CHAPTER IV.
MORPHOLOGY AND CHARACTERISTICS OF TREMEs

IV.1. Introduction – Sprites, Elves and Blue Jets – General Descriptions: At the onset of this effort, the basic morphology of the three major transient electromagnetic events was reasonably well understood. Yet due to the lack of high temporal and spectral resolution measurements, many critical details of structure and energetics of these phenomena were unresolved. A plethora of theoretical models had been developed, but many made assumptions as to the characteristics of the lightning source term that were at best educated estimates and in many cases mere speculation. In this chapter, we review the basic morphology of TREMEs.

IV.1.1. Sprites: It was known that sprites were virtually exclusively associated with +CG flashes as recorded by the National Lightning Detection Network (NLDN) (Lyons 1994, 1996). There was a general tendency for sprites to be associated with higher peak current +CGs, typically 50% larger than others in the same storm. However, numerous sprites have been observed with relatively modest peak current flashes. Their color apparently range from red in the top and body, fading to blue at lower altitudes in the tendrils (Sentman et al., 1994). The highest altitudes peak above 90 km and some of the tendrils extend to below cloud top, though there is no convincing evidence of contact with the underlying cloud tops. As imaged using LLTV, sprites last between one and 10 video fields, with the brightest fields usually occurring in the first few ms. Photometry measurements suggest that the brightest emissions only last on the order of 1-3 ms (Winckler et al., 1996). The sprite is not simultaneous with the +CG flash, but onset often lags a few to often tens of milliseconds. The brighter events tend to have a shorter lag time from the parent +CG. Sprites are like snowflakes - all appear different in size and shape. Yet certain common elements are frequently found. The most basic structure appears to be the columnar or C-sprite (Figure 1 - left). These uniform vertical columns are generally straight, nearly vertically aligned, on the order of 1 km wide and 10 km tall. Tendril-like streamers often extend downward and upward flaring branches often involve the upper structure. Larger sprites often appear to be composed of clusters of C-sprites. Using triangulation of a typical sprite sequence imaged at YRFS and at Jelm Mountain, WY (Wescott et al., 1998), the typical distribution of sprite elements can be seen (Figure 2). This illustrates that the sprite is generally centered within about 25-50 km of the attached point of the parent +CG.

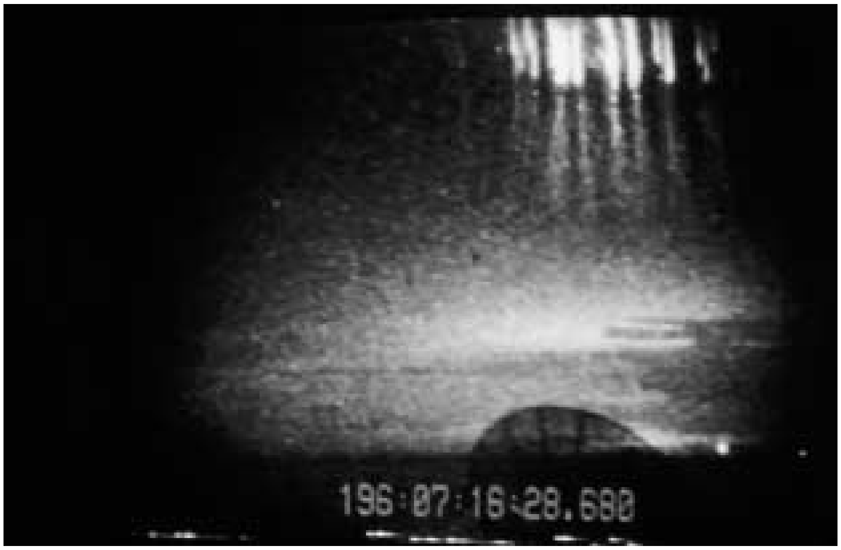


Figure 1. Image of a cluster of C-sprites taken from YRFS.

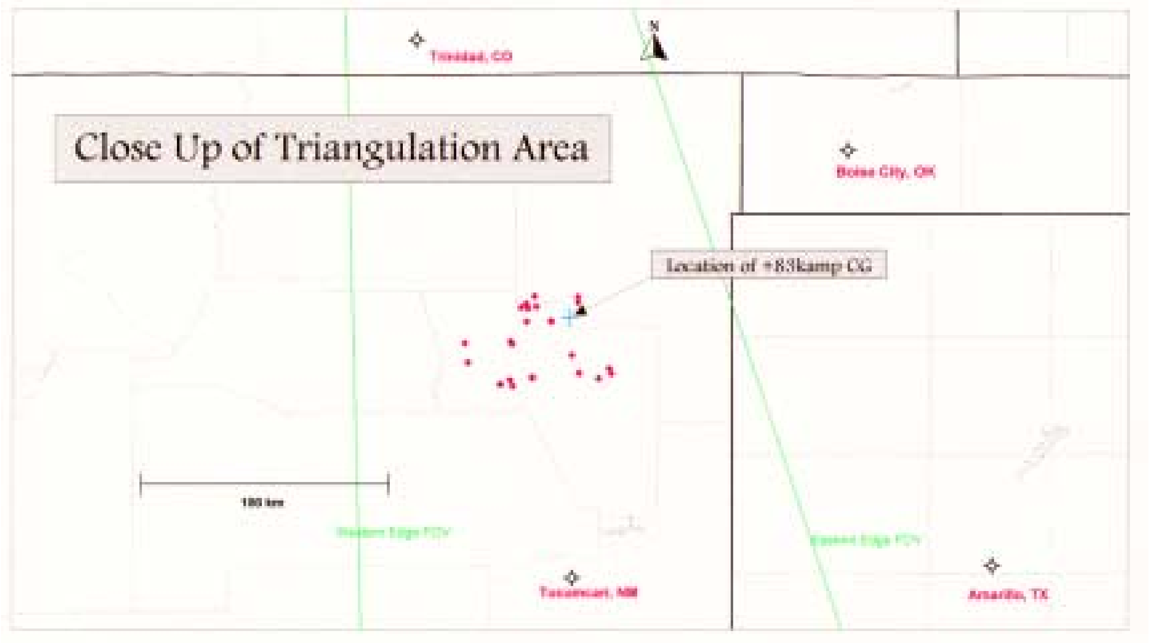


Figure 2. Example of triangulation area and distribution of sprites.

IV.1.2. Elves: Brief high altitude flashes were first noted at YRFS in 1994 and it was suggested that these might be the "airglow brightening" reported by Boeck et al. (1992) (discussed elsewhere in this report). Using high speed photometers, the 1995 campaign yielded evidence of the feature now called elves (Fukunishi et al., 1996). These broad (up to 400 km diameter) expanding, disk shaped structures are layered between 75 and 105 k, on the ledge of the ionosphere. They are associated with extremely high peak current +CGs, often twice the average peak current of those for sprites. The vast majority of optically-detected elves seen with the Xybion LLTV appear to be correlated with positive polarity CGs, although recent evidence has emerged suggesting some correlation with negative polarity CGs. PMT measurements confirm that the onset of elves is on the order of ~300 microseconds, the round-trip traversal time of radiation from the ground discharge to the ionosphere to the observer. The luminous intensity is high but very brief, of duration on the order of 500 microseconds. Theory (e.g. Taranenko et al., 1993) suggests the elve results from the coupling of the EMP from the parent CG with the lower ledge of the ionosphere. Models predict that elves should in fact be a rapidly expanding doughnut shape (Inan et al., 1996). Only rarely has this structure been noted, an example of which is shown below in the detailed discussion. One puzzle that continues is the apparent bias towards +CGs, if EMP is the causal mechanism. Although there are documented examples of negative polarity CGs causing elves, they are much less frequent, even though negative polarity lightning is much more common than positive polarity lightning. The reason may lie in the time-waveform of the –CGs being relatively weak in the required frequency range. This continues as an unresolved issue.

IV.1.3. Blue Jets and Starters: The very rarest of TREMEs are the blue jets. These clearly arise from top of electrically active storms. Some events only rise several kilometers above the clouds (starters) but others can reach altitudes of 40-50 km (Wescott et al., 1995). The jets flare as they ascend at a 10-20 degrees angle, and travel at speeds on the order of 100 km/sec. Blue jets were not found to be associated with specific CG discharges of either polarity. Curiously, after each jet, there appears to be a pause of several seconds in the lightning flashes for the surrounding 15 km in the storm. The greatest fraction of the blue jet video observations of the phenomenon actually come from overflights of a single thunderstorm in Arkansas. This storm was producing large hail, eliciting speculation that the presence of hail is critical to the blue jet mechanism.

The following discussion presents a series of case studies which add to the details of our knowledge of transient electromagnetic events and the troposphere electrical activity which gives rise to them.

IV.2. A Well Documented Sprite Event. Sprites generally first emerge during the early mature states of an MCS that has developed a relatively large stratiform precipitation area. As indicated elsewhere in this report, the radar echo area (>20 dBZ) generally must be on the order of 10,000 km^2 before TREME activity can be expected. The storms may often reach severe levels, but that does not appear to be a prerequisite. Convective core reflectivities typically exceed 50 dBZ, which is in and of itself not at all unusual. This case presents a “typical sprite” from a “typical small storm” of 09Aug98 that was exceedingly well characterized by multiple observations. The meteorological data on the parent storm is shown in Figure 3. GOES infrared images showed the characteristic circular cold cloud top. The radar echo, which included considerable stratiform precipitation area, covered approximately 10^4 km^2. The NLDN indicated relatively low flash rates (under 50 per hour, with about 20% positive polarity). Only five sprites were recorded from this system over a 75 minute period during its late mature stage. The most dramatic event occurred at 0612.47.846 UTC. Four LLTV systems were trained on the region above the storm top, one was quite close to YRFS and permitted an excellent set of images at a range of 147 km (Figure 4). Excellent multi-color, high-resolution photometry of this case was also obtained, as is discussed in detail elsewhere in this report (Armstrong et al., 2000). This sprite began as a

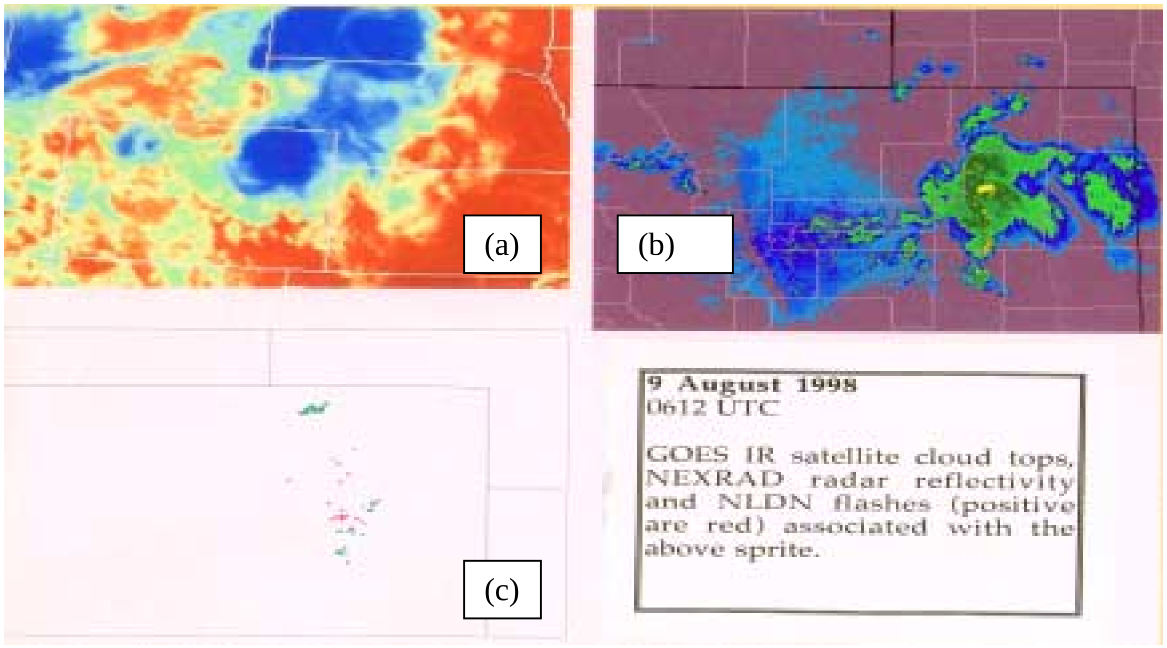


Figure 3. Meterological data on the 09Aug98 storm: (a) GOES image, (b) radar reflectivity, (c), NLDN flash locations.

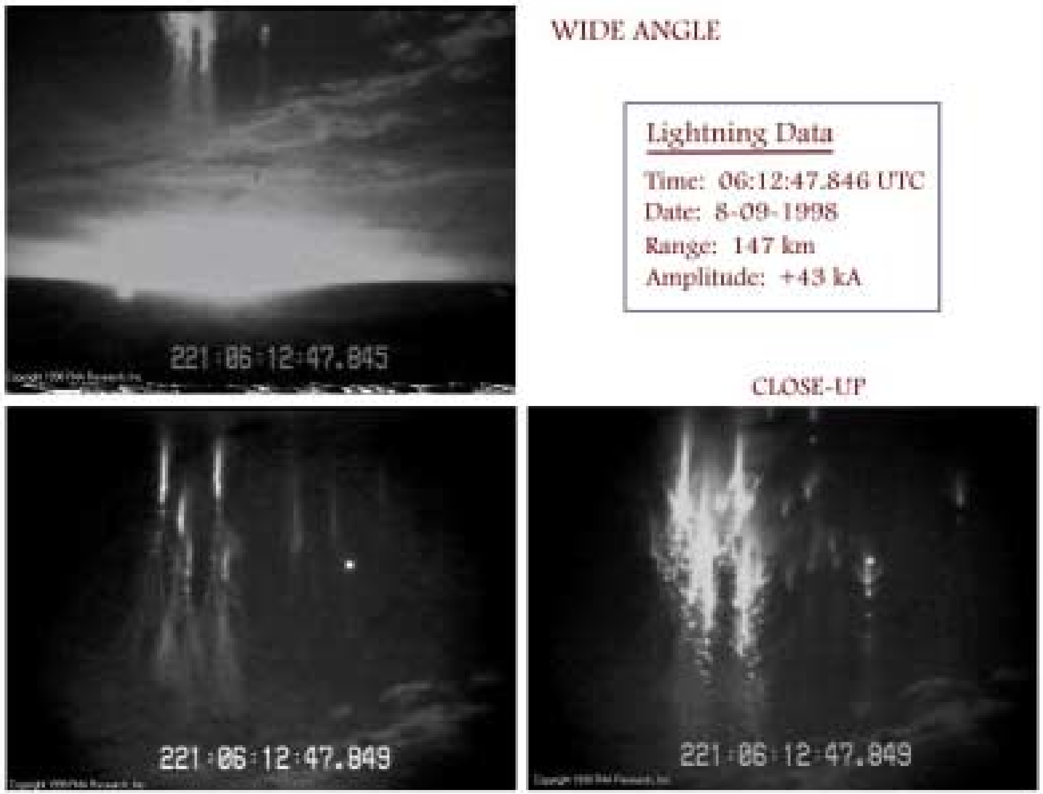


Figure 4. Example of a well-studied sprite event which occurred on 09Aug98.

classic cluster of C-sprites about 3 ms after the parent 43 kA +CG ground flash. The parent CG gave rise to a cloud illumination which was extremely bright, peaking just prior to sprite onset.

While photometers revealed that the brightest and most energetic part of the event lasted less than 3 ms, the LLTV system was able to detect fainter luminous structures for over 50 ms. What makes this event unique is that it remains the only sprite for which LLTV images of the sprite were obtained coincident with high speed images of the parent lightning discharge (Figure 5-left). In this case there appeared to be relatively little preliminary breakdown visible, but once the CG channel was established, it continued for at least 8 ms.. Given the distance (147 km) and the fact that the flash was partially “rain-wrapped”, it is likely that this continuing current may have lasted considerably

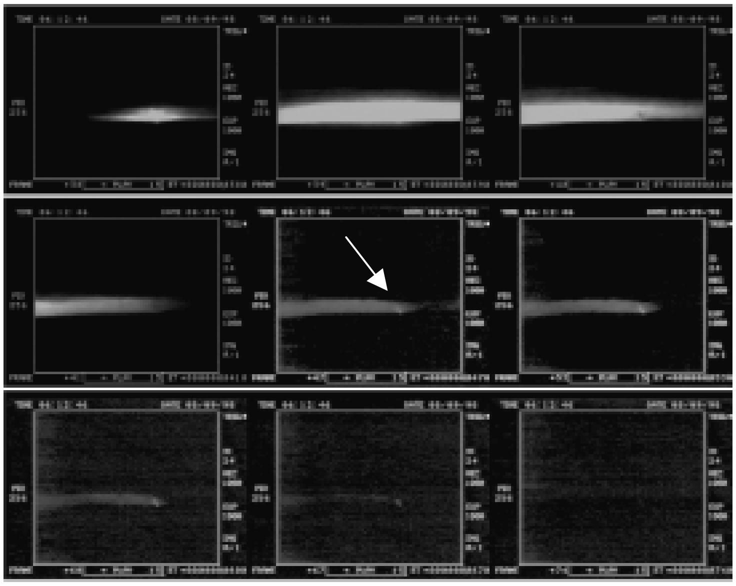


Figure 5. High-speed imagery of the parent lightning associated with the sprite event of figure 4.

longer. It can also be noted that the dimension of the cloud illumination was quite extensive, several tens-of-kilometers across. We have evidence that this case is prototypical of the classic sprite +CG event: a long continuing current (versus the tens of microseconds for a typical return stroke) accompanied by a network of horizontally inter-connected channels within the lower portion of the cloud which serve to feed current to ground over an extended time.

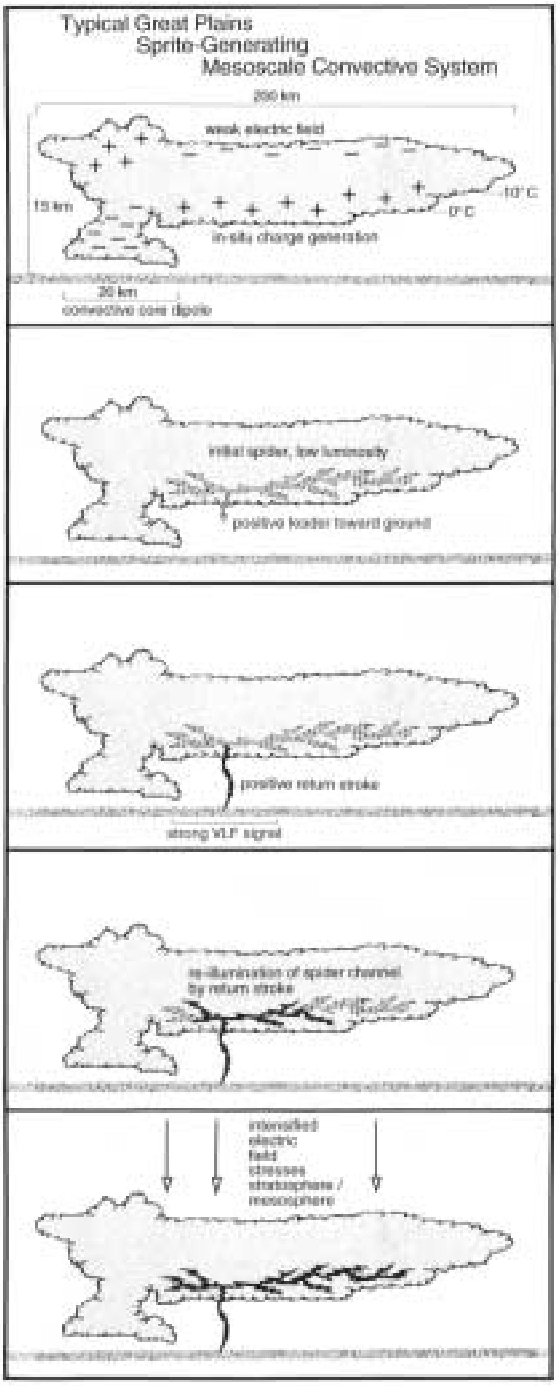


Figure 6. Conceptual model of the development of the lightning-sprite

Figure 6 (left) presents our conceptual model of the sprite parent +CG event that was first proposed by Lyons (1996). The parent +CG of the sprite is clearly very different from "ordinary lightning" in several key aspects aside from peak current. These unique discharges are dependent upon specific cloud dynamical and microphysical mechanisms. Moreover, these forms of lightning only tend to occur within a portion of the stratiform region of larger MCS storms (Williams, 1998) as has been often observed (Lyons, 1996; Lyons et al., 1998). For the U.S. High Plains, at least, this model is being incrementally verified with each sequential observational campaign.

__IV.3 High Speed Imaging Results.__ During the 1998 and 1999 campaigns YRFS had access to a Kodak EktaPro Model 1012 High-Speed Motion Analyzer with a image intensified video. The pixel array size of this system was relatively coarse, 239x192 pixels. The imager was relatively broad band, operating from 350 to 800 nm (10% efficiency) with the 440-770 nm band having 50% sensitivity. The camera system was capable of running at a variety of speeds, but for various reasons we standardized on 1000 fps. Operated with a zoom lens, we nested the field of view within that of the Xybion LLTV patrol camera in order to obtain close-up images. The system has neither the dynamic range nor the effective sensitivity of the Xybion (with is 17 ms integration period), and thus it tended to record only the brighter initial portions of sprite and elve events. The High-Speed Imager quickly provided evidence of what various photometric analyses had suggested (Armstrong et al., 1998 Suszcynsky et al., 1998), mainly that the peak emissions of most sprites lasted only a few milliseconds but secondary features can persist much longer. Figure 7 (left) shows three sequential one-ms fields of an extremely large and brilliant sprite (visible to the naked eye) associated with a 95 kA +CG at 542 km range from YRFS on 18 August 1999. The sprite, along with its well-developed tendrils, growing head and surrounding halo, was fully developed within the first millisecond. Figure 8 and Figure 9 show both conventional Xybion LLTV and Kodak High-Speed sequences, respectively, of another sprite. The first four fields of the standard Xybion, with 17 ms integrated images, show a sprite with clearly developed tendrils present in the first field. Numerous hot spots and bright areas remained in the upper portion of the sprite during the second 17 ms field. Dim remnants of several of the vertical lineaments remained for several tens-of-milliseconds thereafter during the “glow down” phase. The companion High-Speed sequence shows that it took 1-2 ms for the sprite to become fully formed. The downward extending tendrils appear to be much more ephemeral, dissipating within 1-2 ms.

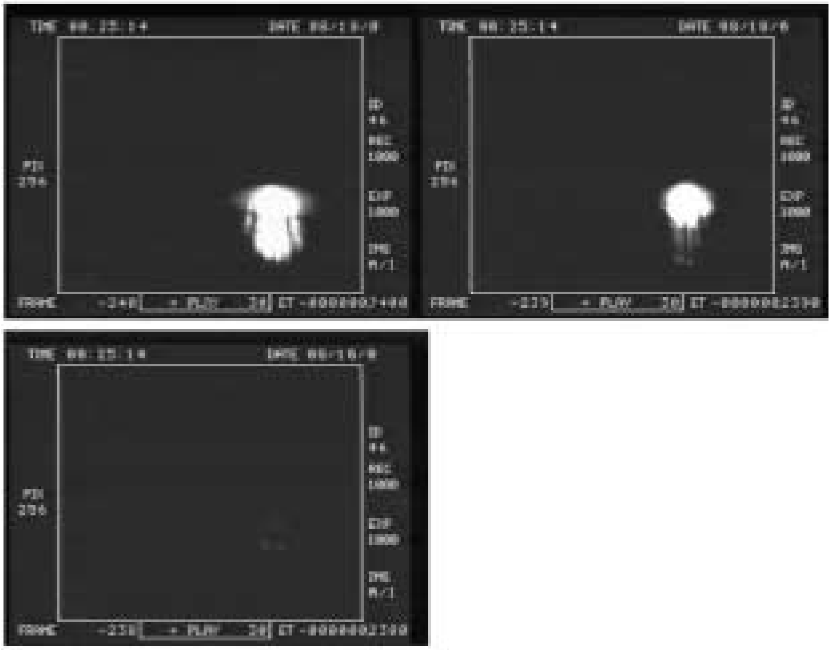


Figure 7. High-speed images of an 18Aug99 sprite.

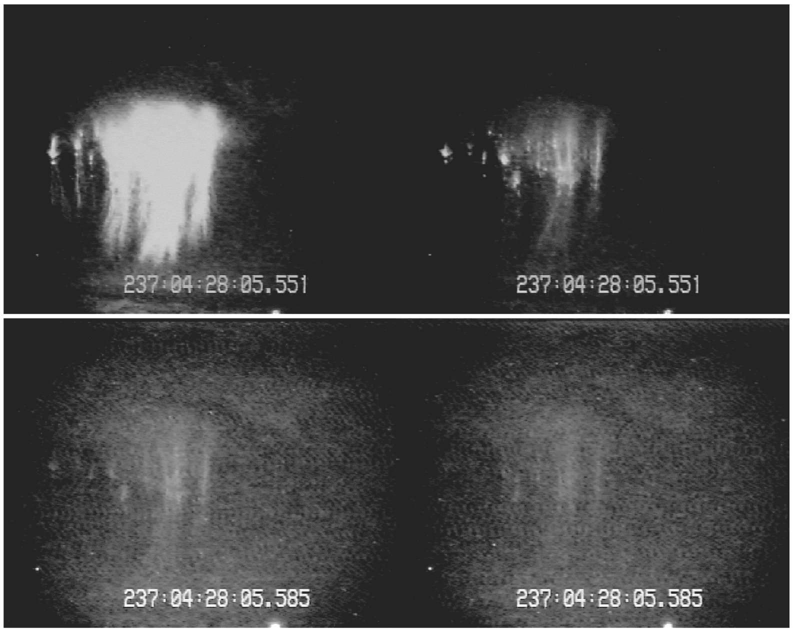


Figure 8. Conventional Xybion images of a sprite.

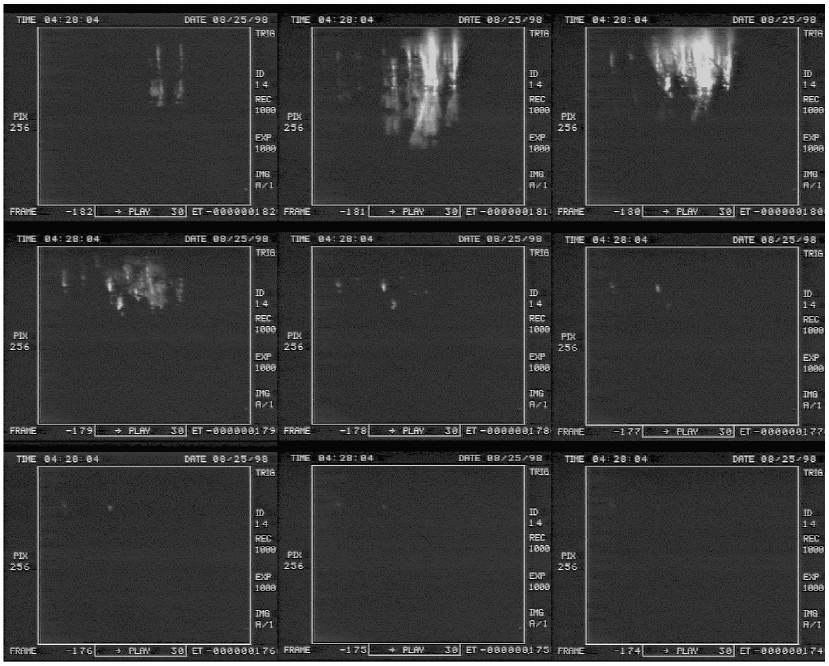


Figure 9. High-speed image sequence of the same sprite shown in Figure 8.

The bright structures in the upper portion of the sprite are, as expected, far more persistent because the quenching at higher altitude is less important. This sequence demonstrates (though not as clearly as some) that many sprites begin as vertical filaments (C-sprites) and exhibit both downward and upward growth, consistent with Stanley et al. (1999).

Figure 10 and Figure 11 show two additional high speed sprite sequences. These both show the initial luminosity is a downward moving elve-like disk which persists for 1-2 ms. On conventional Xybion video this appears as a “sprelve”, an elve-like emission and sprite caught on the 17 ms field. However, the height of the “elve” starts below 80 km and moved downward to the altitude of sprite initiation. Photometric evidence suggests it may not be, in fact, an elve, but rather the early development of a sprite discharge. This feature is currently being referred to as a “halo”. These examples illustrate a fairly common occurrence, mainly that the sprite often starts as a point of a single very thin, often beaded column at an altitude between 70 and 75 km. The initial growth is often downward, very much in the manner of corona streamers. Downward propagation speed of the tip of the streamer at the end of the developing tendril was found to be 1-3 x 10^7 m/s. As the streamers move downward to perhaps 50 km altitude (sometimes higher, sometimes lower), they begin to weaken after 1-2 ms. Then upward growth begins, often at a lower altitude (~65 km) than the original starting point. The upward branching streamers move at a similar velocity, but the elements tend to be more persistent by approximately a factor of five.

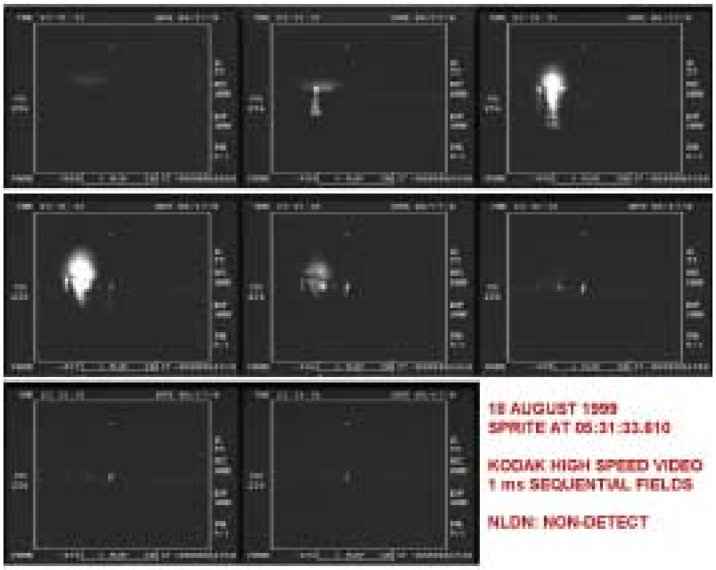


Figure 10. High-speed images sequence showing the development and progression of a sprite.

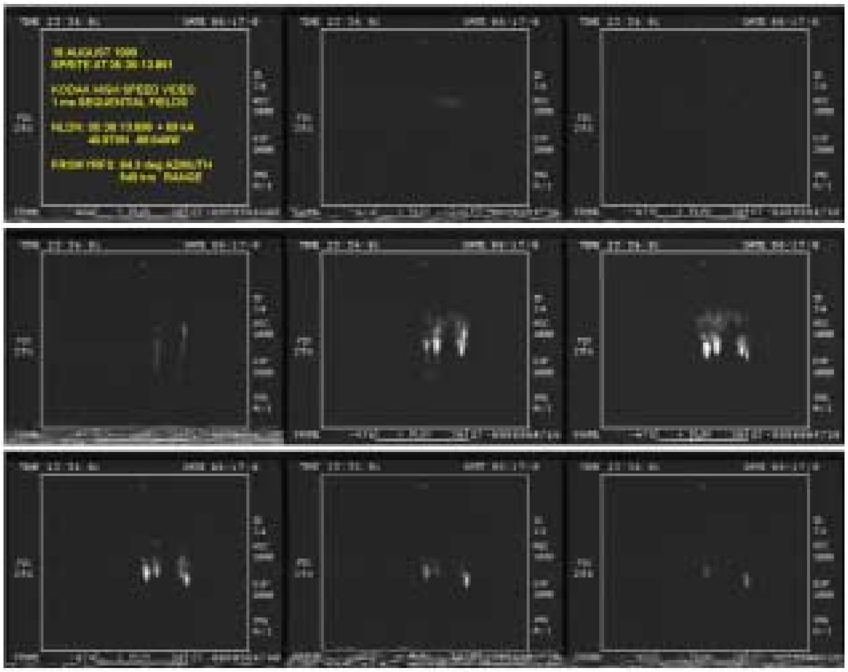


Figure 11. High-speed images sequence showing the development and progression of a sprite.

Secondary quasi-stationary features such as globular hot spots form and are comparatively long lasting. These results are in broad general agreement with results using the same camera system trained on New Mexican sprites from Langmuir Laboratory in 1997 (Stanley et al, 1999).

IV.4. Complex Multiple Sprite Clusters. Larger MCSs often produce the highest frequency of sprites. These events also tend to be more spatially and temporally complex. From the very first ground based sprite observations at Yucca Ridge (Lyons, 1994), it was noted that successive sprites would often appear in sequence above the storm tops, apparently following a horizontally extensive component of a lightning discharge in the underlying cloud. These events have been colloquially termed “dancers.” On 24 July 1996, one of the largest sprite producing storms yet observed moved southwards from Colorado into the Texas-Oklahoma panhandle. This MCS exhibited the classic mesoscale convective complex (MCC) satellite image (Figure 12 - right). The associated radar echo reached a size of 65,000 km^2. Once the system attained maturity, it was organized as a classic leading bow echo with a massive trailing stratiform region. The TREMEs from this system were moni-

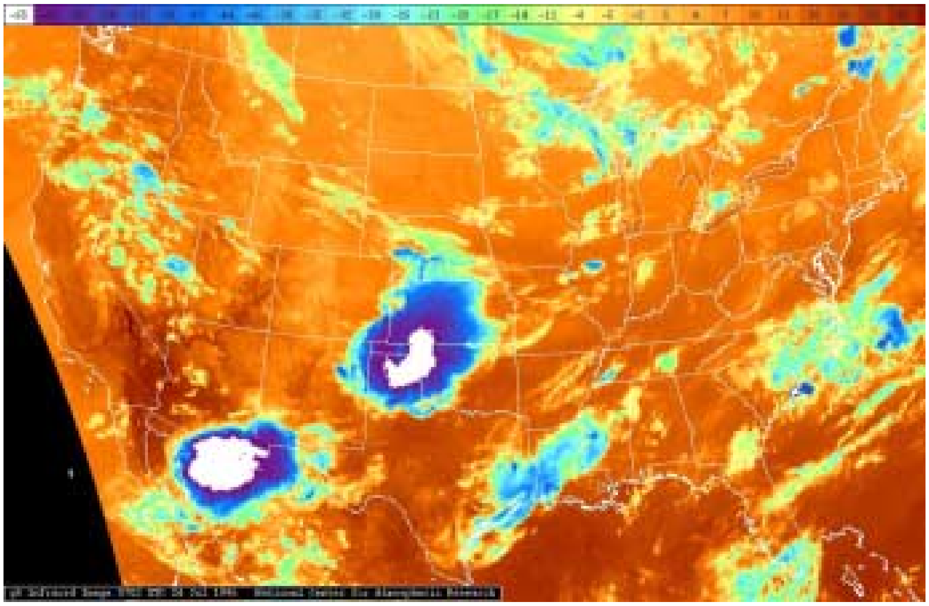


Figure 12. GOES image of 24Jul96 storm which produced “dancing” sprites

tored by dual Xybion LLTVs at YRFS as well as LLTVs at Langmuir Lab in Socorro, NM. This allowed excellent triangulation of sprite locations. RF signatures were detected using the MIT ELF transient system in Rhode Island (Huang et al., 1999), VLF at YRFS, broad band VLF at Socorro and Palmer Station, Antarctica.

LLTV observations commenced at 0300 UTC and the first sprites were detected at 0322. When the experiment was terminated at 0908 UTC, a total of 304 TREMEs (10% of which were elves) were imaged. Analysis of the duration of the TREMEs in the Xybion LLTV systems revealed that the average duration on video was 58 ms, though some events were detectable for upwards of 289 ms (often the result of re-brightening or reformation of the sprite). The brightest field of the sequence occurred in fields 1, 2 or 3 for 60% of all TREMEs (Figure 13). Of the 55 sprites for which triangulations were obtained, the average distance from the apparent sprite center and the +CG attach point was 33 km. The mean breadth of the sprite was 25 km, with an average footprint of about 500 km^2. The largest footprint was 3306 km^2. The average vertical extent of the sprites was 33 km. The lowest altitude to which tendrils were observed to reach was about 31 km.

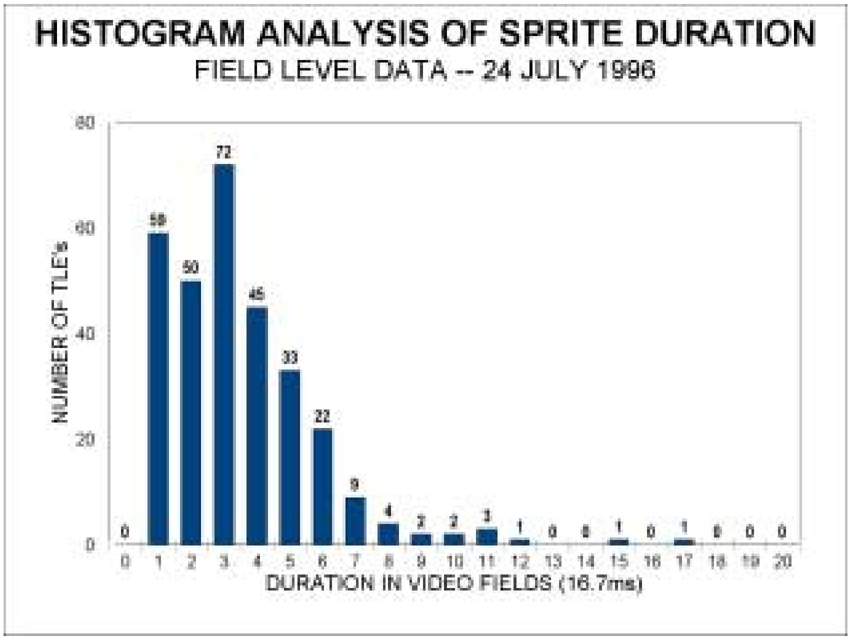


Figure 13. Histogram of characteristic sprite duration

The storm was extremely electrically active, with total hourly CG rates approaching 9000 hr^{-1} around the time of peak TREME activity (0700 UTC). Between 0000-1200 UTC, some 85,000 CGs were logged by the NLDN, and 5.2% of these had positive polarity. The positive rate is relatively low for a nocturnal severe storm in this region, though given the large number of CGs this still represents a considerable number of +CG flashes. In this storm, the –CGs tended to cluster in the high reflectivity cores of the leading bow echo. The +CGs were scattered throughout the trailing stratiform region. The average +CG peak current for this storm was 31 kA (though the value slowly descended from 39 kA at the start of the storm to only 23 kA near dawn). The –CG peak current was characteristically smaller at 21 kA. The peak current of all +CGs associated with TREMEs was 71 kA. Segregating them by type, we find the average sprite +CG had a 61 kA peak current, the “sprelves” were 107 kA and the pure elves were 120 kA. This segregation of TREMEs by average peak current has been noted in many storms.

The CGs associated with TREMEs were clearly segregated by area as well. It has been previously noted that once sprites commence, they tend to occur over a relatively small portion

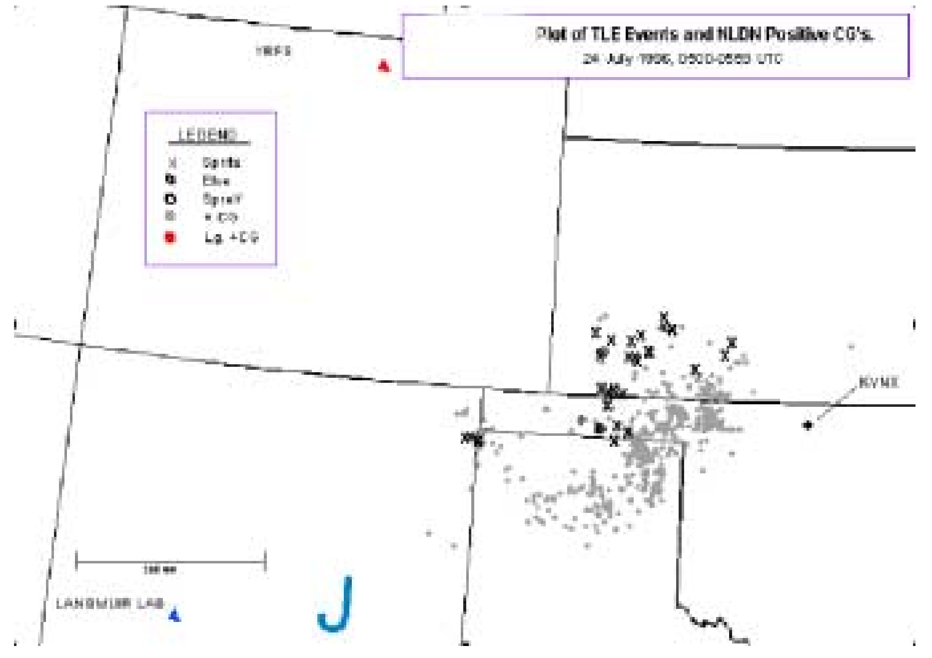


Figure 14. Spatial distribution of +CGs which made TREMEs.

of the larger stratiform region. This area can be as small as 20% of the total (Lyons 1996). The spatial separation of TREME -producing CGs from those which did not is very clear in Figure 14. We obtained Level II NEXRAD digital radar tapes which allowed us to compare the location of the TREME generating CGs to radar reflectivity (Figure 15). It is very evident that neither sprites nor elves occur with any regularity near the high reflectivity (>dBZ) convective cores of such storms. The vast majority were found above the trailing stratiform area where reflectivities varied from 2 to 40 dBZ (Figure 16). In this and other cases, there appears to be a possible correlation with generating cells and the radar bright band region (as indicated by the secondary reflectivity maximum in the trailing stratiform precipitation).

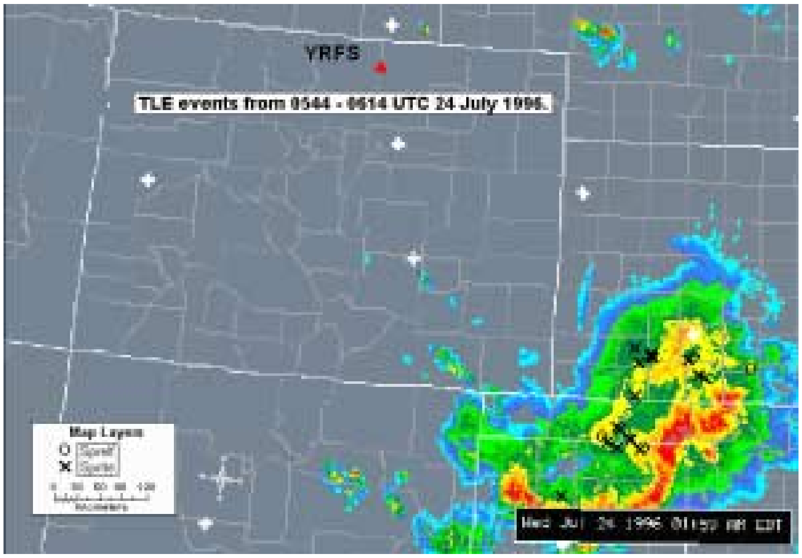


Figure 15. TREMEs and reflectivity for 24Jul96 storm.

While there appear to be distinct differences in +CGs which produce sprites or elves, based upon NLDN-determined peak current, it is not clear that the peak current is a reliable predictor. Reising et al (1996) noted that the presence of an ELF “slow tail” waveform signature proved to be a much better predictor of a sprite occurrence than peak current. A histogram of peak currents for sprites and elves (Figure 17), while suggesting different distributions, also shows considerable overlap. Based on the theoretical and observational results from the MIT ELF transient records, it is expected that charge moment is a more reliable predictor of those +CGs

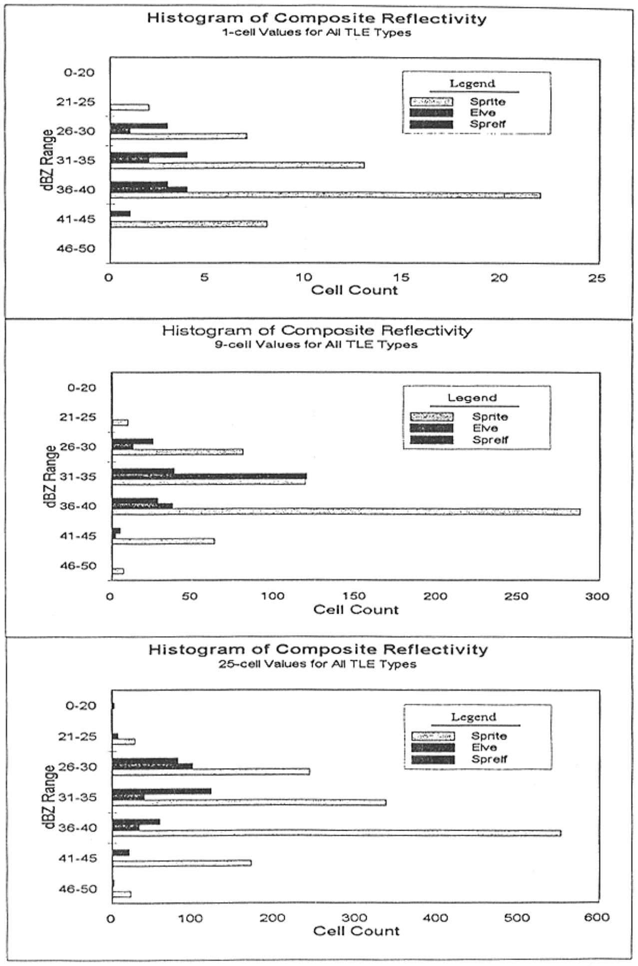


Figure 16. Histogram representation representing the total number of cells with composite reflectivities in the ranges shown (y-axis).

which trigger sprites (Huang et al., 1999). Indeed, for the 24 July 1996 storm, a very clear cut-off around 1000 C-km separated +CGs which did and did not produce sprites. Interestingly, the pure elves, even with their very high average peak currents, showed a very strong tendency to exhibit charge moments <1000 C-km.

Many of the sprites during the 24 July 1996 storm were unusually bright and/or occurred as complex "dancers." One event in particular occurred at 0538 UTC during the peak of sprite activity. The event as viewed from a LLTV at YRFS appeared as a rapid succession of eight discrete "carrot" type sprites (Figure 18). The spatial sequence of the eight events, which lasted 658 ms, spanned about 20 degrees of the horizon at a range of 512 km (Figure 19). The average duration of each sprite segment was 61 ms, with a mean interval of 100 ms. The average top was rather uniform at 88 km, with a base of 43 km. These events were well triangulated between YRFS and Langmuir Lab. The elements traced a southwest to northeast path 178 km long. The "propagation" speed of the series of sprites was about 2.5 x 10^5 m/s, remarkably similar to that of horizontal dendritic lightning channels. When the NLDN records were reviewed, it was revealed that +CG strokes could be associated with three of the individual elements. Typically, +CG flashes have a single return stroke. The sequence appeared to be triggered by a relatively modest 25 kA +CG event. The subsequent strokes had higher peak currents, 43 and 77 kA.

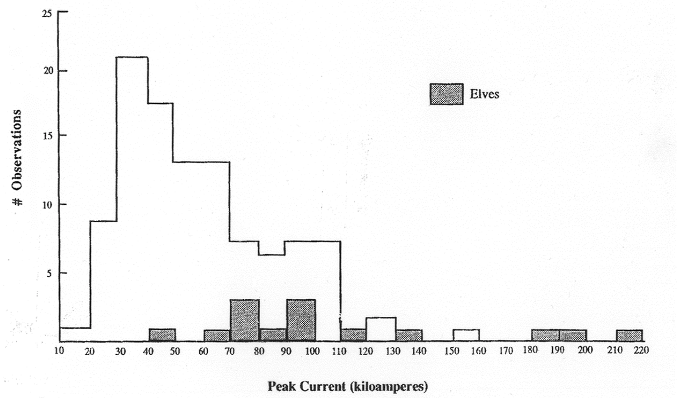


Figure 17. Positive peak current with sprites and elves.

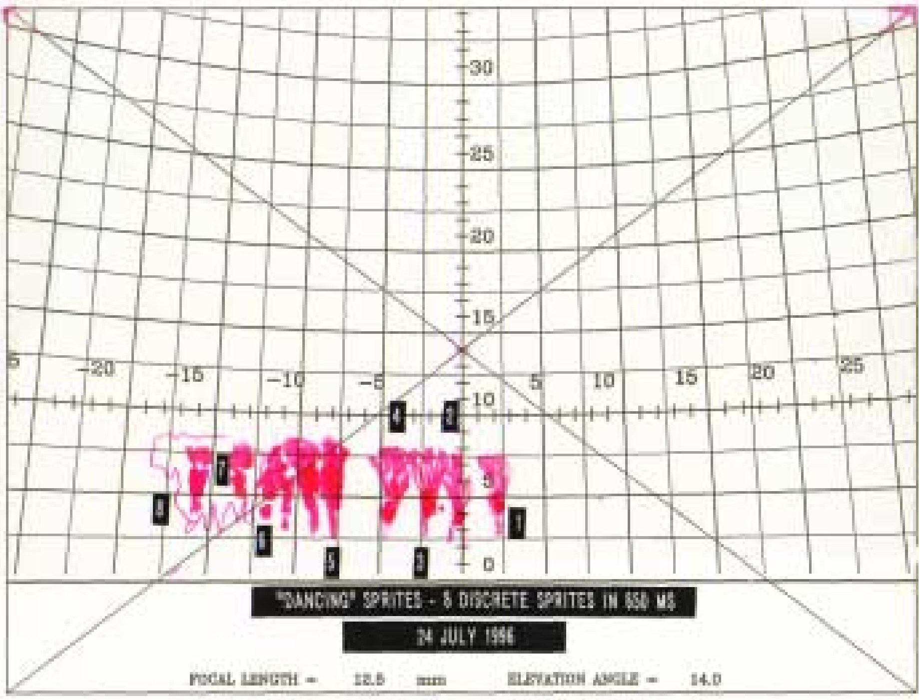


Figure 18. Spatial sequence of the eight events spanning about 20 degrees of the horizon at a range of 512 km.

The triangulated locations showed that the three strokes very closely corresponded in space with the resultant sprite, with a mean separation of only 12.8 km (Figure 20). The first three of the sprite dancers were in the field of view of the YRFS photometers (Figure 21). Each “carrot” yielded the classic sprite optical signature. The associated VLF patterns reveal the signature of the initial 25 kA +CG stroke. The second event appears coincident in time with a 35 kA –CG. The location of this CG was several hundred km distant and therefore not a factor. The third “carrot” was not associated with any detectable VLF signature, and therefore no apparent CG. This event has been very closely scrutinized using ELF and VLF measurements from YRFS, MIT, Socorro and Stanford's VLF receivers in California and the South Pole. As Table 1 shows, there is consistent evidence for sprites 1, 5 and 8 for unique +CG ground strikes. ELF Q-bursts also accompanied sprites 1 and 5. This suggests that there were no NLDN non-detected CGs accompanying the other five sprites. The question arises as to what triggered these specific sprites. Did the other sprites trigger spontaneously in some sort of generally elevated electric field? This seems unlikely given the clear temporal and spatial organization of the event. Is it possible that these sprites were induced by charge transfers associated with the “spider” lightning propagation itself? Perhaps, but then one would have to

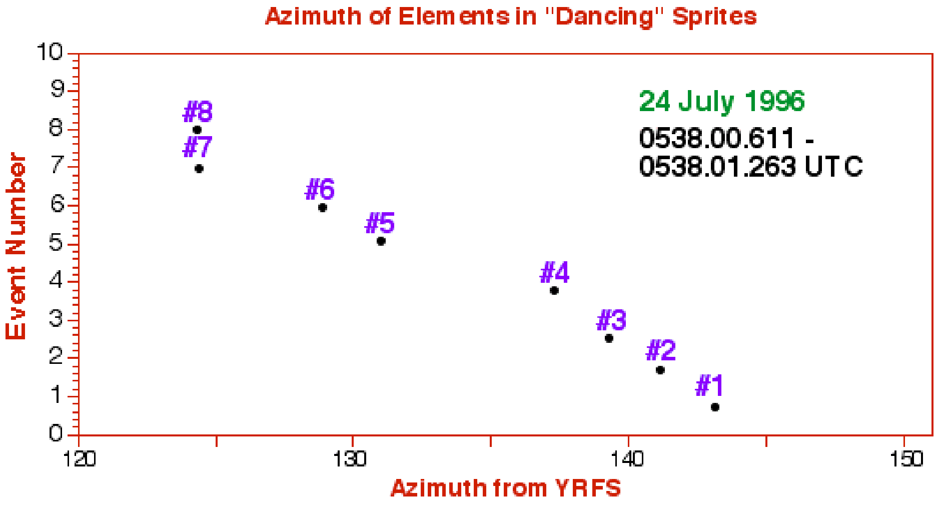


Figure 19. Spatial location (azimuth) of the sequence of sprites.

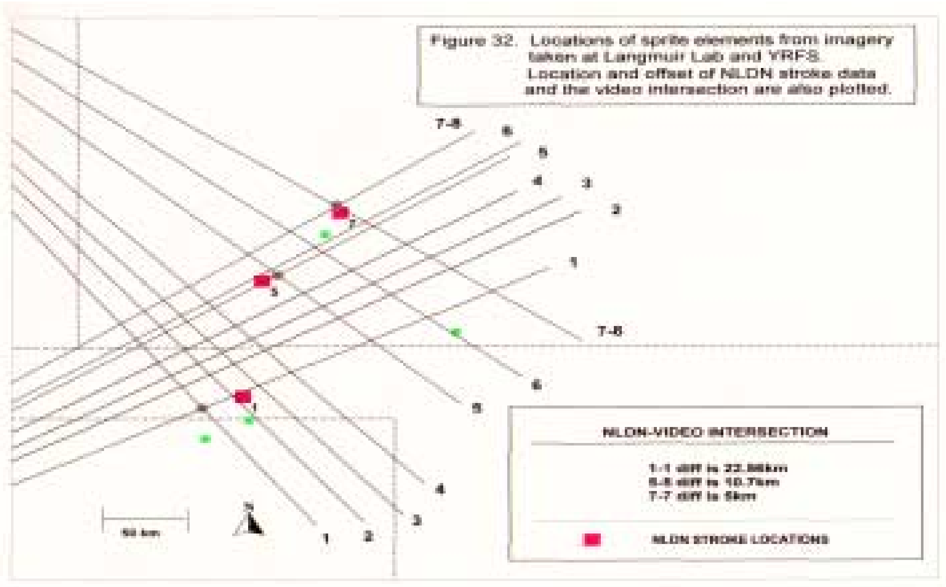


Figure 20. Triangulation-located sprites in "dancing" sequence.

accept that sprites would be triggered more frequently by intracloud discharges, which in severe storms of this type easily outnumber CGs by 10 to 1 or more. Most likely there was one complex lightning event which started with the initial 25 kA +CG from which a northeastward branching series of dendritic "spider" lightning channels extended. Two subsequent +CGs came to ground as the event progressed. Most likely all three +CGs had extensive continuing currents which were fed by the propagating spider discharge reaching new pools of positive charge in the stratiform region. The remaining five events were associated with new surges of charge down the pre-existing continuing current channels. While Cummer et al (1998) have argued that charge transfer inferred during such events might reflect actual current flows in the sprite itself (on the order of several kiloamps), the alternate explanation appears more consistent with what is known about complex +CG events (Mazur et al., 1995; Marshall et al, 1996; Stolzenburg et al, 1994).

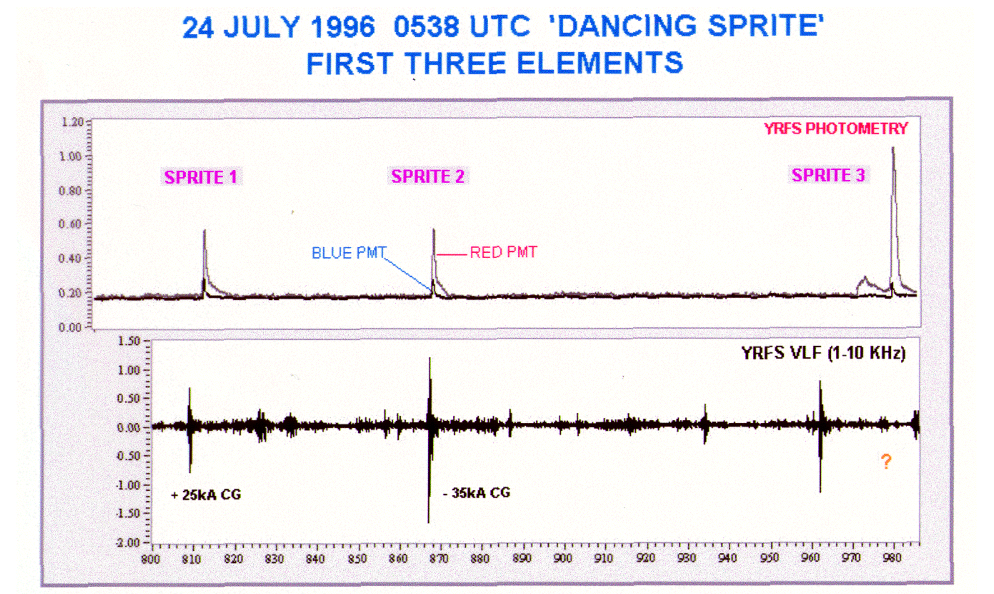


Figure 21. LabView photometer traces for the first three "dancing" sprites.

We present a simple model of this "dancer" in Figure 22. The initial intracloud breakdown is followed by a nearly 200 km long channel moving through the radar bright band in the trailing stratiform region. Three separate +CGs form attach points to ground, presumably with long continuing currents. This event should be considered one continuous electrical discharge, however, extending for over 750 ms (which is not unusually long as evidenced by many YRFS lightning videos showing even more extensive events).

Table 1. VLF and ELF signatures associated with the dancing sprite elements.

Sprite Number	Interval (ms)	NLDN +CG	Socorro VLF	MIT Q-burst	STANFORD VLF Signals		
					California	Antarctica	Slow Tail
1	-	+25 kA	Yes	Yes	Yes	Yes	Yes
2	67	None	No	No	No	No	No
3	100	None	No	No	No	No	No
4	100	None	No	No	No	No	N
5	151	+43 kA	Yes	Yes	Yes	Yes	Yes
6	50	None	No	No	No	No	No
7	33	None	No	No	No	No	No
8	100	+77 kA	Yes	No?	Yes	Yes	Yes

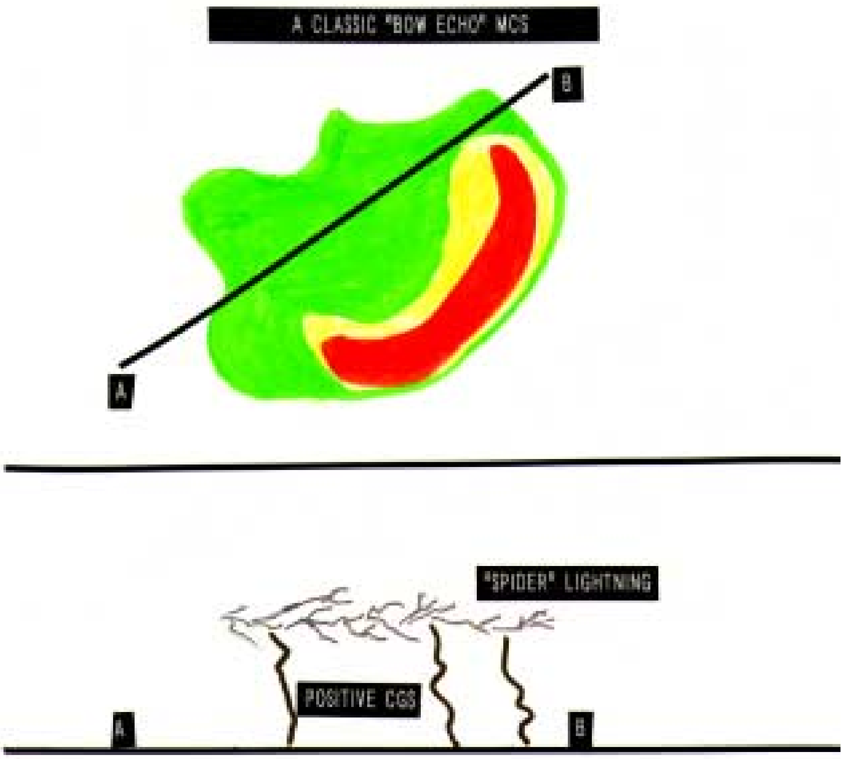
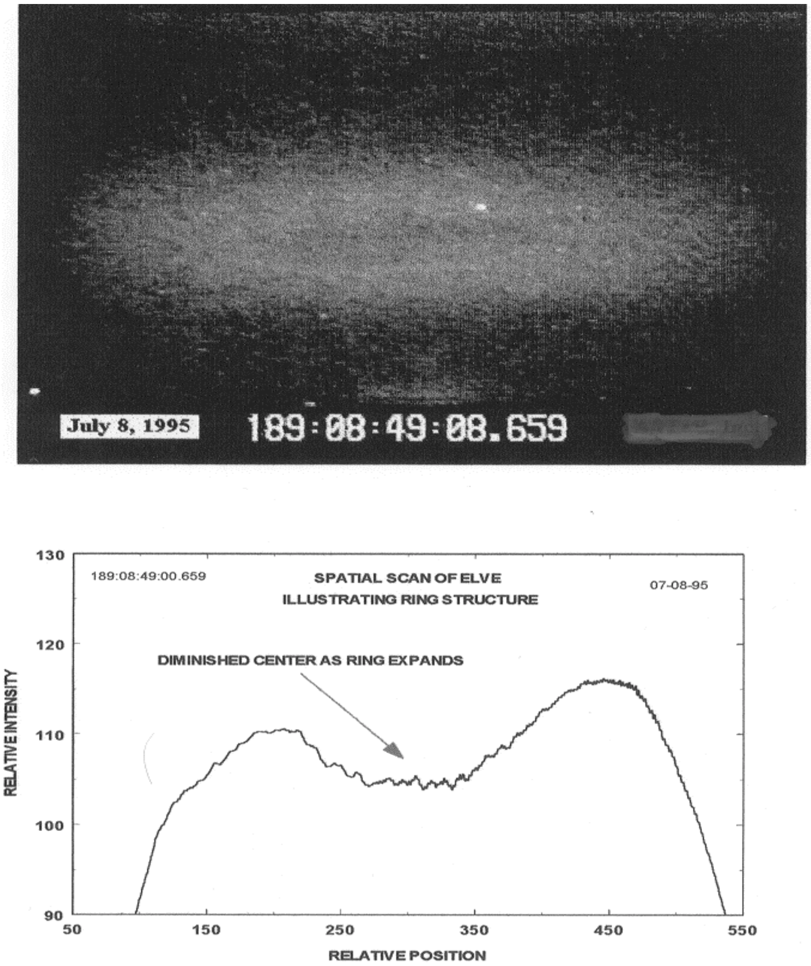


Figure 22. Schematic of the likely connection mechanism of the parent CG sequence which produced the “dancing” sprites.

IV.5. Positive and Negative Elves. Elves, first detected from the ground at Yucca Ridge during the SPRITES'94 season, were confirmed to be a distinct phenomenon during SPRITES'95 (Fukunishi et al., 1996). These observations confirmed theoretical predictions (Taranenko et al., 1993) that emissions near the ledge of the ionosphere would result from the passage of the electromagnetic pulse (EMP) from powerful tropospheric lightning discharges. Various theoretical models have suggested that elves are, in fact, rapidly expanding "doughnuts" of light that can ultimately reach 200 to 700 km in diameter. Images of the "hole" in the "doughnut" have been few, but an excellent example was obtained from Yucca Ridge in 1995 (Figure 23). This elve was associated with a large peak current positive CG event (LPC+CG), as have been the vast majority of elves obtained with low-light imagers such as the Xybion. This, however, is puzzling as there is little in the EMP theory to suggest a polarity dependence. More recently, Barrington-Leigh et al (1999) have presented evidence that suggests "negative elves" can be readily observed, especially if one employs more sensitive photometer arrays (the "fly's eye" device fabricated by Stanford University). It has been frequently noted that elves are associated with LPC+CGs. For instance, in the 25 July 1995 MCS, the peak current distributions of +CGs associated with sprites and elves showed little overlap. Some 68 sprites were associated with +CGs with an average peak current of 58 kA and a maximum of 113 kA. The fourteen elves were found to have an average +CG peak current of 104 kA with a maximum of 200 kA.

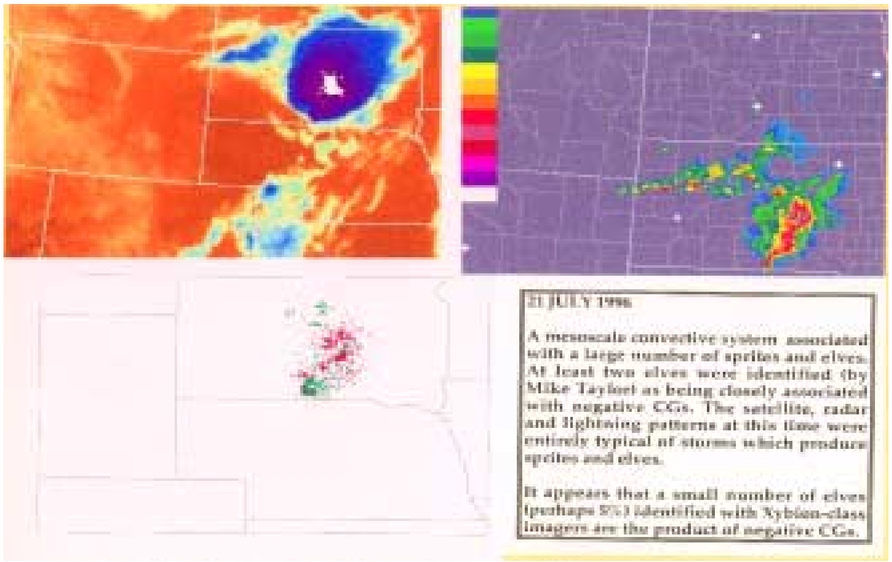


SPATIAL SCAN OF ELVE IMAGE

Figure 23. Image of an elve showing the "donut" morphology and the spatial intensity scan across the middle of the image.

It is often assumed that CGs of positive polarity dominate the upper end of the peak current distribution. This, however, has been found to be false. As will be discussed later in this report, a recent climatology of large peak current CGs of both polarities (LPC+CG, LPC-CG) was presented by Lyons et al. 1998). In this analysis, a composite of NLDN lightning flash data from 14 summer months was stratified by polarity and magnitude. It was found that in all cases, LPC-CGs outnumbered LPC+CGs by more than 3 to 1, even for the very largest peak currents (>400 kA). The discrepancy was less in evidence over the High Plains during the nighttime hours (where the Yucca Ridge TREME observations have been centered), but even there, the large peak current –CGs dominated. This was unexpected. It also made it difficult to understand why elves were not associated on roughly one-to-one basis with LPCCGs of either polarity.

A concerted search began for LLTV of elves associated with –CGs (assisted by Mike Taylor, Utah State University). We indeed did found several cases (from 1996) in which elves appeared to have been triggered by LPC-CGS. On 21 July 1996, an MCS developed in Nebraska, which appeared typical of TREME-producing storms in terms of radar, satellite and lightning features (Figure 24). The events appeared identical to "positive elves" in terms of optical morphologies in the low-light TV imager, the characteristic delay between the CG and the optical signature, and the expected vertical and horizontal extent (Figure 25). The likely parent CGs for these TREMEs were indeed both LPC-CGs. Figure 26 shows the location of one of the TREMEs, the parent LPC-CG (a -186 kA flash) and the horizontal extent of the elve as imaged by the YRFS camera. Assuming the top of the elve's glow was at a characteristic 100 km altitude, it can be seen the upper edge of the disk was perfectly aligned with the surface -CG location as determined by the NLDN.



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A mesoscale convective system associated with a large number of sprites and elves. At least two elves were identified (by Mike Taylor) as being closely associated with negative CGs. The satellite, radar and lightning patterns at this time were entirely typical of storms which produce sprites and elves.

It appears that a small number of elves (perhaps 5%) identified with Xybion-class imagers are the product of negative CGs.

Figure 24. GOES, radar and NLDN data for 21Jul96 elve-producing storm.

We continue to investigate the relationships between CGs of both polarities and TREMEs. During 1998 there were few, if any, "negative elves" noted at YRFS. We examined the NLDN flash data for the SPRITES'98 campaign for the period 0300-0900 UTC for each night on which TREMEs were observed from YRFS. We extracted the location of all LPCCGs (>75 kA, both positive and negative) within 1000 km of YRFS. Interestingly, in this sample, the LPC+CGs did outnumber the large negatives by a factor of 2.3 (3139 versus 1353). The distributions of these CGs are shown in Figure 27. Yet the dearth of elves from –CGs is still very much in evidence. During the 1998 campaign, there were 854 TREMEs, of which 828 were sprites and 26 were elves (only 3%) of which none (so far) have been identified as originating with –CGs. Thus 828 sprites were observed from 3139 LPC+CGs (3.9 LPC+CGs per sprite). The 26 elves originated from 3139 LPC+CGs and none (to our knowledge) from the 1353 LPC-CGs. Note that since all

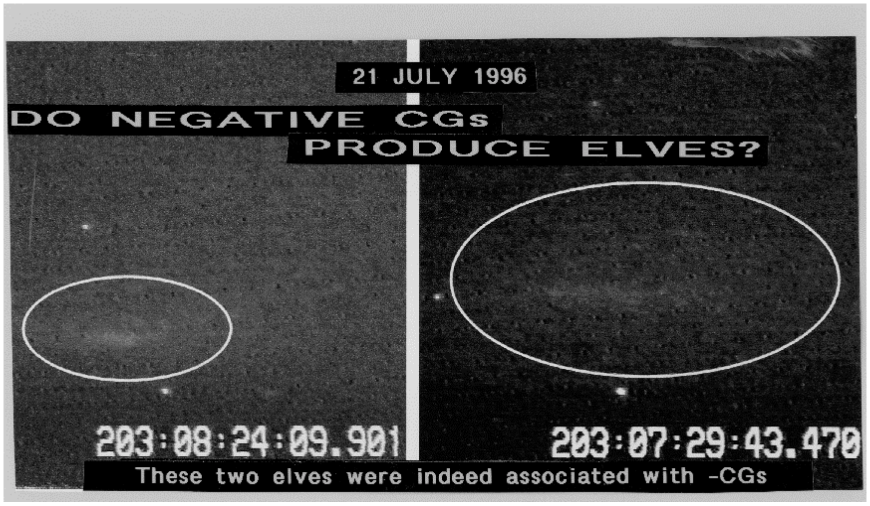


Figure 25. Elves produced from negative CGs.

areas covered in the LPCCG census were not under optical surveillance at all times, these numbers represent a lower estimate of the efficiency of LPCCGs to produce TREMEs. We did, during the 1999 storms, detect several more "negative elves." The question remains - what is different about LPCCGs that produce elves? Clearly polarity is one, but not the deciding factor. Assuming that EMP is the causal source of the elve, then the frequency must be appropriate for coupling to the lower ledge of the ionosphere. There is no reason to believe that the leading edge of the waveforms of positive and negative CGs are identical. Thus the likely source of the proclivity for positive CG elves over negative CG elves is the differential nature of the waveforms.

Part of the detection issue for elves may lie in the determination of just what constitutes an elve in LLTV images. It is becoming more and more apparent that an elve-like feature often forms just before a sprite, but at considerable lower altitude (80 km or less). This "halo" as it now being termed, often appears in the same 17 ms field as the initial sprite image. In the past these have been termed "sprelves", indicated an elve followed by a sprite. In fact, photometry data suggests that these are a feature of sprites, which are almost exclusively associated with +CG flashes. It also suggest that very bright (enough to be seen with the Xybion system) true elves may be even less common that previously assumed.

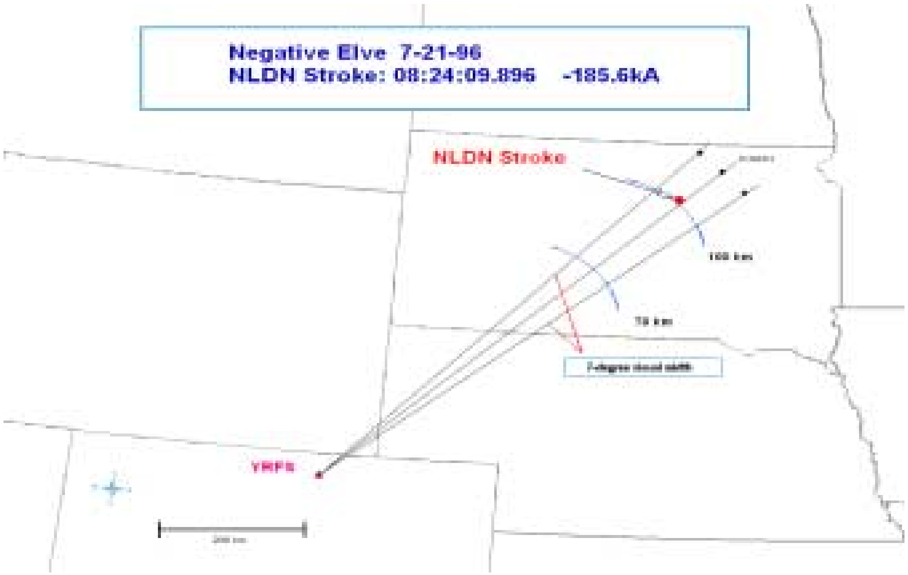


Figure 26. Location of elve-producing –CG and spatial extent map.

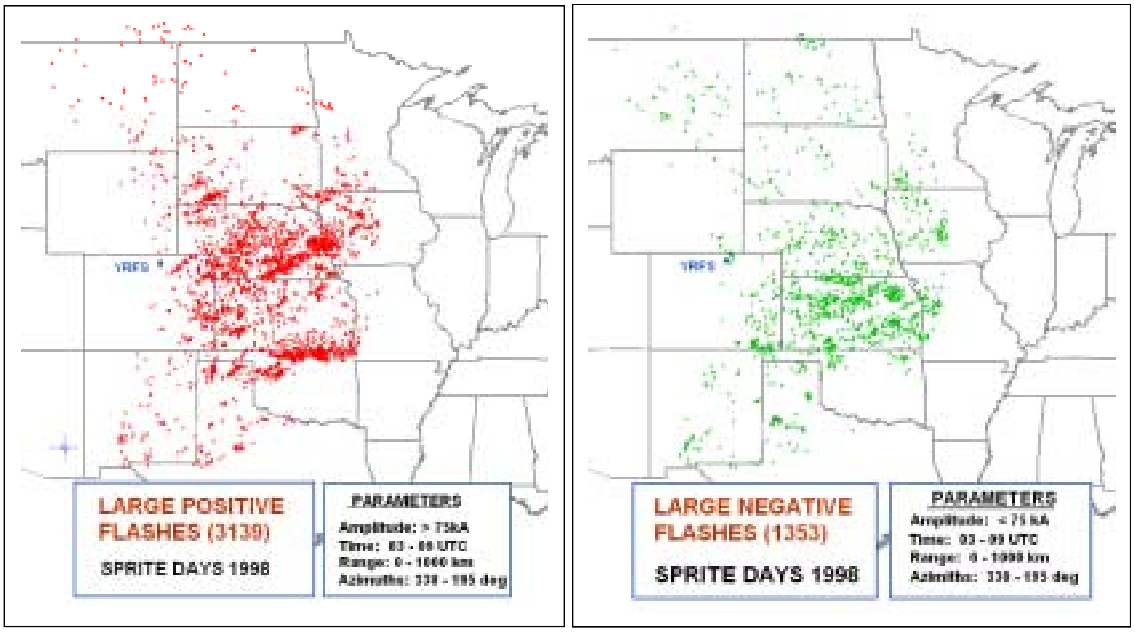


Figure 27. NLDN location map of large positive and large negative CGs.

IV.6. Blue Jets and Trolls: Blue jets have remained rather enigmatic during the period covering this contract. The first were documented during 1994 jet flights of the University of Alaska (Wescott et al., 1995). More than 50 events were imaged with highly sensitive color television (normally used for aurora work) as well as LLTV systems from high flying aircraft from just two storm cells over southwestern Arkansas on 1 July 1994. These storms were at the time producing very large (7 cm) hail. Comparatively as bright as sprites (around 1 mega-Raleigh), they emerged from cloud tops at over 100 km/sec, flaring outward as they rose to a terminal altitude around 35 to 40 km. Since this initial flurry of events, few have been reported from the air, and none from Yucca Ridge. One 1995 case that was suspected to be a blue jet has subsequently been classified as a new form of TREME (below). Several naked eye observations in the literature appear to have been blue jets, notably seen by an airline passenger over a severe Texas squall line (Fisher, 1990) and by pilots circumnavigating severe north Texas hailstorms on 5 May 1995 (O.H. Vaughan, personal communication, 1996). Thus blue jets, have become associated with hailstorms. Various attempts to image blue jets above High Plains supercell hailstorms during the past three summers have yielded negative results.

It has been suggested that blue jets cannot be easily monitored from the ground (Wescott et al., 1998). Several reasons have been proposed. First, the viewing geometry for relatively nearby storms often makes it difficult to see the areas above these cloud systems where blue jets might emerge. If the cell is more than 400 km distant, atmospheric absorption and scattering make detection against the background increasingly difficult. Finally, most of the cameras utilize a GEN II red-biased CCD with poor response below 500 nm. Given these plausible explanations, it is even more remarkable that at least two photographs of blue jets taken by amateur photographers have surfaced. Figure 28(a) shows an image of a blue jet taken in Australia in

Figure 28. (a) Image of a blue jet taken from Darwin Australia. (b) Image of a blue jet taken from La Reunion Island (Courtesy, M. Heavner, U. of Alaska)

1988 above very large, electrically active thunderstorm near Darwin. Using a long exposure and Kodachrome film, the image clearly shows an upward-extending lightning channel which flares into a blue "flame" rising many kilometers above the storm (it is difficult to see in this reproduction). An even more spectacular image was attained, again totally by accident, by an astronomer working on La Reunion Island, in the Indian Ocean (Figure 28(b)). She was taking a two-minute time exposure of a distant thunderstorm over Madagascar (using 400 ISO film). The blue "flame" appears to rise to a height approaching 40 km. These images raise the question as to why there have not been more blue jet images acquired during the various High Plains SPRITES campaigns. It remains an open question as to whether blue jets may be the source of high level radar echoes reported by Rumi (1957) and Roussel-Dupré and Blanc (1996).

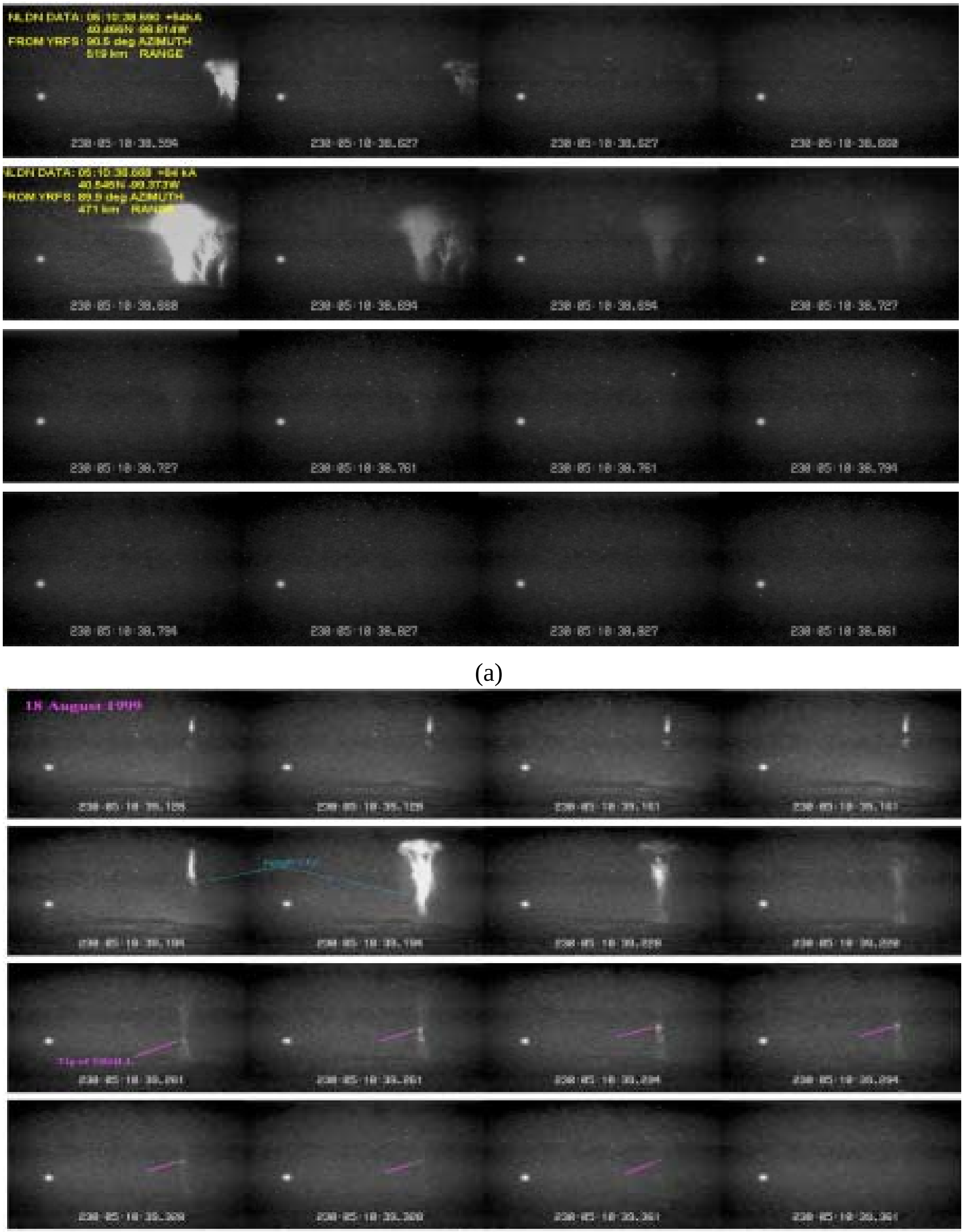
There is now growing evidence that another form of transient electromagnetic event exists. Over the past several years, researchers have noted several cases from ground, aircraft and Space Shuttle low-light-level cameras suggesting a direct optical connection between cloud tops and the mesosphere. On 18 August 1999, several vivid examples of this phenomenon were imaged using Xybion LLTV systems. At first glance, they resembled blue jets, and had the following characteristics:

- The are predominately red in color (based on red-filtered video images)
- Their brightness is comparable to weak sprites
- They appear to arise from the cloud tops themselves, though this is still not confirmed
- They reach terminal heights around 40-50 km
- They have a luminous head with a glowing trail
- The initial upward speed is on the order of 150 km/sec, gradually slowing with altitude
- They are not directly associated with any apparent CG reported by the NLDN

- Most importantly, they appear to retrace a pre-existing channel left behind by a previous well-developed sprite tendril, somewhat in the manner of a return stroke coming back the channel created by a leader.

We have tentatively named these events trolls (Transient Red Optical Luminous Lineaments - Lyons et al., 2000). A very clear example of this was obtained at 0510.38 UTC 18 August 1999. The troll occurred after an exceptionally long lasting and complex series of sprites. The amorphous glowing head was followed by a dim trail (Figure 29a,b). The event sequence began with two conventional sprites associated with rather large +CG flashes. The second sprite was extremely bright and had well-developed tendrils extending downward to around 30 km. After about 420 ms, an unusual C-sprite shaped column appeared, but was not associated with a detected CG flash. It persisted, gradually growing brighter over the next 85 ms, and then suddenly bloomed into an usually bright and complex sprite. Again the tendrils extended far downward towards the cloud tops (with the view of the distant storm top restricted by intervening low clouds). Then as these tendrils dimmed, but in the same apparent channel, a somewhat poorly defined glowing head rises back upward to around 50 km before slowing and dissipating. The entire sequence took over 700 ms.

In retrospect it now appears that the “blue jet” of 0600.26 UTC 15 July 1995 imaged using the same Xybion ISS-255 LLTV system was likely a troll. The luminous head emerged from behind a foreground cloud fragment at a speed of 125-150 km/sec and dissipated between 45 and 50 km altitude (Figure 30). What is not shown in that sequence is that the troll retraced the path of the tendril of a bright sprite which had appeared in the same space shortly before. The storm system which produced this event was not as vigorous as the 18 August 1999 system but was still significant on radar. A plot of NLDN CG data showed there were many +CG flashes in this storm, but as in the other cases, there was no direct linkage of the troll to a specific CG .



(a)

(b)

Figure 29. Two examples of image sequences showing the formation of trolls.

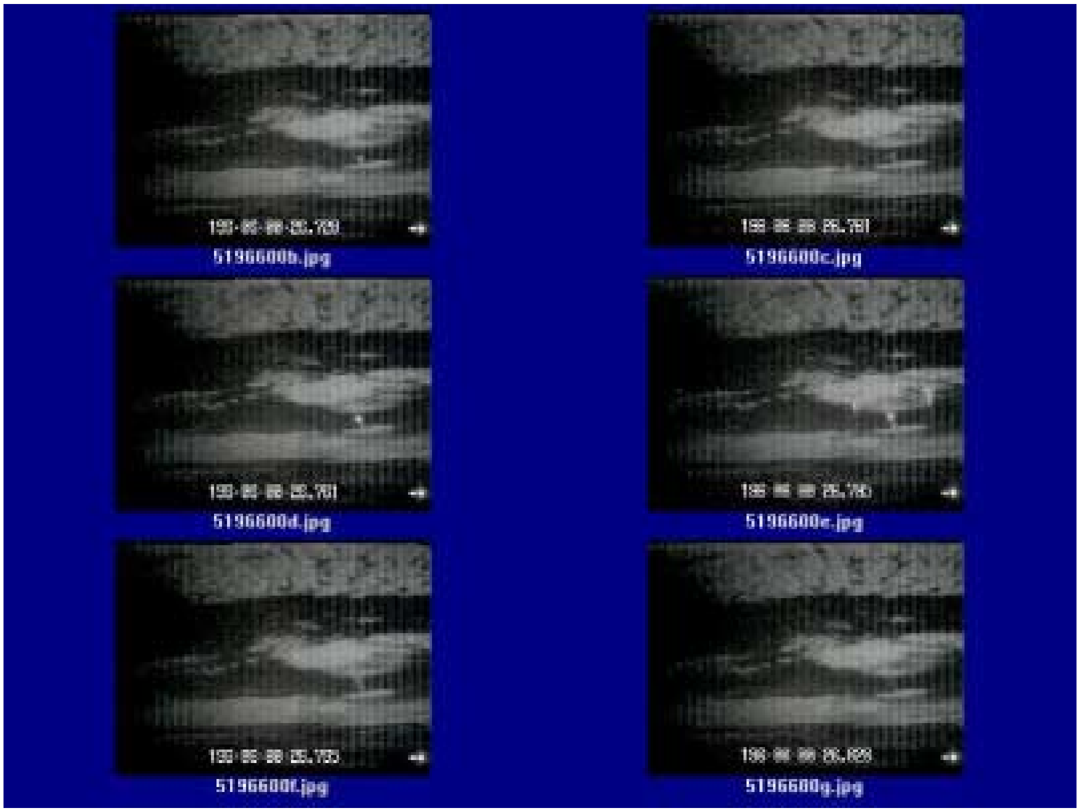


Figure 30. Image sequence of the 15Jul95 sprite sequence with a troll.

IV. 7. A Summary of Characteristics of Transient Electromagnetic Events: Over the past decade, TREMEs (primarily sprites) have been observed worldwide (Lyons et al., 1999) above a variety of storm types including mesoscale convective complexes (Lyons, 1996; Sentman et al., 1995), squall lines (Lyons et al., 1998), tropical deep convection (Dowden, personal communication, 1997; Boeck et al., 1995) and winter snow squalls over the Sea of Japan (Fukunishi et al., 1999). It appears, however, that the U.S. High Plains may be home to some of the most prolific sprite-producing storms on the globe. Numerous studies have documented that sprites follow, by several milliseconds, +CG ground flashes, often with higher than average peak currents. Only two documented cases of sprites associated with negative polarity CGs having unusually high charge moments have been noted to date (Stanley et al., 1999). Growing interest in +CGs (Rust et al., 1981) has revealed that a summertime maximum in the percent of CGs with positive polarity exists over the U.S. High Plains (Orville and Silver, 1997). Recently it has been found (Lyons et al., 1998) that this same region has an unusually high concentration of large peak current (>75 kA) positive flashes (LPC+CGs). In the High Plains, two distinct meteorological regimes produce LPC+CGs, supercells and MCS stratiform regions (Williams, 1998). Within supercell storms associated with hail and tornadoes (MacGorman and Burgess, 1994), +CG lightning is often concentrated near compact (~10 km) convective cores believed to have updrafts which may exceed 50 m/s. During 7 years of monitoring TREMEs at YRFS, we have detected a few supercell sprites and then only during the decaying phases of several storms. MCS positive lightning is widely distributed over very large trailing stratiform regions with up and downdrafts in the tens of cm/sec (Rutledge et al, 1993; Houze et al, 1989). While peak currents are large in both regimes, a very distinctive difference may be the magnitude of the current transferred to ground, possibly reflecting the massive positive charge reservoirs from which a +CG can draw. As shown by Stolzenburg et al. (1994) and Marshall et al. (1996), within the multiple charge layers of MCS stratiform regions can be found horizontally extensive bands near the 0°C layer (often associated with a radar bright band) with charge densities in the 1-3 nC/m^3 range. Integrated over the scale of a large MCS system this can amount to thousands of Coulombs. Evidence is growing that large charge transfers and particularly large charge moments appear to be a necessary (though not sufficient) condition for sprites (Huang et al., 1999; Wilson, 1925). Sprites seems to occur most readily above MCS stratiform precipitation regions with radar echoes greater than $\sim 10^4$ km^2, suggesting the role of vast horizontal dendritic channels ("spiders") in tapping the extensive charge pools. The smallest known storm to produce sprites, a Florida convective system of 2500 km^2 (Stanley et al, 1999), was still, however, larger than the typical "airmass" cell. Visual observations have frequently noted that sprite parent CGs are associated with dendritic or "spider" lightning with horizontally extensive lateral components.

Elves generally occur within storms producing sprites (typically 3 to 10% of the total TREMEs), though not necessarily in the same region. While medium to large peak current +CGs produce sprites, elves seem to be reserved for the very largest events (usually >100 kA). Although the issue of the frequency with which elves are produced by -CGs is contentious (Barrington-Leigh and Inan, 1999), the low-light imagers at YRFS have only confirmed 2 elves apparently associated with large peak current negative CGs in seven years. Yet the EMP mechanisms generally agreed to play a role in elves (Taranenko et al., 1993) should not have a polarity bias. What is different about +CGs (and the occasional LPC–CGs) and their parent storms that create elves? The likely source of the polarity difference is due to the specifics of the waveform, especially the rise time. The frequency must be in the critical range for the EMP to effectively couple with the ionosphere.

Blue jets and blue starters, while clustering near regions of intense –CG activity, are not associated with specific CG flashes. Interestingly, CG activity within ~15 km of blue jets ceases for 2-3 seconds after each event. An anecdotal link between blue jets and storms producing large hail has been noted (Wescott et al., 1998) and this remains an outstanding question. The majority of blue jets and blue starter observations have been obtained from aircraft, with only a few possible candidates noted from the ground. Absorption of the shorter wavelengths and the red bias of most LLTV systems deployed to date are possible limiting factors. Different imaging methods than heretofore used should be employed to monitor the middle atmosphere above supercells (film and next generation color CCD cameras).

The general morphological characteristics of the three major types TREMEs and their associated tropospheric electrical discharge (of any) are summarized in Table 2. At least for the central U.S. a general pattern appears to be emerging about the characteristics of storms which routinely do and do not produce sprites. Table 3 summarizes current understanding about the general characteristics of the TREMEs associated with these major storm types.

Table 2. Current understanding on the characteristics of TREMEs and their parent lightning (none for blue jets)

	SPRITE	***ELVE***	***BLUE JET***
Color of Emission	Red Top/Blue Base	Likely Red	Deep Blue
Polarity of Parent CG	Positive	Positive (mostly)	none
+CG Peak Current	>~50 kA	>~100 kA	none
Charge Transferred (C)	Largest	Large	N/A
Charge Moment (K-km)	Largest	Large	N/A
Parent CG Location	Stratiform Area	Stratiform Area?	N/A
CG Vertical Channel Height	5 km?	10 km?	N/A
dI/dt Value (waveform)	?	?	N/A
Total Flash Duration	Very Long	Short?	N/A
Spider Involved	Yes?	No?	N/A
Continuing Current Duration	Very Long?	Short if any?	N/A
VLF/ELF Slow Tail	Distinct	Possible	N/A
ELF Spectral Color	Red	White	none
VLF Audio Character	Low Freq.	Higher Freq.	none
Duration of TREME	1 –150 ms	0.5 ms	100-200 ms
Altitude Range of TREME	25 – 95 km	75-105 km	Cloud-40 km
Onset Delay After CG	1-100 ms	0.325 ms	N/A
Brightness	50-600 kR	1000 kR	1000 kR
Horizontal Size of Emission	1 km – 100 km	100-400 km	~ 2 km

Table 3. Current understanding on TREME storm/lightning parameters in selected storm types

	Core of Supercells	***MCS, Squall Line Stratiform Region***	***"Ordinary" Convection***
+CG Peak Currents	> ~40 kA	>~60 kA	~ 30 kA
Storm Dimension	10- 20 km	10-500 km	<100 km
Spider Discharges	Few/ small	Many/ large	Some
Continuing Current	Short if any	Longest	Some
+CG Channel Height	10-15 km ?	5 km ?	10 km?
Sprites Occur?	No (except end)*	Many	Rare?
Elves Occur?	No (except end)*	Many	Rare?
Blue Jets Occur?	Yes?	Rare?	Rare?

*Some supercells may generate a few sprites during their final phase when/if extensive stratiform develops

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