Lightning charge moment changes for the initiation of sprites

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[1] The transient ELF (~50–5000 Hz) magnetic field radiated by lightning discharges across North America was continuously measured at Duke University during the summer of 2000. In total, 881 sprite-associated lightning discharges over 17 days were analyzed. We report in detail on 76 sprites for which we could reliably determine the lightning charge moment change from the ELF data at the time of sprite onset. The charge moment change for the initiation of a sprite is found to be as low as 120 C km. By folding together the charge moment distributions of sprite-producing lightning and all positive lightning, we find that the probability of sprite generation for lightning with >1000 C km charge moment change in <6 ms is >90%, while the sprite probability for lightning with <600 C km charge moment change in <6 ms is <10%. *INDEX TERMS:* 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 0689 Electromagnetics: Wave propagation (4275); 3324 Meteorology and Atmospheric Dynamics: Lightning; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3360 Meteorology and Atmospheric Dynamics: Remote sensing

1. Introduction

[2] The discovery of sprites about ten years ago [*Franz et al.*, 1990] has motivated research to understand the mechanisms that generates these mesospheric optical emissions. An important step toward this goal is to measure the lightning charge moment change required for the initiation of sprites. Current theories [*Pasko et al.*, 1997a] predict sprites are driven by sustained mesospheric quasi-static electric field generated by lightning. This field is essentially linearly proportional to the charge moment change in the lightning discharge that generates the sprite. Thus measuring charge moment change at the time of sprite initiation gives valuable insight into both sprite mechanism and characteristics of sprite-producing lightning.

[3] Lightning charge transfer is not always easy to measure. Most measurement methods, such as measuring currents when lightning striking an electrical tower [*Berger et al.*, 1975], multi-site electrostatic field measurements [*Krehbiel et al.*, 1979], and direct current measurement from a rocket [*Hubert et al.*, 1984], have to be conducted near the charge center. In this work, a remote measurement technique is used to measure the distant electromagnetic field radiated by lightning discharges and then extract the vertical charge moment changes caused by sprite producing lightning discharges. This technique enables us to analyze a large number of sprite events with data from a single instrument location.

[4] Previous studies have applied similar techniques to analyze sprite-producing lightning discharges, but these studies have all been limited in some way. *Cummer and Inan* [1997] examined 6 sprite-producing strokes from a single day and found the charge moment change varied from 25 to 3250 C km during the first 5 ms of the stroke. *Bell et al.* [1998] investigated 17 sprite events that occurred during one 15-minute period on a single day and deduced the total charge moment changes. *Huang et al.* [1999] analyzed many sprite-producing discharges from one day and found a minimum total charge moment of 300 C km for sprite production. However, *Huang et al.* [1999] measured the charge moment change for the entire lightning discharge, which by definition exceeds charge moment change responsible for initiating the sprite. Because factors such as the local neutral density and the ionospheric conductivity profile influence mesospheric electrical breakdown, it seems unlikely that there is a single invariant charge moment threshold for initiating sprites. We thus take a statistical approach in this work and determine how likely sprite generation is after a lightning discharge of a specific strength.

2. Experimental Details

[5] The transient magnetic field radiated by distant lightning discharges was continuously measured with a wide band extremely low frequency (ELF, ~50–5000 Hz) receiver at Duke University during the summer of 2000. The data were sampled continuously at 25 kHz, and a GPS receiver provided accurate absolute system timing for comparison with video observations. Optical emissions from sprites were directly monitored on video recordings made at Yucca Ridge Field Station (YRFS), Colorado, during the STEPS (Severe Thunderstorm Electrification and Precipitation Study) Campaign during May, June, and July 2000. Radiation from lightning during a total of 881 sprite events, about 90% of all the sprite events observed at YRFS during the Campaign, was measured by our system. Our system did not record during the times of the remaining 10%.

[6] From ELF magnetic field, we measured lightning current moment waveforms. Our measurement method is based on the propagation model discussed by *Cummer and Inan* [2000]. The bandwidth of our system provides submillisecond time resolution in the extracted current waveforms, which is very important for our application of measuring charge moment change at the time of sprite onset.

3. Data Analysis

[7] The sprite timing from video suffers from a 16.7 ms uncertainty, and as mentioned above we can only reliably measure the current moment waveform for 10–20 ms because of signal-to-noise ratio limitations. We avoid these limitations by analyzing two different classes of sprite events for which we can accurately determine the sprite initiation time, namely, sprites with confirmable short initiation delays and sprites that generate sprite currents.

3.1. Short-Delayed Sprites

[8] The uncertainty in the initiation time of some sprites can be improved beyond the 16.7 ms time duration of the video fields

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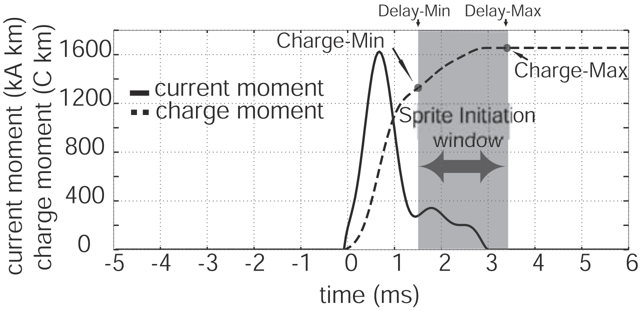

Figure 1. The relationship between the sprite initiation window and the maximum charge moment change for a sprite event on July 19, 2000, 06:50:38.8080 UT.

because we know the precise time of the causative lightning. In this case, a relatively narrow range of the charge moment change can be determined. We define Delay-Max as the time difference between the end of the video field first showing the sprite and the lightning time, with the necessary speed of light propagation differences subtracted. We further define Charge-Max as the lightning charge moment change at Delay-Max. Charge-Max is thus the maximum possible charge moment change responsible for initiating the sprite. We also assume that the sprite initiates at least 1.5 ms after the return stroke onset. This assumption is consistent with high time resolution imaging data [*Cummer and Stanley*, 1999]. We thus define Charge-Min as the charge moment change 1.5 ms (Delay-Min) after return stroke onset. The sprite initiation charge moment change must be between these two values. In the special case where the causative lightning occurred within a few milliseconds of the end of the video field, we have a much smaller sprite timing uncertainty and a correspondingly better estimate of the initiation charge moment change. Consider the event on July 19, 2000, 06:50:38.8080 UT shown in Figure 1. The maximum possible lightning-to-sprite delay in this case is only 3.4 ms. The maximum possible charge moment change is 1660 C km, and the minimum (based on an assumed 1.5 ms minimum delay) is 1330 C km.

[9] After removing those sprites with sprite currents (we will consider these in the next section), we could reliably measure Charge-Max for 181 of the recorded events with sufficient signal-to-noise ratios and sufficiently short delays. We further require a maximum lightning-to-sprite delay of 6 ms so that our bounding of the charge moment threshold is relatively narrow. Also, removing a few events where we cannot positively identify the causative lightning discharge leaves 24 events for detailed analysis. These 24 sprite events were all caused by positive lightning discharges. We find a minimum Delay-Max of 1.4 ms in these 24 events, validating our estimated minimum lightning-to-sprite delay of 1.5 ms. The best estimate of the charge moment change

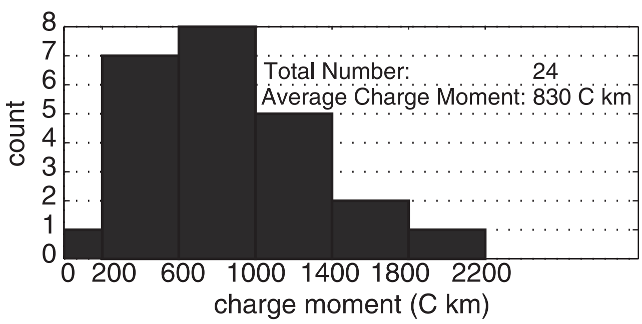

Figure 2. The charge moment changes for 24 sprite events with no sprite current and lightning-to-sprite delay smaller than 6 ms.

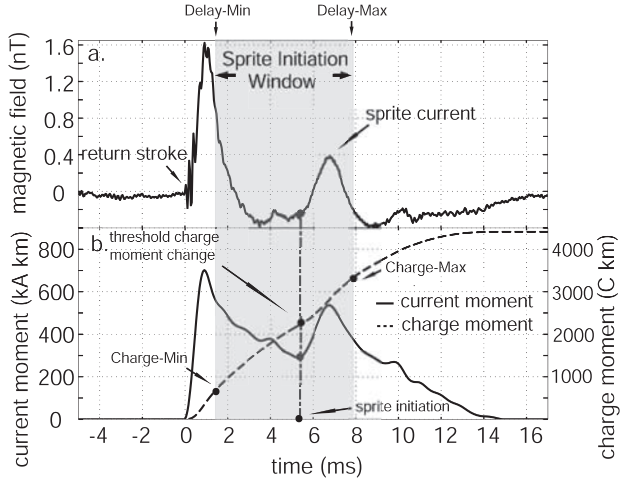

Figure 3. A sprite current associated sprite event on June 24, 2000, 3:36:47.6630 UT. (a) The sferic waveform before low-pass filtered. (b) The extracted source current waveform.

at sprite initiation is the average of Charge-Max and Charge-Min. The statistical distribution of this initiation charge moment change for these 24 events is shown in Figure 2, which shows that the charge moment change required to initiate sprites varies considerably from 120 C km to 2080 C km. We note that the spread between the average Charge-Min and the average Charge-Max is only 25%, indicating that we have tightly constrained the lightning charge moment change at the time of sprite initiation.

[10] It is surprising that sprites can initiate with charge moment changes as low as 120 C km, but this appears to be an exceptional case. Other factors may play a role in initiating a sprite [*Pasko et al.*, 1997b; *Zabotin and Wright*, 2001; *Wescott et al.*, 2001]. The lightning discharges with small charge moment changes initiating sprites are usually very impulsive, i.e. they move the charge to ground on time scales less than a millisecond. During the STEPS campaign most impulsive positive cloud-to-ground discharges like these produced only elves and not sprites. The reason why some small impulsive source currents produced sprites is still under investigation.

3.2. Sprites with Sprite Currents

[11] Some observed sferic waveforms contain ELF electromagnetic radiation from the sprite itself. This has been demonstrated with temporal analysis of the ELF radiation and the sprite optical emissions [*Cummer et al.*, 1998; *Reising et al.*, 1999] and by measuring the geographic displacement between the source locations of the discrete pulses [*Füllekrug et al.*, 2001]. For sprite events that generate sprite currents, we can determine the time of sprite initiation directly from the sferic because of the simultaneity of the onset of the second peak of the source current and sprite brightness [*Cummer et al.*, 1998]. We can unambiguously identify these secondary peaks as sprite currents because they lack the higher frequency (>1 kHz) radiation present in return strokes. Figure 3 shows how we derive the threshold charge moment change accurately for this particular kind of sprite.

[12] The statistical distribution of the charge moment change required to initiate these events with sprite current is plotted in Figure 4. These events were all produced by positive lightning discharges. The shape of the charge moment change distribution for sprite events with sprite currents is similar to that without sprite current. Two slight differences are that the sprite current distribution (Figure 4) drops off more quickly below 600 C km than the no current distribution (Figure 2) and the sprite current distribution falls more slowly above 1400 C km. We conclude that sprite

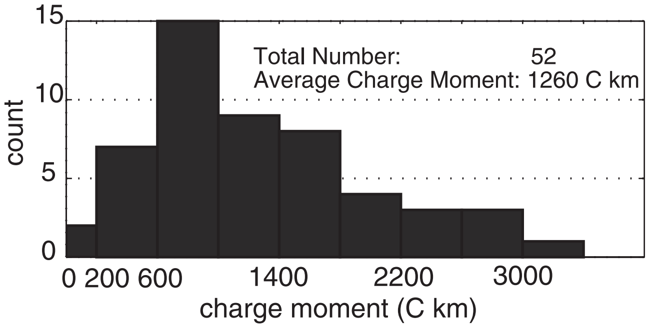

Figure 4. The charge moment changes for 52 sprite current associated sprite events.

currents are relatively unlikely to initiate in <600 C km sprites, and are likely to initiate in >1400 C km sprites.

3.3. Probability of Sprite Initiation

[13] It is unlikely that there is a single sharp charge moment threshold for sprite initiation because other factors, such as ionospheric conductivity and mesospheric neutral density, are at play. Sufficiently large discharges will almost always make a sprite, while smaller discharges may or may not make a sprite, depending on these other factors. We thus define the sprite initiation threshold statistically: given a positive discharge with a certain charge moment change, what is the probability that a sprite is generated?

[14] To calculate this probability distribution, we need the charge moment change distribution in positive lightning in the Midwest. This distribution has not been measured statistically, but the distribution for positive lightning elsewhere has been measured [*Berger et al.*, 1975]. We thus use a log-normal distribution [*Uman*, 1987] based on these measurements as representative of that in the Midwest. To convert these charge measurements to the needed charge moments, we assume a mean charge removal altitude of 8 km [*Stanley*, 2000].

[15] We can derive the probability of sprite initiation for lightning discharges with different charge moment changes by dividing our measured charge moment change distribution for sprite events by the positive lightning discharge probability distribution function (PDF), which is shown in Figure 5. The resulting distribution gives the relative likelihood of a sprite initiating given that a positive lightning discharge of a given strength has occurred. We convert the result to a meaningful probability by assuming the probability of sprite initiation for lightning discharges with charge moment change above 1400 C km is unity. This assumption is reasonable in the light of current theoretical results [*Pasko et al.*, 2001] for initiating streamers at mesospheric altitudes. The derived sprite

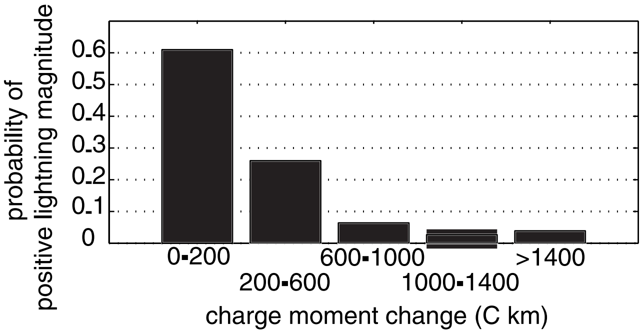

Figure 5. Probability of positive lightning occurrence with different charge moment change based on the measured data in [*Berger et al.*, 1975].

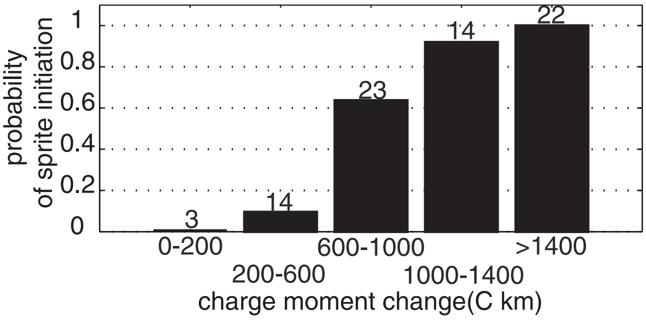

Figure 6. Probability of sprite initiation for positive lightning discharges with different charge moment changes. The number labeled above each bar corresponds to the number of sprite events in each bin.

initiation probabilities for lightning discharges with different charge moment changes are shown in Figure 6. The number of sprites in each bin is sufficient to give our results statistical significance.

[16] We find for positive lightning discharges with charge moment change below 600 C km, the probability of initiating sprites is less than 10%. Sprites do initiate after lightning this small, but the relative rarity indicates that special conditions [*Pasko et al.*, 1997b; *Zabotin and Wright*, 2001; *Wescott et al.*, 2001] are probably required. On the other hand, for those with charge moment change above 1000 C km, the probability of sprite initiation is greater than 90%. The transition region is between 600 and 1000 C km, over which the sprite initiation probability is about 60%.

4. Conclusions

[17] In this work, 76 observed sprite events from 17 days are analyzed to derive the charge moment change at the time of sprite onset. The lightning charge moment change for sprite initiation can be as low as 120 C km and as high as 3070 C km.

[18] Rather than finding a single charge moment change threshold for sprite initiation, we computed the probability of sprite initiation given that a positive discharge of a known charge moment change has occurred. We combined the charge moment change distribution for the 76 sprites analyzed with a measured charge moment change distribution for all positive lightning. We find that sprites are more than 90% likely to initiate after positive lightning with a charge moment change greater than 1000 C km in less than 6 ms. Sprites are less than 10% likely to initiate after positive lightning with a charge moment change less than 600 C km in less than 6 ms. These results are consistent with existing theories for mesospheric breakdown [*Pasko et al.*, 2001]. However, the low but non-zero probability for sprite initiation after relatively small charge moment changes suggests that in certain conditions other factors may play a role in helping to initiate a sprite [*Pasko et al.*, 1997b; *Zabotin and Wright*, 2001; *Wescott et al.*, 2001]. This empirical sprite initiation probability criterion should make it possible to accurately determine the global occurrence rate of sprites by using charge moment measurements from a single Schumann resonance remote sensing system.

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