in this study has shed new light on the role for halos in resolving the sprite polarity paradox, the full temporal resolution of the halo has not yet been achieved. Nevertheless, for purposes of discussion, we may approximate the short lightning charge transfer causal to halos as exponential forms with simple time constants τ, in the manner of *Hiraki and Fukunishi* [2006].

$$\mathrm{I(t) = I_o \exp(-t/\tau)\ amperes} \tag{1}$$

From which it follows that the time-dependent charge transfer by the lightning is

$$Q(t) = \int_o^t \mathrm{I(t)dt = I_o\tau(1 - \exp(-t/\tau))\ C} \tag{2}$$

And the total charge moment change, for a discharge from mean height H, is then:

$$\mathrm{M = Q_\infty H = I_o \tau H\ C\text{-}m.} \tag{3}$$

[31] For a rough quantitative estimate, taking numbers consistent with the findings in this study, for a flash with I_o = 200 kA, τ = 0.5 ms and H = 6 km, then M = 600 C-km. Following the criteria set forth by *Wilson* [1925], and elaborated on more recently [*Williams*, 2001], this charge moment is sufficient to cause dielectric breakdown (i.e., ionization) at altitudes where halos are observed (70–85 km [*Barrington-Leigh et al.*, 2001]; 80 km [*Frey et al.*, 2007]) by the imposition of an electrostatic field.

[32] Assuming that the halo in the mesosphere is driven by the electric field imposed by this charge transfer over a time scale τ, the duration of the halo should be on this order. *Hiraki and Fukunishi* [2006] emphasize the need to resolve τ with a scale of 100 microseconds. The Stanford observations with PIPER satisfy this requirement. The halo durations in Figures 6 and 7 are measured with 80 microsecond resolution.

6.2. Optical Detectability of Halos

[33] When the sprite polarity paradox first presented itself over a decade ago in collective TLE observations [*Boccippio et al.*, 1995; *Williams*, 2001; *Williams et al.*, 2007], halo detections were quite scarce, and the majority of sprite detections were linked with ground flashes with positive polarity. This point is illustrated by ground-based records of TLE observations with a standard-frame rate camera (30 fps), the mainstay of such observations at the time. Table 2 shows comparisons of documented detections of

Table 2. Relative Numbers of Sprites and Other TLEs in the 'E' Category[a]

	Number of Sprites Observed	Number of 'E' Events Observed
July 5, 1996	10	0
July 7	65	4
July 8	24	1
July 11	33	0
July 13	5	0
July 17	1	1
July 19	72	4
July 20	3	0
July 21	133	14
July 24	267	24
August 4	72	12
August 5	71	8
August 7	61	8
August 10	93	3
July 11, 1997	33	4
July 12	6	2
July 27	4	0
May 20, 1998	336	5
June 20, 2007[b]	224	24
Totals	1513	114

[a]Observed with a standard frame-rate video camera from Yucca Ridge Field Station on a representative selection of nights.
[b]*Lang et al.* [2010].

sprites ('S') and the other category of TLE, then labeled 'E' for elves but in retrospect also including halos (which had not yet been identified as a separate category of TLE), from the Yucca Ridge Field Station near Ft. Collins, CO. In contrast to later findings with ISUAL and PIPER (documented in this study) in which halos dominate over sprites, the 'E' events constitute only 8% on average of the total TLE detections. (These records were discussed earlier when the sprite polarity paradox was first identified [*Williams et al.*, 2007].

[34] The collective evidence presented here indicates that this scarcity of halo and elve detections (relative to sprites) is attributable to the limitations of conventional frame-rate video cameras, whose effective integration time (17 ms) is $\sim$17 times the mean duration of 'positive' halos and $\sim$34 times that for 'negative' halos (Figure 6). In contrast, recent measurements of sprites with high-speed optical equipment [*Montanyà et al.*, 2010; *Newsome and Inan*, 2010] show mean durations of 10–40 ms, values comparable to or greater than a single standard video frame. Optical reciprocity guarantees that events of shorter duration should be detectable so long as their brightness is proportionately greater. But according to recent ISUAL observations [*Kuo et al.*, 2008], the mean brightness of halos (0.3 MR) is actually fivefold less than that for sprites (1.5 MR) in ISUAL observations, thereby making halo detection with standard frame-rate cameras even less likely. A possible additional explanation for the paucity of halos in early video recordings is simply observer selection bias. Sprites were brighter and more distinctive than diffuse halos, and still being relatively novel, tended to be the events selected for saving.

[35] The important early observations of *Bering et al.* [2002a] showing greater numbers of halo TLEs with lightning with negative polarity and lacking the characteristic 'slow tails' of positive ground flashes (consistent with the findings reported here in section 4) were puzzling at the time, simply because the great majority of sprites had been linked with positive ground flashes (initial findings by *Boccippio et al.* [1995] and summary of many published results by *Williams et al.* [2007]. But the optical measurements in Bering's Sprites99 balloon campaign [*Bering et al.*, 2002a, 2002b, 2004a; *Bhusal et al.*, 2004; *Bering et al.*, 2004b] possessed superior temporal resolution ($\sim$1 ms, but with absolute timing uncertainty of $\sim$4 ms (E. A. Bering, personal communication, 2011). The advent of optical instruments with millisecond resolution or better, beginning with the Sprites99 campaign and with the work of others [*Barrington-Leigh et al.*, 1999; *Hsu et al.*, 2008; *Stenbaek-Nielsen and McHarg*, 2008; *Newsome and Inan*, 2010] is a key factor in exposing this important 'dark horse' of TLEs, the halo. Increased emphasis on calibrated brightness measurements [e.g., *Kuo et al.*, 2008; *Takahashi et al.*, 2010] has also shown that halos are absolutely dimmer than sprites, and that high temporal resolution is needed to capture sprite streamer features with short duration [*Yaniv et al.*, 2009], a comparison also contributing to their missed detection in early observations. The ISUAL satellite observations in limb view with 100 μs resolution have shown a global population of halos more than twice as numerous as sprites [*Hsu et al.*, 2008], but it now appears that the limb view from space played only a secondary role in exposing this huge halo population. In the majority of ground-based observations, the distance from camera to TLE is usually substantially greater than the height of the TLE, and so nearly edge-on. The ground-based PIPER observations (Table 1) also show a great abundance of halos undetected by conventional frame-rate video observations from the same location. The PIPER observations also help explain why earlier low frame-rate camera observations (i.e., Taylor and Pautet (unpublished observations, 2006) and section 4) were dominated by halos caused by positive rather than negative ground flashes. This interpretation requires that the PIPER instrument has more sensitivity than the conventional frame rate cameras to enable detection of the inferred weaker 'negative' halos over land. The mean brightness of the 'positive' halos observed over land in Figure 2 is substantially greater than that of negative events.

[36] Curiously, the ISUAL halo events discussed first in section 2 tend to show the opposite result—i.e., the 'negative' halos are brighter than the positive ones (Figure 3). This opposite result has been a source of consternation in the present study. In contrast with the halo events observed with PIPER and described in section 4 that are entirely over land, the ISUAL events shown in Figure 2 predominate over seawater. We speculate that these halo-parent lightning flashes over seawater tend to take on relatively greater peak current than the positive events [*Lyons et al.*, 1998; *Füllekrug et al.*, 2002; *Williams*, 2006], and by virtue of equation (3), produce charge moments there larger than for their positive counterparts. Though the quantity τ in equation (3) may be less for negative flashes over seawater than for positive ones, the value of H may be greater for negative flashes. More work on oceanic lightning is needed to verify the suggested reversal in brightness with polarity between land and ocean.

6.3. Distinction in Halo Behavior Over Land and Sea

[37] The global reach on halo behavior afforded by the ISUAL satellite observations and the long-range ELF

observations of parent lightning have together exposed a contrast in behavior between land and ocean. Though the data sets are small, they do show evidence that "negative" halos over ocean are brighter (Figure 3), on average, than "positive" ones, but over land the situation is reversed (Figure 5).

[38] The polarity asymmetry in the lightning "final jump" in ground strikes has been addressed earlier [*Williams*, 2006], where evidence for a notably shorter final jump in the case of negative ground flashes has been shown. This suggestion is now strengthened by the growing evidence that negative leaders propagate substantially faster than positive ones in the same electric field [*Williams and Heckman*, 2011], and that by consequence the negative leader serves to bridge the final gap to ground in a shorter time (and produce larger peak current). But why does one have a different behavior between land and sea? Both quantities peak current [*Lyons et al.*, 1998; *Cummins et al.*, 2005; *Orville et al.*, 2011] and peak halo brightness (this study) associated with negative flashes to sea remain anomalous relative to positive polarity. It is suggested here that for lightning over land, positive streamers initiate readily from the rough land surface and progress upward to meet the descending negative leader [*Rakov and Uman*, 2003], thereby suppressing a rapid gap closing in the region of strong field. Over ocean, a relatively smooth electrode with a particularly short electrostatic relaxation time, the faster negative leader may succeed in reaching the surface without this retarding effect. The predominance of the 'negative' halo events over ocean with measureable charge moment change for the parent lightning suggests that the seawater electrode is playing a role in 'brightening' these events relative to those over land. High-speed video observations of lightning striking the sea at close range are needed to support or refute these ideas.

6.4. The M-Component as a Source for Halos?

[39] The observations that sprites are occasionally delayed by 10–100 ms after the lightning return stroke have led to suggestions that the fast charge transfer in the M-component, superimposed on the continuing current, is causing the delayed sprite [*Yashunin et al.*, 2007; *Asano et al.*, 2009; *Campos et al.*, 2009]. This mechanism will require extraordinarily large charge transfers in the M-components, as most documented M-components involve transfers of only several coulombs [*Rakov and Uman*, 2003]. Nevertheless, we examined the time differences between the NLDN-measured return stroke times and the PIPER-recorded halo times (section 4) as a test of these ideas. At 1 ms resolution, 88% of these time differences were less than or equal to one millisecond, pointing to an important role for the return stroke peak currents in initiating and dominating the observed haloes. In the remaining 12% of cases, time differences of 1–4 ms were noted between the return stroke time and the halo time, but no cases of long delays (5–100 ms) were noted. Further documentation of M-components in ground flashes with high peak current is needed to support a role for this phenomenon in the production of halos.

6.5. Global Production of TLEs as Documented by ISUAL

[40] ISUAL satellite observations have been compiled recently to make an assessment of the global population of TLEs: sprites, halos and elves [*Hsu et al.*, 2008]. The estimated relative prevalence is 1: 3.7: 72, respectively. To resolve the sprite polarity paradox, and assuming the breakdown threshold for positive and negative TLEs is the same, one needs a global TLE population with only 10% as many 'negative' halos as sprites [*Williams et al.*, 2007], and according to ISUAL observations of this global population and the evidence included here that 'negative' halos outnumber 'positive' ones, this condition is clearly fulfilled. The question then arises as to the apparent surplus of halos. If impact excitation is the predominant mechanism for halos [*Hiraki and Fukunishi*, 2006; *Adachi et al.*, 2008], then one expects the threshold electric fields in the mesosphere, and accordingly, the threshold charge moment changes due to lightning, to be less than for the production of sprites. (This expectation is complicated by the nonlinear effects of electron attachment [*Pasko et al.*, 1998; *Barrington-Leigh*, 2000], but the PIPER-documented time scales for halos (Figure 6) are as small as the estimated attachment times [*Pasko et al.*, 1998] for typical halo altitudes.) Lower thresholds for halos on both positive and negative ends of the charge moment distributions could result in substantially greater halos than sprites. The measured distribution of CMC values in Figure 4 does not lend strong support for substantially lower thresholds for halos, however, as the values are quite similar to those associated with sprites [*Huang et al.*, 1999; *Hu et al.*, 2002].

[41] The global elve population in ISUAL observations dominates the TLEs, and is substantially greater (72 times greater) than that for sprites. The contrast with the ground-based video camera observations (Table 2) is dramatic. The elves have been under-represented relative to sprites in the ground-based observations with standard frame-rate for the same reason as halos: their durations are also very short (<1 ms [*Newsome and Inan*, 2010; *Montanyà et al.*, 2010]). The same observer selection bias noted earlier for halos may have also contributed to this under-representation for elves in the early video camera observations. The limb viewing geometry for elves is also favorable for the detection of their horizontally wide and vertically thin emission in comparison with ground-based observations. This abundance of elves in an absolute sense is also readily understood on the basis of the well-established prevalence of lightning polarity for positive and negative ground flashes. Elves are believed to be caused by the radiation field from lightning whose magnitude is proportional to the peak lightning current [*Inan et al.*, 1996]. Either lightning polarity will serve [*Barrington-Leigh and Inan*, 1999] and so elves have no lightning polarity asymmetry. But since most network measurements show 10x as many negative flashes as positive, negative flashes will dominate the elve population, particularly over the ocean, where other observations [*Lyons et al.*, 1998] show a relative surplus of negative flashes with large peak current. In contrast, as noted previously [*Williams et al.*, 2007], sprites are produced almost exclusively by positive ground flashes, far fewer in number than flashes with negative polarity [*Orville et al.*, 2011].

6.6. Are Halos Ionized?

[42] The same controversy pertaining to sprite ionization a decade ago is currently unresolved in the literature on halos. *Hiraki and Fukunishi* [2006] and *Adachi et al.* [2008] have

proposed electron impact excitation of neutral nitrogen as the source for halo light, and by definition, ionization of neutral species is not involved. It is not clear however what prevents the achievement of a sufficiently large field for acceleration of ambient electrons to ionization energy over a large region in the mesosphere, given the appropriate impulsive forcing by a CG with large peak current and short duration. The imposed electric field on the mesosphere should be proportional to the CMC, and the CMC values for halos found in this study by direct ELF measurements (Figure 4) are not appreciably smaller than those found earlier for sprites [*Huang et al.*, 1999; *Hu et al.*, 2002]. In recent modeling studies by *Luque and Ebert* [2009] halos can be ionized. Theoretical studies by *Gordillo-Vázquez et al.* [2011] on halos likewise support a production of a surplus of free electrons. Furthermore, *Adachi et al.* [2008] allow for the possibility of halo ionization beyond impact excitation, and argue that the charge moments for halo-producing lightning were less that for sprite-producing lightning because of the need for ionization of sprites. The experimental results shown in Figure 1 are interpretable in the same way: If the lightning emission intensity in Figure 1 (middle) is an indicator of electric current, the time-integrated emission intensity shown in Figure 1 (bottom) is an indicator of charge transfer. The fact that the blue line (for halo) is below the red (sprite halo) and the green (sprite) lines at t = 10 ms is evidence for a lower charge moment change for the pure halo events, on average. In contrast, the theoretical phase diagram of *Hiraki* [2010, Figure 1] does not allow for halo ionization without a sprite, in the limit of forcing by a lightning flash with sufficiently large charge moment, over a sufficiently small time interval. Ionization in halos could be verified in optical spectra, but their short durations have discouraged the procurement of reliable spectra.

6.7. Metrics for Halos

[43] Regardless of the physical mechanism for halo production (impact excitation versus ionization), the key physical quantity at the incipient halo location is the electric field. But for pure halos, the need to form the halo and prevent the ensuing sprite places important constraints on the forcing by the parent lightning. For charge transfer that is appropriately fast (<1 ms), and for lightning currents that conform to the exponential forms of section 6.1, either the charge moment M or the peak current I_o should suffice as metrics for halo production, and halo brightness. Despite these expectations, the regressions of halo brightness against lightning charge moment (Figure 3) and lightning peak current (Figure 5) show considerable scatter, only weak correlation and imprecise indications for threshold quantities. Only rough thresholds of 500 C-km and 50 kA can be estimated. These vagaries may arise from variation in the altitude at which halos are initiated, from ionospheric-related uncertainties in the ELF determinations of charge moments, and/or path-dependent uncertainties in the determination of halo brightness. Considerable experimental effort will be needed to improve on these sources of uncertainty.

6.8. Why Are There So Few 'Negative' Sprites?

[44] Given what is known about ground flashes with negative polarity, the rarity of 'negative' sprites remains a rather remarkable result. Evidence exists for accumulations of negative space charge extending over many tens of kilometers in mesoscale convective systems, and that negative flashes can have both large peak currents and long continuing current, all of which tend to contribute to a large charge moment change. The limitation may be that one cannot have simultaneously large peak current and long and large continuing current with negative flashes, as one has with positive CGs [*Saba et al.*, 2006, 2010]. This behavior in turn may be due to the slower positive leaders, which often serve to keep negative ground flashes in a current cutoff mode favorable to discrete strokes [*Williams and Heckman*, 2011]. The high peak current with negligible continuing current in many events favors halo production over sprite production for negative CGs.

7. Conclusion

[45] Halos, discovered after sprites and elves and for a long time the dark horse in the race to understand TLEs, appear to resolve the sprite polarity paradox documented earlier by *Williams et al.* [2007], as hinted at in that study. Early observations of lightning charge moment change with ELF methods gave expectation for discharge and luminosity in the mesosphere over negative events, and the evidence now is that this does occur, but was not being detected in observations with standard frame-rate cameras. This conclusion is strongly supported by the simultaneous PIPER and standard frame-rate camera observations in section 4. Negative polarity flashes have been shown to dominate halo production over land and over water as shown by the ELF observations described in section 3, in contrast with earlier evidence on sprite behavior, for which the polarity dominance is reversed. Halo dominance by negative flashes with high peak current over seawater is particularly strong as shown in the global map in Figure 2. Negative ground flashes are in sufficient global abundance relative to sprites as to make plausible their appearance for all negative flashes with supercritical moment changes, as was documented earlier on a global basis by *Williams et al.* [2007]. Negative ground flashes with high peak current and negligible continuing current, documented in the PIPER observations, are abundant relative to positive ground flashes with the same characteristics, and so are well suited to making short-duration halos. Some positive flashes can make halos, and when they do, the halos tend to have longer durations, consistent with having finite-duration continuing current.

[46] Resolving why so few negative flashes are able to make sprites remains puzzling, but when this issue is better understand, we will have a more thorough understanding of the polarity asymmetry in cloud-to-ground lightning flashes.

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