LED. Indeed, initial experiments have shown this to be the case. Devices have been stored for more than 1 year without the appearance of the black spots that typically limit the shelf life of polymer LEDs. After such relatively long-term storage, the polymer LECs operate without loss of efficiency. Although stress life measurements have just begun, the initial results obtained from nonoptimized devices appear promising with on lifetimes comparable to control devices made with the same luminescent polymer in the conventional polymer LED configuration.

The polymer LEC offers both opportunities and challenges. For example, because the *p-n* junction is created in situ, the thickness t of the luminescent polymer layer is less critical than in the conventional polymer LED, where the tunneling injection current I is exponentially sensitive to the electric field E: $I \propto \exp[-k/E] = \exp[-kt/V]$, where k is a constant (8). Moreover, the use of prepatterned interdigitated electrodes enables the polymer LEC to be fabricated simply, in a single step, with little sensitivity to film thickness. On the other hand, performance optimization will require the synthesis of multifunctional polymers that are luminescent semiconductors with high ionic mobility.

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Sprites, ELF Transients, and Positive Ground Strokes

Dennis J. Boccippio, Earle R. Williams,* Stan J. Heckman, Walter A. Lyons, Ian T. Baker, Robert Boldi

In two summertime mesoscale convective systems (MCSs), mesospheric optical sprite phenomena were often coincident with both large-amplitude positive cloud-to-ground lightning and transient Schumann resonance excitations of the entire Earth-ionosphere cavity. These observations, together with earlier studies of MCS electrification, suggest that sprites are triggered when the rapid removal of large quantities of positive charge from an areally extensive charge layer stresses the mesosphere to dielectric breakdown.

"Red sprites" are mesospheric, striated glows that typically recur at intervals of several minutes over mature and dissipating organized convection (*1–3*). They have recently been documented over the stratiform regions of mid-latitude MCSs (*4*). Sprites tend to occur in clusters, sometimes appearing to follow the horizontal progression of in-cloud lightning. Compared to the typical MCS lightning flash rates of 40 to 50 per minute (*5*), sprites are infrequent, although not rare, occurrences.

D. J. Boccippio and R. Boldi, Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
E. R. Williams, Parsons Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA.
S. J. Heckman, Phillips Laboratory, Hanscom Air Force Base, MA 01731, USA.
W. A. Lyons and I. T. Baker, Mission Research Corporation, ASTeR Division, Fort Collins, CO 80522, USA.

*To whom correspondence should be addressed.

Electric field soundings through MCS stratiform anvils suggest a strongly layered charge structure, which includes concentrated positive charge near the 0°C isotherm (*6*); this structure differs considerably from the conventional dipole structure that is characteristic of active deep convection, in which positive charge overlies negative. In MCSs, cloud-to-ground (CG) lightning also occurs in a "horizontal bipole" pattern (*7, 8*), with negative strokes occurring in areas of active convection and positive strokes dominant in the stratiform regions. These positive CG strokes are infrequent but often exhibit extremely large peak return stroke currents (9) and may lower tens to hundreds of coulombs of charge to ground (*10, 11*). They are also often associated with horizontally extensive "spider lightning" discharges, long dendritic channels that may finger for many tens of kilometers along cloud base (*12–17*).

Positive CG strokes are also disproportionately associated with electromagnetic "Q-burst" events in the ELF Schumann resonance (SR) band (*18, 19*), the large-amplitude ringing of the entire Earth-ionosphere cavity (*20*). The SR "continuous" spectra are believed to be driven by the integrated effects of all global lightning, with Q-burst events identifiable as transient amplifications of the SR continuous signal of up to 20 dB. These Q bursts, separated in time by minutes to hours, are thought to be excited by the largest lightning events on the planet (*21, 22*).

Sprites, Q bursts, and positive CG strokes are all rather exceptional electromagnetic events. The MCS is an unusual meteorological phenomenon. We studied MCS systems on 2 days to search for possible physical connections among these various phenomena.

We obtained visual documentation of sprite events at ranges up to 1000 km with the low-light monochrome video systems located at the Yucca Ridge Field Station some 20 km northeast of Fort Collins, Colorado (*1, 23, 24*). Vertical electric (E_z) and horizontal magnetic (H_{NS} and H_{EW}) fields in the ELF SR band were measured at a culturally quiet field station in West Greenwich, Rhode Island, where long-term observations of the background SR have been under way (*23, 25, 26*). Large-amplitude transient events were frequently observed during the periods of study. Ground strokes were identified by the National Lightning Detection Network (NLDN) of magnetic direction finders, which has a detection efficiency of better than 70% and an accuracy of better than 10 km for negative CG strokes (*8, 27, 28*). The detection efficiency of positive CG strokes is as yet undocumented, although several studies have suggested that the NLDN robustly identifies positive flashes with negligible false detection (*29*).

The video system recorded at 17-ms time resolution during the period of study. The ELF data were sampled at 350 Hz with 12-bit resolution. We extracted ground flash data from the NLDN archives in 5-s windows around the reported sprite events and within a geographical region corresponding to satellite-observed cloud tops in the infrared.

On 12 July and 7 September 1994, we conducted intercomparisons between visual observations of sprites in Colorado and the SR signal in Rhode Island in real time using a phone link (Fig. 1). These communications suggested a connection

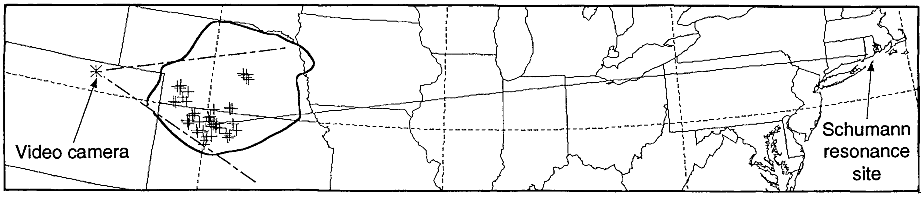

Fig. 1. Position of the study MCSs in relation to the low-light video and ELF SR observation sites. The satellite-observed cloud shield for 7 September 1994 is shown; the cloud shield for 12 July 1994 was of similar size and location. Locations of sprite-related positive lightning and the great circle path (~2300-km range) from the SR site to one of the CG strokes are overlaid.

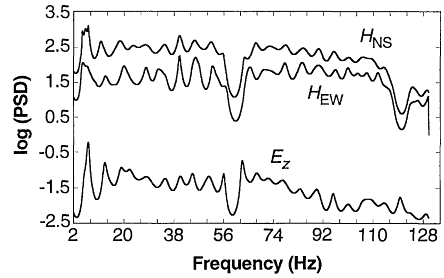

Fig. 4. Spectral decomposition (average maximum entropy spectra, 40 to 120 poles) of the Q-burst event in Fig. 3. Theory predicts that the SR modes should be spaced by approximately 6 Hz, beginning with the fundamental (8-Hz) mode. The fundamental and higher mode structure are well resolved in this event, substantiating the global nature of the transient.

between the observed events. Subsequent examination of the observations confirmed this connection. Intercomparisons on both days began near 0400 UTC (Universal Time Coordinated) (nighttime conditions at the video camera location), after low-level scud clouds and altocumulus had cleared from the Yucca Ridge site and afforded a clear view of the mesospheric sprite region over the MCSs. At this point, the convective systems had already developed a large (10^5 km^2) cirrus anvil shield and regions of stratiform precipitation. Data collection continued through 0700 to 0800 UTC, during which time the cloud-top heights in the infrared gradually decreased (*30*). The ground strokes during this period exhibited a typical horizontal bipole pattern (Fig. 2).

The ELF data recorded at the Rhode Island site were time-tagged with an internal PC clock that exhibited severe drift (~13 s/day). We generated a correction algorithm by comparing the (erroneous) recorded onset times for ELF transients with the GPS (global positioning system)-timed sprite events. A total of 42 sprite-ELF events were considered on 12 July and 55 on 7 September. The PC time errors were found to be consistent with a constant drift model. Once corrected, the onset times for sprites and ELF transients agreed to within 20 to 30 ms. This interval is much shorter than that between successive transients (several seconds) and is comparable to the video time resolution (17 ms). The assumptions involved with this time correction prevent the correlation of specific features of the ELF waveform with sprite development.

The combined data, however, provide confirmation of sprite and ELF transient overall coincidence. For example (Fig. 3), the time of the first video detection of a sprite is overlaid on an ELF transient waveform. The sprite, consistent with our correction model, is coincident with the transient's onset to within a few milliseconds. The time of an associated positive ground stroke, having a NLDN-derived peak current of 327 kA, is also shown. The close coincidence of this stroke with both the transient and sprite onsets lends further credence to the ELF timing.

Before we can clearly associate the observed ELF phenomena with the observed sprites and ground strokes, we should first confirm (i) that they are indeed Schumann band signals and (ii) that they originate in the MCSs under study. Using the known frequency response of the Rhode Island system and measurements of natural lightning spectra and attenuation from 100 Hz to 100 kHz (*31*), we confirmed that the observed transients are probably ELF signals and not contamination from higher frequency [very low frequency or low frequency (VLF or LF)] noise. Spectral analysis of some of these events (Fig. 4) shows evidence for the entire sequence of SR modes, beginning

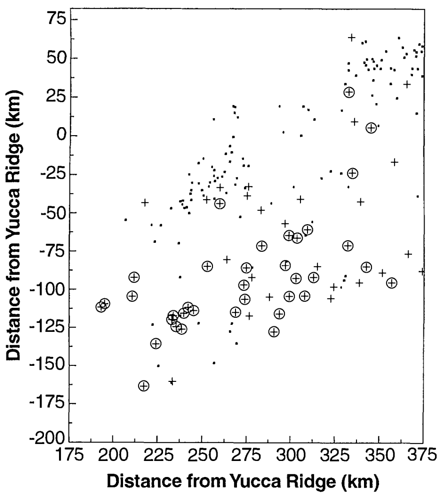

Fig. 2. Spatial distribution of lightning ground strokes within 10 s of sprites in the 12 July MCS. Negative strokes are shown by dots, positive strokes by plus symbols, with sprite-related strokes circled. The traditional "horizontal bipole" of stroke polarity is evident. The positive strokes were located within regions of stratiform precipitation in the National Radar Summaries (not shown). Note the strong clustering of many of the sprite-related positive strokes.

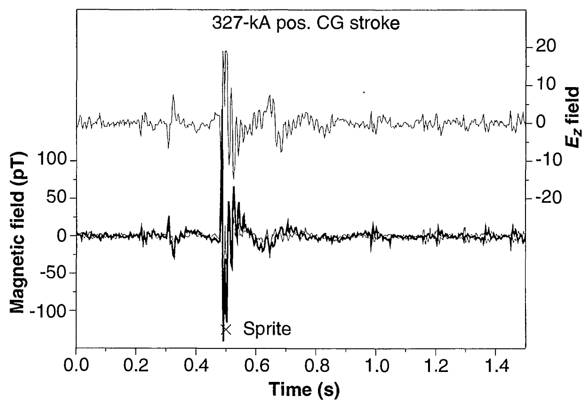

Fig. 3. A typical sprite-related ELF transient (7 September 1994, 07:14:18.889 UTC). Vertical electric and horizontal magnetic fields are shown (north-south magnetic field is bold, east-west magnetic field is thin). The times of the associated sprite and the positive CG stroke are overlaid. Following (*18*), the observed ~25-pT magnetic amplitude implies a change in total dipole moment greater than 1000 C-km.

Table 1. Coincidence of sprites with other electromagnetic events (positive ground strokes and ELF transients) for 12 July and 7 September 1994.

Date (1994)	Number of sprites	Sprites with +CG strokes (%)	Sprites with ELF transient (%)	Sprites with +CG strokes and ELF (%)
12 July	42	86	95	86
7 September	55	82	78	78

with the fundamental mode at 8 Hz and extending beyond the power line frequency at 60 Hz, where some distortion is experienced as a result of line noise filters. The existence of discrete modes at specific frequencies is strong evidence that these transients are indeed Schumann-type resonant phenomena.

Discharge events removing positive charge (that is, positive ground strokes) exhibit negative rises in our ELF electric field data (the event in Fig. 3 is typical). On 12 July and 7 September, 86% and 78%, respectively, of the transients associated with sprites were also coincident with detected positive strokes in the MCS region (Table 1) and agreed in polarity with these strokes. This polarity agreement is further evidence that the ELF transients are originating in the MCSs under study.

There is also some agreement in amplitude between ELF transients and NLDN peak currents (Fig. 5). If, as we believe, the two instruments are observing the same phenomenon at different frequencies (3 to 120 Hz and 1 to 500 kHz, respectively), this correlation would be expected, as both are magnetic crossed-loop measurements. The NLDN peak currents are also anomalously large (Fig. 6); the sprite-related positive CG peak currents are two to three times the median negative CG peak current and are larger than (albeit with some overlap) the median peak currents for positive CG strokes without sprites. The sprite-related positive CG strokes fall primarily within the upper 3 to 15% of the distribution of all positive strokes seen by the NLDN (32).

Further support for the notion that ELF transients and the sprite-associated positive CG strokes originate in the same region comes from single-station location of several events. Standard magnetic crossed-loop, direction-finding methods give the bearing β to the source as

$$\beta = \tan^{-1}\left[\frac{H_{NS}(\omega)}{H_{EW}(\omega)}\right]$$

where ω is the frequency. We took power spectrum density (PSD)–weighted averages of individual spectral azimuth estimates and found, for each of nine events, bearings within 10° to 15° of ground stroke locations independently determined by the NLDN (33). For all events on the comparison days, the polarity correlation between E_z and H (needed to resolve quadrant ambiguities) correctly placed the sources in the western quadrants. We thus believe, given the timing, polarity, amplitude, and bearing agreement, that the observed transients were clearly associated with sprite-related positive ground strokes in the MCSs under study (34).

The common link between sprites and ELF events appears to be the positive CG event. We may infer further characteristics of the sprite-related positive CG strokes on the basis of this coincidence. The detection of ELF transients [resonant transverse magnetic (TM) modes in the Earth-ionosphere cavity] with distant origins requires a large change in the total vertical dipole moment on time scales up to ~30 ms (35). Thus, the sprite-related positive CG strokes exhibit both anomalously large peak currents (as observed by the NLDN) and total charge transfer (as inferred from the ELF signal).

This large charge transfer favors an explanation for sprites in which rapid electrostatically induced field changes aloft stress the mesosphere to dielectric breakdown, as originally proposed by Wilson (36). To achieve dielectric breakdown at altitudes at which sprites are observed, the field change must be fast compared to the relaxation time (which decreases with altitude) in the mid-upper (nighttime) mesosphere and should exceed the local breakdown strength (which also decreases exponentially with altitude). Most lightning processes are faster than the relaxation time, which at 80 km is about 10 ms but may vary by an order of magnitude (37). This mechanism will also be most effective if charge is neutralized over a large area, as a linear or planar charge removal will ostensibly stress a larger region above the storm than a conventional point dipole-like discharge and will induce a larger field change at a given altitude.

This mechanism is consistent with the observed morphology of other MCS stratiform regions and many positive discharge events. Electric field soundings through stratiform anvils detect concentrated lower positive charge of ~1 to 2 nC/m^3 (6). If this layer is indeed horizontally extensive, it represents an enormous reservoir of positive charge available to discharges. Moreover, the dendritic network of channels contained in "spider lightning" events is often consistent with propagation through lower

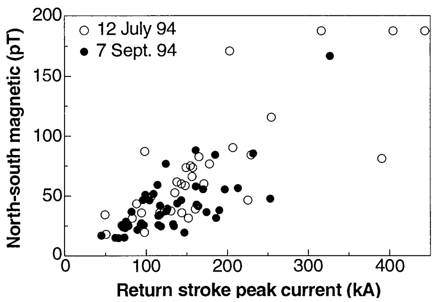

Fig. 5. Correlation between the magnitude of the initial ELF magnetic field rise and coincident ground-stroke peak currents for events on 12 July (open circles) and 7 September (closed circles). The positive correlation is further evidence that the ELF system and the NLDN are detecting the same events. Note the apparent threshold peak current of ~50 kA for sprite occurrence.

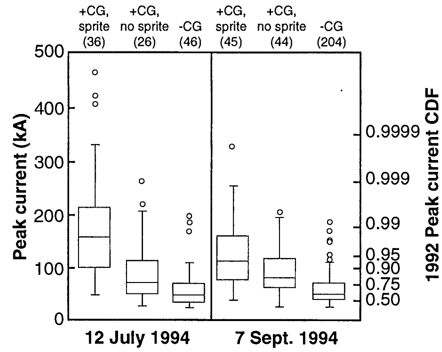

Fig. 6. Box plot statistics of positive CG peak currents within 10 s of sprites in the two MCSs. The plots show the median, quartiles, and outlier points for CG strokes associated with and not associated with sprites. The CG statistics cover the entire infrared cloud shield region, whereas sprite video detection was restricted to a 50° field of view. Sprite-related CG strokes show median peak currents nearly twice that of non–sprite-positive CG strokes and up to three times that of negative CG strokes. The right axis maps peak currents onto the cumulative distribution function (CDF) of all positive ground strokes observed by the NLDN in 1992 (32).

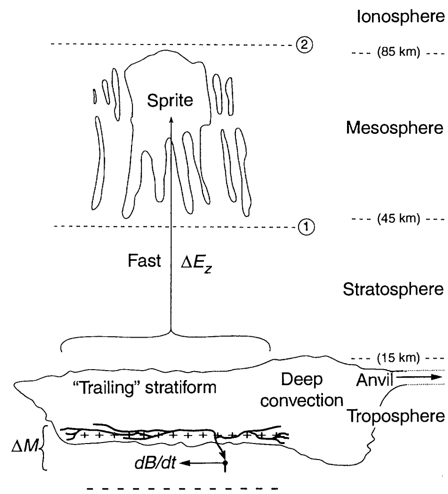

Fig. 7. Schematic picture of the proposed connections between sprites, positive CG strokes, and Q bursts. The positive CG stroke is the electrostatic source for the sprite and the electromagnetic source for the Q burst. Radiation upon ground attachment (*dB/dt*) of the CG stroke is detected by the NLDN. The return stroke rapidly delivers negative charge through an existing areally extensive dendritic structure near cloud base. More complicated charge structures undoubtedly exist higher in the anvil but are not central to the current argument. Aloft, the rapid electrostatic field change from this event results in breakdown if it exceeds the local breakdown strength (above altitude 1) and occurs faster than the local relaxation time (below altitude 2). The change in the total dipole moment ΔM from the event excites resonant TM modes (Q bursts) at ELF in the Earth-ionosphere cavity.

positive-charge regions (*15, 38, 39*). The observed charge densities and altitudes and inferred changes in the total dipole moment are evidence that the positive CG strokes must be tapping a horizontal region of $\sim$150 km^2, either through long horizontal channels or through areally extensive dendrites (*40*). Either configuration is favorable for both electrostatically stressing the mesosphere to breakdown and exciting large-amplitude ELF transients (Fig. 7).

Because (electrostatic) mesospheric breakdown favors rapid charge transfer, we further postulate that much of the total charge transfer is occurring within a few milliseconds of the stroke's ground attachment, rather than being associated with slow ($\sim$100 ms) processes in a long continuing current later in the flash. The return stroke would thus rapidly progress into existing dendrites aloft (*41*). This behavior would be consistent with recent observations that positive return stroke progression does not decelerate with height (*42*), that the brightest illumination of positive return stroke channels aloft lasts for several milliseconds (*43*), and that up to 50% of the total field change of positive flashes occurs during the first few milliseconds of the return stroke initiation (*11, 44*).

Other studies have suggested that sprites are caused by the radiated electromagnetic fields associated with charge acceleration in intracloud flashes (*45*) or return strokes. We believe that the coincidence of sprites with ELF transients (implying extraordinarily large charge transfer) favors an electrostatic over an electromagnetic triggering mechanism (*46*). High bandwidth waveform measurements of sprite-related ground strokes and aircraft measurements of electric fields above stratiform anvils are needed to further substantiate this claim.

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