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Detection of daytime sprites via a unique sprite ELF signature

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Abstract. On August 14, 1998, 3 separate daytime sprite events were detected via a unique extremely low frequency (ELF) sprite signature. The onset of the sprite ELF signatures was delayed by 11.0-13.2 ms from positive cloud-to-ground strokes which had attained exceptionally large charge moment (charge times height) changes of 3900-6100 C·km. It is shown that a charge moment change of 6100 C·km may have been sufficient for conventional breakdown at ≃54 km altitude, assuming an experimentally measured ion conductivity profile of *Holzworth et al.,* [1985]. The daytime sprites themselves contained unusually large charge moment changes of ≃2800 C·km, ≃1200 C·km, and ≃910 C·km.

1. Introduction

Sprites are luminous discharges which photometrically have only been documented at night in part because of the dominance of Rayleigh scattering of sunlight during the day. ELF measurements indicate that sprites are primarily correlated with positive cloud-to-ground (+CG) strokes that have slow tails produced by large continuing currents [*Boccippio et al.*, 1995; *Reising et al.*, 1996; *Cummer and Inan*, 1997; *Sukhorukov and Stubbe*, 1997; *Reising et al.*, 1999; *Cummer and Stanley*, 1999]. Light-intensified high-speed video of nighttime sprites has revealed that sprites initiate only a few kilometers below the ionospheric conductivity ledge [*Stanley et al.*, 1999a; *Cummer and Stanley*, 1999], which is at 80-85 km altitude [*Hale*, 1994]. The observed initiation height, $\gtrsim$300 C·km parent discharge charge moment changes [*Cummer and Stanley*, 1999; *Huang et al.*, 1999], and corona streamer characteristics [*Stanley et al.*, 1999a] are consistent with a conventional breakdown mechanism for sprite initiation and development under the influence of a CG's quasi-electrostatic field [*Wilson*, 1925; *Fernsler and Rowland*, 1996; *Pasko et al.*, 1998]. During the daytime, ionospheric conductivity is greatly enhanced at the altitudes of nighttime sprite initiation. This would force daytime sprites to initiate at lower altitudes and hence higher atmospheric densities with a proportionally larger electric field required for conventional breakdown [*Wilson*, 1925]. Consequentially, the charge moment change threshold for daytime sprite initiation would be much larger than for nighttime sprite initiation [*Fernsler and Rowland*, 1996].

At the AGU Fall Meeting in 1996, New Mexico Tech (NMT) researchers reported slow electric field changes which were correlated with bright sprites on video but were temporally distinct from +CG slow tails. These slow field changes were unique in that they were not immediately preceded by the very low frequency (VLF) radiation produced by a CG's return stroke. NMT researchers attributed these isolated slow field changes to vertical charge transfer within sprites and this was subsequently confirmed by photometric measurements which showed that the slow field changes were directly correlated with spatially-integrated sprite light output [*Brook et al.*, 1997; *Cummer et al.*, 1998; *Reising et al.*, 1999]. When video is available at night, the isolated slow field changes have always been found to be correlated with bright sprite events and this correlation enables the detection of bright sprite events via ELF measurements when video is not available [*Brook et al.*, 1997].

In this paper, we report the first detection of daytime sprite events via their ELF "fingerprint". It will be shown that the value of the parent discharge charge moments at the onset of the daytime sprite ELF signatures is much greater than for the onset of nighttime sprite ELF signatures.

2. Instrumentation

The GPS-based NMT radio atmospheric (sferic) system was used to acquire very broadband (<1 Hz - 250 kHz) electric field data. Pre- and post-trigger data of a combined fixed length was stored at a 500 kHz sample rate whenever a bipolar threshold was exceeded. The system was able to immediately rearm after the post-trigger was stored. This feature, combined with a high data bandwidth, translated into a 100% detection efficiency for all sferics which met the sensitive trigger criteria. This resulted in an unambiguous identification of CG occurrence, making it possible to discriminate between slow tails which are associated with CGs and delayed slow field changes associated with sprites. The pre- and post-trigger lengths were configurable, but were set to 2 and 6 ms respectively on August 14, 1998. The electric field data was also stored continuously at a 10 kHz sample rate.

The NMT sferic system was located on a mountain ridge at Langmuir Laboratory, NM. In order to determine the electric field intensification due to the ridge, sferics at >800 km range were compared between the NMT sferic system and an electric field sferic system located ≃30 km away on level terrain. This comparison revealed that the ridge intensified the electric field by a factor of 1.9±0.2. The NMT system's electric field values were converted to flat terrain values and these were used for the ELF propagation model.

3. Analysis method

The lightning current moment (current times vertical channel length) was extracted quantitatively by a tech-

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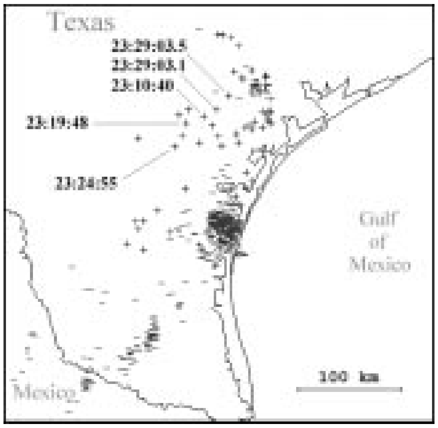

Figure 1. National Lightning Detection Network (NLDN) data for a Mesoscale Convective System (MCS) over southern Texas is displayed for the time period 23:07-:42 UT on August 14, 1998. The five energetic +CGs discussed in this paper are labeled.

nique which was described in detail by *Cummer and Inan* [1999]. This technique had been used previously for sprite-producing discharges of both positive [*Cummer et al.*, 1998; *Cummer and Stanley*, 1999] and negative polarities [*Barrington-Leigh et al.*, 1999]. In order to separate the probable lightning and sprite current (i.e., the second peak), we assume that the lightning current moment varies linearly after the first few milliseconds of the discharge. The charge moment changes were obtained by integrating the respective current moments according to the formula: $M_q(t) = \int_0^t M_i(\tau)d\tau$.

4. Experiment

On August 14, 1998, the sferic system was armed between 23:07-:42 UT (6:07-:42 pm CDT). During this time interval, there was a large mesoscale convective system (MCS) over southern Texas with less than 2 hours remaining before the sun would set shortly after 8 pm CDT. NEXRAD radar data (not shown) indicated that the areal coverage of base reflectivity (>15 dBz) for this MCS was >66,000 km^2, which exceeds the mean of ≃50,000 km^2 for nighttime sprite-producing MCSs [*Lyons et al.*, 1999]. Figure 1 shows National Lightning Detection Network (NLDN) data for southern Texas during the time period that the sferic system was armed. A horizontal bipolar pattern is clearly evident, which is a common feature of nighttime sprite-producing MCSs [*Boccippio et al.*, 1995; *Lyons*, 1996].

5. Results

Starting at 23:19:48.535 UT, the electric field system was triggered 3 consecutive times during the same event. The broadband electric field data, sampled at 500 kHz, is shown in Figure 2. A -CG waveform precedes a +CG waveform with a large slow tail which is followed by a large and isolated slow field change with a waveshape very similar to that produced by energetic nighttime sprites [*Brook et al.*, 1997; *Cummer et al.*, 1998; *Reising et al.*, 1999; *Cummer and Stanley*, 1999]. The +CG had a peak current of 70.9 kA and occurred in the MCS over southern Texas (see Figure 1) while the -CG was produced by an unrelated small storm in central Wyoming. The onset of the sprite field change occurred 13.2 ms after the +CG onset.

The charge moment change of the 23:19:48 UT parent +CG discharge and sprite event are shown in Figure 3. The charge moment change of the +CG at the onset of the sprite field change was 6100 C·km. In contrast, nighttime sprite ELF signatures onset at +CG charge moment changes well below 1100 C·km [*Cummer and Stanley*, 1999]. Charge moment changes exceeding 6000 C·km may be exceptionally rare since *Huang et al.,* [1999] found no charge moment changes larger than ≃5000 C·km across the entire globe during an ≃18 day observation period in the summer of 1997.

To obtain an estimate of the charge transferred to ground by the +CG, we assume that the average charge height was no lower than ≃4 km, which is the base altitude of a significant positive charge layer in stratiform regions [*Marshall et al.*, 1996]. We also assume that the charge was no higher than the maximum cloud top height of ≃15 km indicated by infrared satellite measurements (not shown) of cloud top temperature. Thus, the total charge transferred to ground would have been between 410 C and 1500 C before the onset of the sprite field change. The largest directly measured total charge transfer that the authors are aware of is ≃450 C (also associated with a +CG) [*Berger*, 1972], which further attests to the highly unusual nature of this event.

The sprite event added ≃2800 C·km to the total charge moment change, as denoted in Figure 3 by the separation between the total charge moment change (solid line) and the estimated parent discharge charge moment change component (dashed line) for the 23:19:48 UT event. To put this into perspective, the largest sprite charge moment change found by *Cummer and Stanley,* [1999] for 11 nighttime sprite events was ≃840 C·km while *Reising et al.,* [1999] found no sprite charge moment changes larger than ≃380 C·km for 81 nighttime sprite events. Since nighttime sprite charge moment changes are known to be linearly correlated with spatially-integrated sprite brightness [*Reising et al.*, 1999], it is likely that this daytime sprite event was unusually bright.

At 23:24:55.658 UT, a second +CG struck within the same +CG region as the first (Figure 1) and produced the second sprite field change. The onset of the sprite field change occurred after 11.0 ms had elapsed when the parent discharge charge moment change had reached 4300 C·km (Figure 3). Although this was less than the threshold for the previous sprite ELF signature onset, it is still far in excess of that observed for nighttime sprites. The sprite event added ≃1200 C·km to the total charge moment change.

At 23:29:03.129 UT, the third consecutive +CG to strike within the same general region as the previous two produced the third (and final) sprite field change. Figure 3 shows that

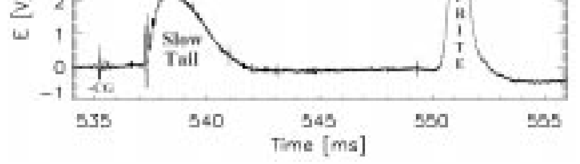

Figure 2. The VLF radiation from a +CG return stroke is followed by a large slow tail indicative of a large continuing current. More than 13 ms after the return stroke, there is a large slow field change which is not immediately preceded by VLF radiation. The slow field change was likely produced by an energetic sprite event.

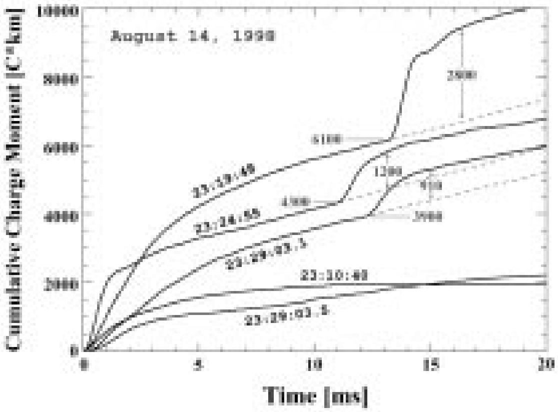

Figure 3. The cumulative charge moment changes of the five +CGs which produced the largest such changes (within 20 ms of the return stroke) during the data acquisition period. The three most energetic discharges produced sprite events with charge moment changes of 910-2800 C·km, as shown by the separation between the total charge moments (solid lines) and the estimated parent discharge components (dashed lines).

the parent discharge charge moment change for the onset of this sprite field change was 3900 C·km after 12.3 ms had elapsed. The sprite event added ≃910 C·km to the total charge moment change.

There were some other +CGs during the 35 min data acquisition period which also produced large slow tails but were not accompanied by any isolated slow field changes. The two such discharges with the largest charge moment changes occurred at 23:10:40.964 UT and at 23:29:03.532 UT and their charge moment changes are shown in Figure 3. The larger of these +CGs produced a charge moment change of 2200 C·km in 20 ms, which was either insufficient to initiate a sprite or at the very least, a sprite with a detectable ELF signature.

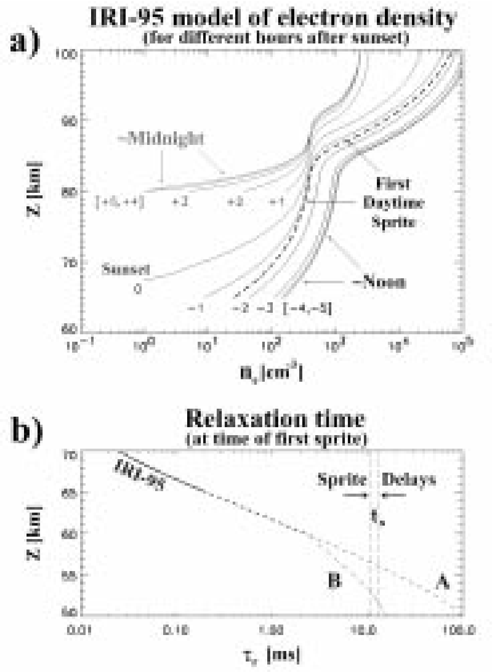

Figure 4. a) The IRI-95 model of electron density (n_e) as a function of time in hours relative to sunset over S. Texas on August 14, 1998. The dashed line shows the IRI-95 n_e at the time of the first sprite. b) The relaxation time (τ_r) at the time of the first sprite, with the IRI-95 model (thick solid line) extrapolated below 65 km (thick dashed line) and incorporating the effects of different ion concentrations of *Holzworth et al.,* [1985] (Profile A) and *Hale,* [1994] (Profile B) below 60 km. The vertical dotted lines show the range of sprite delay times (t_s) reported in this paper.

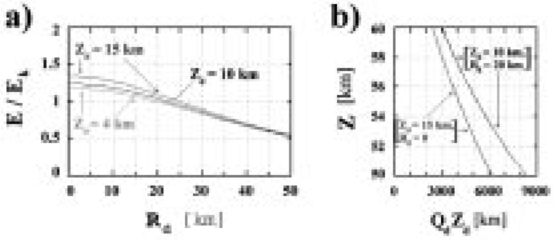

Figure 5. A static field approximation for a uniformly charged disc of radius R_d and height Z_d along with an ionosphere conducting plane at $Z=62$ km is used to calculate a) The ratio of the electric field to the breakdown field at $Z=54$ km due to a total charge moment ($Q_d Z_d$) of 6000 C·km. b) The minimum $Q_d Z_d$ required to initiate breakdown for a $Z_d=15$ km point charge and a more realistic example of $R_d=20$ km and $Z_d=10$ km.

6. Relaxation time

Observations of nighttime sprites show that they initiate at altitudes of ≃75-80 km [*Stanley et al.*, 1999a; *Cummer and Stanley*, 1999] and $\gtrsim$300 C·km parent discharge charge moment changes [*Cummer and Stanley*, 1999; *Huang et al.*, 1999], which is roughly consistent with conventional breakdown predictions [*Fernsler and Rowland*, 1996] for a relaxation time (τ_r) vs. height profile of *Hale* [1994]. In this section, we will estimate τ_r as a function of height around the time of the daytime sprites. The results will then be used in the next section to estimate the initiation altitude of the sprites and an approximate altitude for the base of the ionosphere.

Figure 4a shows the IRI-95 model [*Rawer et al.*, 1978] of electron number density (n_e) relative to local ground-level sunset over S. Texas on August 14, 1998. The base altitude of model output is 65 km for daylight hours and 80 km for night. A significant change in n_e occurs within ±3 hours of sunset, with the greatest change at sunset when the change in incident solar flux is greatest. The dashed line in Figure 4a is the IRI-95 n_e profile at 23:19:48 UT, the time of the first sprite event. The solid line in Figure 4b shows τ_r based on the IRI-95 n_e profile and a "cold electron" assumption (see *Pasko et al.,* [1997]) for 65-70 km altitude at 23:19:48 UT. Note that although n_e at the time of the sprites was significantly less than at midday, the corresponding τ_r was still very small.

The thick dashed line in Figure 4b shows the IRI-95 τ_r extrapolated down to 60 km altitude using the τ_r scale height at 65 km altitude. Below 60 km, ion conductivity begins to dominate over the electron conductivity [*Reid*, 1986]. The thin dashed line (Profile A) in Figure 4b below 60 km is based upon combining the IRI-95 electron conductivity extrapolation with the experimentally measured ion conductivity of *Holzworth et al,* [1985]. The dot-dash line (Profile B) in Figure 4b is an interpolation between the IRI-95 τ_r profile and Hale's mid-latitude τ_r profile for 53 km altitude and below [*Hale*, 1994]. The vertical dotted lines in Figure 4b denote the range of daytime sprite initiation time delays (t_s: 11.0-13.2 ms) reported in this paper. Note that τ_r exceeds all t_s below ≃56 km altitude for Profile A but does so only below ≃51 km altitude for Profile B.

7. Discussion

It has been estimated that a parent discharge charge moment change of 8000 C·km would be required to initiate a daytime sprite at 50 km altitude [*Fernsler and Rowland*, 1996]. In order to better assess the possibility of conventional breakdown onset as a function of parent discharge charge height and horizontal extent parameters, we implement a static field approximation identical to that of *Krehbiel et al.,* [1996]. In this approximation, the parent discharge is modeled as a uniformly charged disc of total charge Q_d at an altitude Z_d (with a $-Q_d$ image at $-Z_d$), the electric field is calculated along the central axis above the disc, the ionosphere is approximated to a conducting plane boundary, and the first image pairs above the ionosphere and below ground are included in the static field calculation. Z_d was varied discretely between 4, 10, and 15 km and the disc radius (R_d) was varied continuously between 0 (point charge) and 50 km. A breakdown threshold ($\frac{E_k}{N}$) of $\simeq$124 Townsends (1.24×10^{-19} $V{\cdot}m^2$) [*Bazelyan and Raizer*, 1998, p. 25] was used for the calculations and the base of the ionosphere was approximated as 62 km altitude (where $\tau_r \lesssim 1$ ms).

Figure 5a shows that conventional breakdown ($\frac{E}{E_k} \geq 1$) probably would have occurred at 54 km altitude (where $\tau_r \gg t_s$ for Profile A of Figure 4b) for $Q_d Z_d = 6000$ C·km (ie, the first sprite-producing discharge) if $R_d < 25$ km. It is interesting to note that R_d has been measured to be much less than 25 km for a nighttime sprite-producing +CG [*Stanley et al.*, 1999b], which lends support to the possibility that the radius of even this unusually energetic flash might have been small enough to produce conventional breakdown for Profile A. However, it is clear from Figure 5b that the first sprite-producing discharge would probably not have been able to initiate conventional breakdown at altitudes where $\tau_r > t_s$ in Profile B.

The charge moment changes at the onset of the second and third sprite field changes was shown to be 4300 C·km and 3900 C·km, which would have been insufficient to initiate conventional breakdown at 54 km according to Figure 5b. One speculative possibility is that the conductivity above 54 km altitude had somehow been decreased by the energetic first sprite event on the time scale of minutes, leading to a higher initiation altitude and hence lower initiation threshold.

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