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Triangulation of sprites, associated halos and their possible relation to causative lightning and micrometeors

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Abstract. Sprite halos were recently identified as an impulsive but spatially diffuse phenomenon that sometimes occurs just prior to, but distinct from, sprites. The lack of discernible spatial structure and the temporal development sequence in halos differs markedly from the highly structured bodies and tendrils and the complex development sequences of sprites. However, both phenomena are thought to result from an electric field due to charge moment changes usually associated with large positive cloud-to-ground (CG) lightning but also following negative CG flashes. Three-dimensional triangulations of sprites and sprite halos were made between stations in South Dakota and Wyoming in August 1999 during the NASA Sprites99 balloon campaign. Halos were found to have a Gaussian $1/e$ diameter of ~66 km and $1/e$ thickness of ~4 km. Comparison with the location of the underlying lightning strokes, as recorded by the National Lightning Detection Network (NLDN), confirms that the horizontal position of sprites may be laterally offset by as much as 50 km from the underlying parent lightning discharge, as has been previously reported. The point of maximum apparent brightness for sprite halos occurs at an altitude of ~78 km, similar to that of sprites. However, unlike sprites, this point tends to be centered directly above the underlying parent lightning discharge, 4.6 ± 2.7 km mean distance from the center of the halo to the NLDN location. This difference in spatial location relative to the underlying lightning suggests that the electrical breakdown associated with discrete sprites may require a random ionizing event such as a micrometeor. In contrast, sprite halos do not appear to require such a random component.

1. Introduction

Sprites are brief (~10 ms) optical phenomena that occur above thunderstorms in the region between the stratosphere and the lower ionosphere and have been documented only in the last decade. *Franz et al.* [1990] made the first serendipitous low light level television observation of a sprite event consisting of two columns over a large Midwestern United States thunderstorm in 1989. They estimated that the "...discharge began at the cloud tops at 14 km and extended into the clear air 20 km higher" (p. 48). This very low estimate of the sprites' altitude continued to be reflected in the titles of early papers: "cloud-to-stratosphere electrical discharges" [*Lyons*, 1993; *Lyons and Williams*, 1993], "luminous structures in the stratosphere" [*Lyons*, 1994a], "The tops of some of the CS events may extend 50 km or more above the surface" [*Lyons*, 1994b], and "stratospheric flash" or "lightning in the stratosphere" [*Boeck et al.*, 1995].

Knowledge of the altitude of sprites and related phenomena is of crucial importance to an understanding of local optochemical production mechanisms. *Sentman and Wescott* [1993] demonstrated that sprites were not stratospheric phenomena with the first reasonable height estimates of the terminal heights of sprites (65-90 km) from data obtained with an all-sky TV camera in the NASA DC-8 Airborne Laboratory flying around large thunderstorms over Iowa in 1993. *Sentman et al.* [1995] made the first accurate two-station, three-dimensional triangulations of sprites and blue jets using data from two corporate jets flying at 12.2-12.8 km altitude in trail formation separated by 10-75 km. They demonstrated conclusively that sprites are a mesospheric/*D* region phenomenon with tops reaching over 90 km, essentially reaching to the base of ionosphere. The ultimate precision of these observations was limited by the use of wide-angle lenses and real time GPS aircraft positions that were updated only once per second.

Following the 1994 dual aircraft campaign triangulations [*Sentman et al.*, 1995], several additional sets of ground station observations of sprites have been triangulated. Longitude-latitude positions of seven sprites were triangulated in a storm on September 7, 1994, using TV data from a site at the U.S. Air Force Academy near Colorado Springs, Colorado, and the F.M.A. Yucca Ridge site near Fort Collins, Colorado, [*Lyons*, 1996]. These results did not include triangulated altitudes. In 1995, columniform sprites, or c-sprites (long vertical columns about 10 km long and <1 km in diameter), were identified and named [*Wescott*, 1996; *Wescott et al.*, 1998]. Three-dimensional triangulations of c-sprites and other sprites were made using data from the Denver University Observatory on Mt. Evans, Colorado, and the F.M.A.Yucca Ridge sprite observatory. In 1996, more sprites were triangulated with data from the Wyoming Infrared

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Observatory (WIRO) and Yucca Ridge [*Wescott et al.*, 1998]. Most recently, during August 1999 the University of Alaska operated sites at WIRO and at Bear Mountain in South Dakota separated by 360 km. Continued study of the sprite dimensions have shown that their maximum heights as observed at night in white light using intensified video cameras are ~88±5 km and exhibit little variation from event to event or season to season.

Elves are diffuse optical flashes with a duration of <1 ms and a horizontal scale of 100-300 km which occur at ~100 km altitude in the lower ionosphere just after the onset of cloud-to-ground lightning [*Fukinishi et al.*, 1996; *Inan et al.*, 1997]. Elves are thought to be a result of the heating by the electromagnetic pulse (EMP) from a CG lightning discharge. Sprite halos are a distinctive type of transient, diffuse optical emission associated with lightning discharges that bear a casual resemblance to elves but upon close examination are revealed to be a separate, lower-altitude phenomenon from elves. Sprite halos were initially thought to be elves by most observers using normal frame rate, low light level TV systems until *Barrington-Leigh et al.* [1999b, 2001] presented evidence from a high-speed imager and a photometer array that true elves are observed at a higher altitude (~100 km), with a much larger diameter (~300 km) and shorter duration (< 1 ms) than sprite halos.

Sprite halos may occur with or without a following sprite. *Barrington-Leigh et al.* [2001] attribute this fact to the time-scale of the CG discharge: "a lightning discharge with a fast (<1 ms) charge moment change may be sufficient to cause diffuse emissions at higher altitudes where the threshold for ionization and optical emissions are, but if lightning currents do not continue to flow, there may not be sufficient electric field to initiate streamers below ~75 km".We have many examples of sprites without an apparent sprite halo, but some of these may be due to the signal to background light level. *Heavner* [2000], shows a spectrum of a sprite halo from 550 to 830 nm, which is similar to spectra of sprites. This suggests that a common mechanism for excited molecular nitrogen optical emissions is involved in producing both sprites and sprite halos. Theoretical models by *Pasko et al.* [1995; 1997; 1998] show that the electric field responsible for the quasi-electrostatic heating, ionization, and optical emissions of sprites is caused by the charge moment changes associated with the movement of large thundercloud charges during +CG or –CG discharges. These models predict a diffuse region near the top of sprites, which can now be identified with the observations and triangulation of halos reported in this paper.

Sentman et al. [1995] showed that sprites are loosely correlated with +CG occurrences in the decaying portion of a thunderstorm, and *Boccippio et al.* [1995] demonstrated with more examples that sprites are associated, within a few milliseconds, with +CG flashes. *Barrington-Leigh and Inan* [1999] showed that elves may be caused by both positive and negative cloud-to-ground (-CG) strokes. More recently, *Barrington-Leigh et al.* [1999a] have shown that both sprites and elves may also be occasionally produced by –CG flashes.

Estimates of sprite, elve and sprite halo locations and altitudes can be obtained by assuming that the form is directly over the National Lightning Detection Network (NLDN) [*Cummins et al.*, 1998] positive or negative CG flash position. However, actual triangulations have shown that sprite structures may occur as much as 50 km horizontally from the underlying CG position [*Desrochers et al.*, 1995; *Wescott et al.*, 1998]. *Lyons* [1996] confirmed these results using seven triangulated positions with an average displacement of 42 km from the NLDN locations in a storm on September 7, 1994. He also used one-station estimates of 36 other sprite locations and found an average displacement of 35 km of the sprite groups from the NLDN +CG flash. The one-station approximation is probably a valid means of showing large displacements of the sprites from the CG NLDN lightning. However, the average altitude of 78 km reported for these 36 examples is suspect, as the altitudes were not computed using the star background, assumed that the point below the sprite on the horizon was at zero elevation angle (i.e., neglecting that the Earth is round) and is some 10 km lower than triangulated positions reported by *Sentman et al.* [1995].

In this paper we present three-dimensional triangulations of sprites and sprite halos from the 1999 observations. From these results we speculate that a trigger such as a micrometeor is needed to produce discrete sprites, but not sprite halos.

2. Triangulation Technique

Accurate geographic positions (latitude, longitude, and altitude) of identifiable features in the TV images are derived by triangulation using views from two or more stations. The triangulation is performed using computer routines developed originally at the University of Alaska for the analysis of image data acquired as part of our auroral and chemical release research [*Stenbaek-Nielsen et al*, 1984]. The triangulation method involves detailed comparison of star positions within the image scene with star positions obtained from a star catalog. Given the center of the field of view of an image, the orientation of the image about this axis, and the dimensions of the image map to a region of the stellar canopy, stars within this region are obtained from a star catalog and overlaid to their corresponding positions in the image. The image direction and orientation are then rotated and the dimensions are stretched until the catalog stars overlaid on the image match the image stars. The accuracy of the direction can be quantitatively evaluated by the degree of fit between the stars present in the image and the overlaid catalog stars. The match with the star catalog to video star fields obviously can never be better than one pixel. The computer programs for fitting stars to the video images have an option to read out the pixel value by moving a cursor. This feature can also be used to test the fitted star position with the maximum star intensity to one pixel, and the fit can be adjusted if necessary. The best fit is when many stars are in the region of interest near the center of the frame, down to eighth or ninth magnitude. Then the faint stars are only one or two pixels in size. It may be worse than one pixel in several situations: (1) when seeing conditions are poor and there are only a few stars which can be used, (2) when very bright stars are near the area of interest, as they may spread out over many pixels, and one has to judge the center of the star by eye (As mentioned above, the star center can be found with the cursor to find the maximum brightness where the very best accuracy is needed.), and (3) when the object of interest is near the edge of the frame, where the lens distortion is greatest and there may not be many stars.

With observing station position (latitude, longitude and altitude) and UT time, the line of sight direction (azimuth and elevation, or right ascension and declination) to any pixel in the image is thereby uniquely established. With images of the same feature, for example, a bright spot or the top or bottom of a sprite, obtained from two or more different viewing locations, it is therefore possible to derive its three-dimensional location as the intersection of the lines of sight obtained from the separate images. The internal calculations in the triangulation program are carried out in geocentric Cartesian coordinates; station positions and local look angles (azimuth and elevation) are determined using the International geoid [*Moritz*, 1984]. The use of stars for determining the position of sprite features also corrects for atmospheric refraction near the horizon, as both a star and the sprite are above the atmosphere and refraction affects the elevation angle of both identically.

Uncertainties on the triangulations depend on the accuracy of the star fits near the feature of interest, the pixel size, and the slant range from the site to the sprite feature. It also depends somewhat on the accuracy of the lines of sight intersecting for the separate images, although in practice this has not been found to be a serious source of error. The absolute limit of location accuracy depends upon the angular size of one pixel and the slant range. In the typical sprites with discrete features triangulated during the August 18, 1999, activity, one pixel corresponded to 370 m horizontally by 310 m vertically for the Bear Mountain location and 960 m x 730 m for WIRO. However, for diffuse objects such as a sprite halo it is not possible to judge the center of luminosity to better than two or three pixels Thus we assume that the triangulated altitudes of halos are within ±1.5 km. Images from the WIRO high speed-imager have better intrinsic angular definition. A pixel at a slant range of 661 km represents 290 x 290 m at the halo.

There are additional sources of errors and uncertainties when the features are diffuse. The brightest part of an atmospheric feature, for example, a sprite halo, is where the line-of-sight integrated brightness is maximum after the background has been subtracted. Here we assume the sprite halo emission region is optically thin and the emissivity is azimuthally symmetric about some vertical symmetry axis. From two observing sites at approximately equal observing distances but different azimuths, the line-of-sight integrated horizontal and vertical emission structure will look much the same, except for angular scale. Here we assume that the point of maximum line of sight integrated intensity passes through the point of maximum emissivity, is viewable from both viewing stations, and may therefore be triangulated.

The horizontal diameter or vertical thickness of a sprite halo is more difficult than the center to determine, as the intensity falls off gradually vertically and horizontally, with no sharp edges. Tests with various fitting functions revealed that a Gaussian of the form

$$I(x,y) = I_0 \exp -[(x-x_0)^2/\,\Delta_x^2 + (y-y_0)^2\,/\Delta_y^2] \qquad (1)$$

provides a good fit to the luminosity. Here, $I(x,y)$ is the luminosity as a function of pixel position (x,y), and the offsets are (x_0, y_0). The horizontal and vertical thicknesses are Δ_x and Δ_y, respectively.

3. Triangulation Results

3.1. The 0428:09.628 Event: August 18, 1999

A series of events associated with NLDN +CG flashes of 115.7 kA, and 38.85 kA and 47.0 kA, both at 0428:09.628 UTC on August 18, 1999, has been analyzed in detail. This whole series of events was recorded with a high-speed imager (1000 frames/s, 6.4° x 6.4° field of view (FOV)), coaligned with the WIRO medium FOV (20.76° x 17.28°) TV system and partially with a narrow FOV TV system (10.26° x 8.4°) at Bear Mountain. The series starts with an elve followed 1 ms later by a sprite halo lasting 4 ms, then 36 ms after the elve a weaker sprite halo lasting 3 ms, and finally 47 ms after the elve a c-sprite appeared which developed into one of the typical sprites resembling a carrot, persisting for 34 ms. As far as we know, this is the first time that an elve has been captured by high-speed imagery. The first, brighter sprite halo and the carrot sprite were recorded by narrow field of view intensified CCD TV systems operating at 60 fields/s at both Bear Mountain and WIRO. Images from those systems were used for the triangulation of the first sprite halo and the sprite. The altitude and diameter of the elve and the second weaker sprite halo were estimated from the elevation angles and the assumption that they were directly over the lightning flashes.

Figure 1 shows high-speed imager frames for the elve and the first halo from the WIRO observatory, one millisecond apart. The high-speed imager consists of four CCDs of 3.2° x 3.2° read out through separate electronics. In stretching the gray scale to show weak features, such as an elve, the slightly different background level of each CCD is brought out. Images in Figure 1 show both of the top two CCDs and a part of the two lower CCDs. The top frame, 45, shows the background. Frame 46 shows a very weak brightening in the upper portion assumed to be an elve, coincident within 1 ms, considering speed of light propagation, with a two-stroke +CG flash at 0428:09.628 (115.74 and 13.91 kA). It is obviously higher in elevation than the following sprite halo in frame 47. To estimate the altitudes of the elve and halo, we subtracted the background frame (45) from the elve, frame (46) and the halo, frame (47). The pixels were then summed horizontally to produce a combined plot of intensity versus vertical line number. An excellent star fit from the high-speed imager allowed conversion to elevation angle, and using the slant range to the upward projected of the NLDN flash, the profile was converted to altitude, as shown in Figure 2. The altitude of the elve center was found to be 100 km, and that of the halo was 79 km. *Inan et al.* [1996] predicted the elve altitude to be 80-95 km on the basis of an electromagnetic pulse model. *Barrington-Leigh and Inan* [1999], using single-station photometer-pointing angles, estimated elve altitudes to be 85-95 km.

The next three frames, 47-49, in Figure 1 show the development of the sprite halo. The dark features are patchy low-level clouds near WIRO. Figure 3a-3j, from left to right, shows an sixteen-frame ms sequence, 0.375° wide, 2.36° high, of vertical strips through the center of the halo. The elve starts in the second strip 3b, followed in the next seven frames by the halo. The halo center obviously drops in altitude over 7 ms and is estimated to be ~2 km. This drop in altitude was also mentioned and discussed by *Barrington-Leigh et al.* [1999b, 2001] and explained by modeling predictions of *Pasko et al.* [1997]. With their model, the diffuse luminosity (halo) occurs at altitudes of 70-85 km, localized (~70 km wide) over the source currents, and descends in altitude in rough accordance with the local electrical relaxation time $\tau = \varepsilon_o/\sigma$, where ε_o is the permittivity of free space and σ is the local conductivity.

Figure 2 also illustrates another fact about the relative light emission between elves and halos. By integrating the area under the curve, we found that the halo emitted more photons in 1 ms than the preceding elve by a ratio of 100 to 84. Considering the fact that the halo lasted for about 5 ms, the total number of photons emitted by the halo is about 5 times the number emitted by the elve.

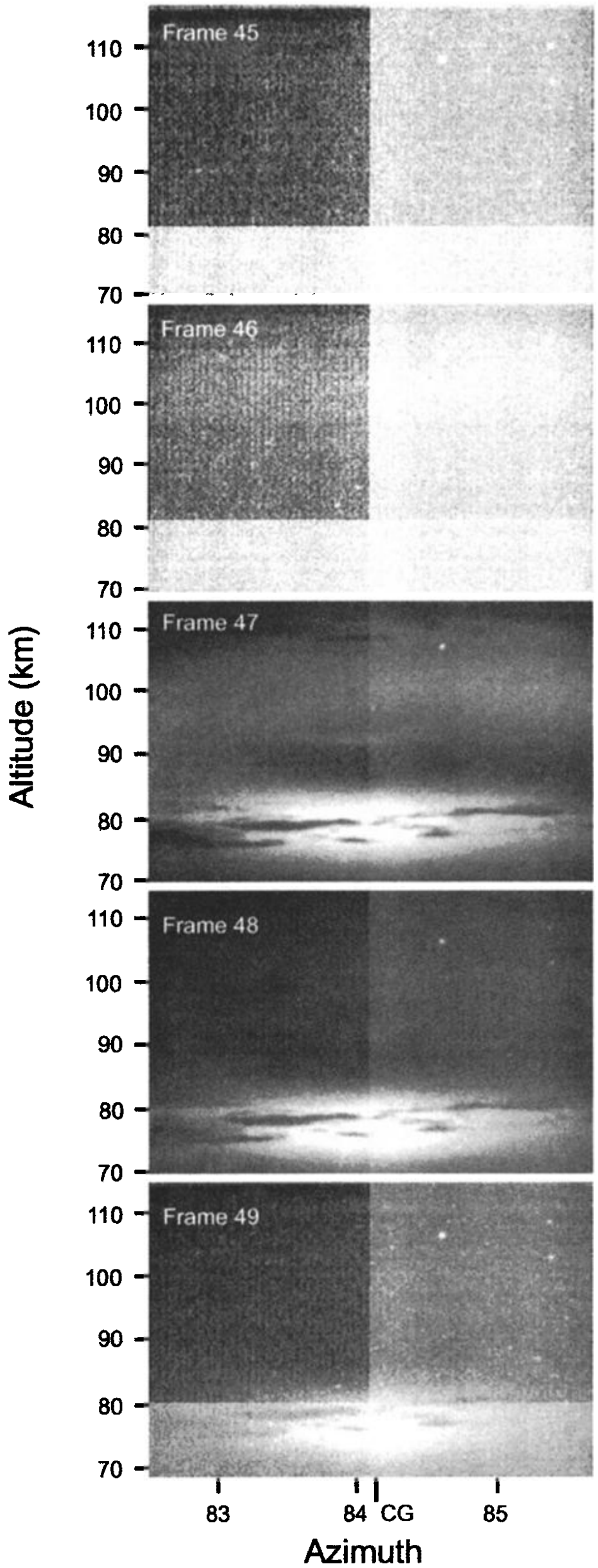

Figure 1. High-speed imager frames from the Wyoming Infrared Observatory (WIRO), 1 ms apart, of elve and sprite halo event at 0428:09.628 UT, August 18, 1999. The frames shown have a 6.4° horizontal by 4.3° vertical field of view. Frame 45 shows the background at 0428:09.627 UT. Frame 46, 1 ms later, shows the appearance of an elve at an estimated altitude of 100 km. Frames 46-49 show the development of a sprite halo centered initially at 79 km altitude.

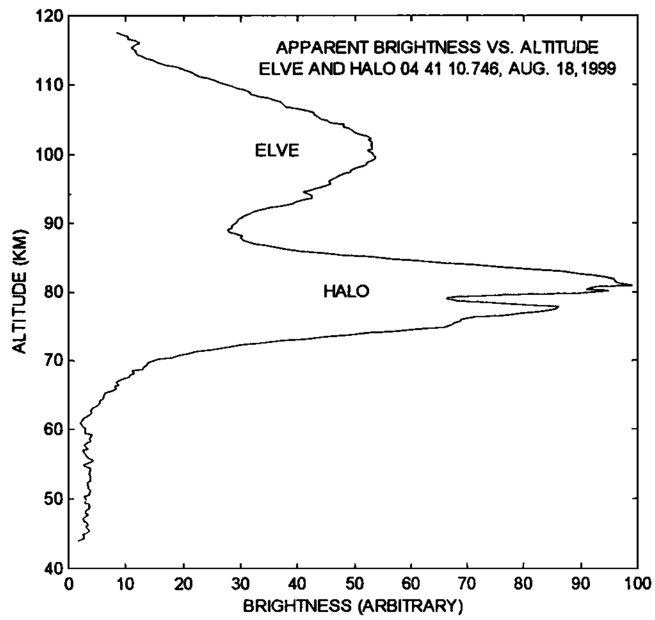

Figure 2. Vertical profile of the apparent brightness of an elve and the sprite halo, which followed 1 ms later, at 0428:09.627 UT, August 18, 1999. The data are from the high-speed imager at WIRO shown in Figure 1. The irregularity of the halo profile is due to clouds between the site and the halo. Integration of the area under each feature shows that in 1 ms the halo emitted ~20% more light than the elve.

Figure 4 shows the background-differenced image (17 ms integration) of the sprite halo viewed from Bear Mountain on the narrow FOV TV (10.26° x 8.4°) and horizontal and vertical profiles through the palpable center of the halo. The halo was triangulated with the corresponding TV image (67 ms integration) from WIRO. The center of the halo was located at 41.41° latitude, -98.21° longitude, and 77 ± 1.5 km altitude. The slant range from Bear Mountain to the center is 539 km and from WIRO is 661 km. The sprites that followed, eventually developing into a carrot form, were also triangulated. Figure 5 is a map showing the location of the sprite group (solid circles) that followed the halo, the probably causative +115.74 and +13.91 kA NLDN lightning strokes, and a 33 km radius circle around the triangulated center point of the halo. Note that the center of the halo is displaced from the flash by only 3 km, while the sprites are 27 km away.

3.2. Halo Model of the 0428:09.628 Event

A line of sight from Bear Mountain to the halo makes an angle with respect to the horizontal that varies from 9.285° near the bottom to 11.274° near the top. This makes the vertical thickness of the halo seem larger than the true thickness. In order to correct for the different path lengths through the halo, models of the radiation density were integrated to compare with the measured profiles. Tests with various fitting functions revealed that a Gaussian function provided a good fit to the apparent luminosity. The radiation density models were chosen to be Gaussian distributions, both vertically and radially horizontal, of the form

$$I(r,z) = I_o \exp\text{-}(r^2/w^2 + z^2/t^2), \qquad (2)$$

where I_o is the center radiation density, r is the horizontal radial distance from the center, w is the radius where the intensity falls

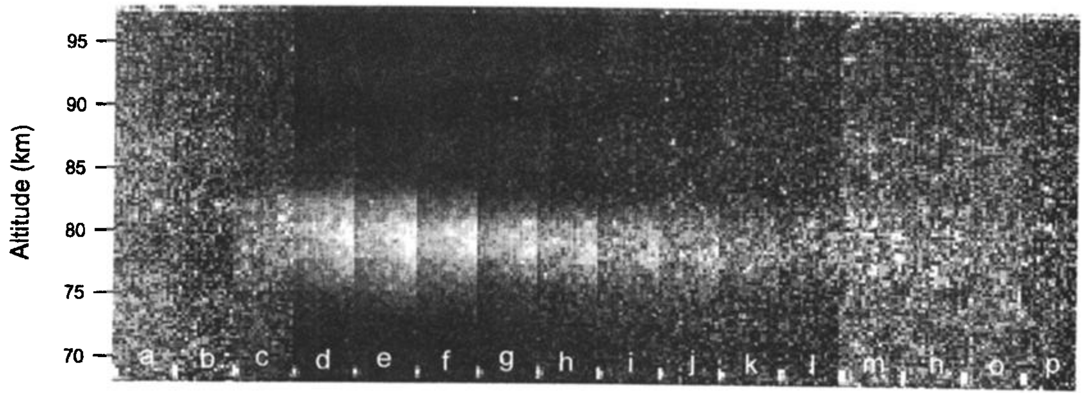

Figure 3 a-p. Series of vertical strips 0.375° wide by 2.36° high through the center of the 1 ms frames of Fig.1 showing the drop of 2 km in altitude of the center of the halo over 7 ms (c-i).

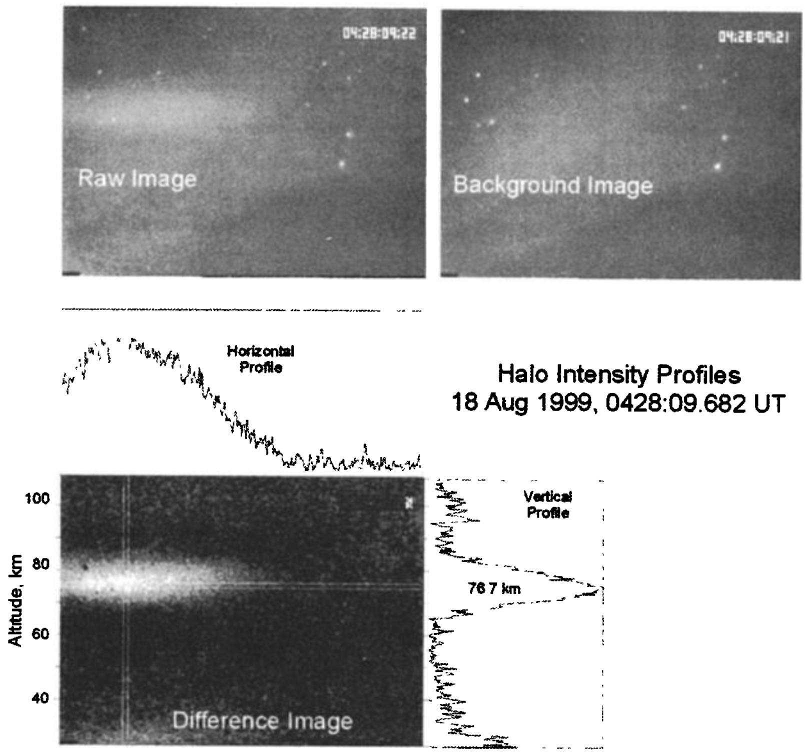

Figure 4. The raw and background halo images and the background-differenced narrow field image (17 ms integration) of the sprite halo shown in Figure1 viewed from Bear Mountain in the narrow field TV camera (10.26° horizontal by 8.4° vertical), and horizontal and vertical profiles through the palpable center of the halo. The halo was triangulated with the corresponding image from WIRO. The result was located at 41.413° latitude, -98.209° E longitude and 77 km altitude.

$1/e$, z is the vertical distance measured from the center, and t is the thickness where the intensity falls to $1/e$.

Figure 6 shows the best fit model to the observed halo. The thickness and width from $1/e$ points are 6 km and 66 km, respectively. This does not take into consideration the vertical motion of the halo, obvious in Figure 3. We calculated that the halo center moved 2 km downward, increasing the apparent thickness by the same amount. Thus we estimate that the true Gaussian thickness is 4 km.

3.3. The 0441:10.746 Event: August 18, 1999

A simpler series of events was studied in the next example, also using the high- speed imager frames, Figure 7, and the medium and narrow field of view 60 fields/s TV systems for triangulation. There was only one positive 50.98 kA CG flash at 0441: 10.746. It was followed by a sprite halo triangulated at 78 km altitude, located 3.4 km from the stroke. It is obvious from Figure 7 that the center of the halo brightness dropped ~5 km in altitude during 5 ms. The apparent diameter of the sprite halo is

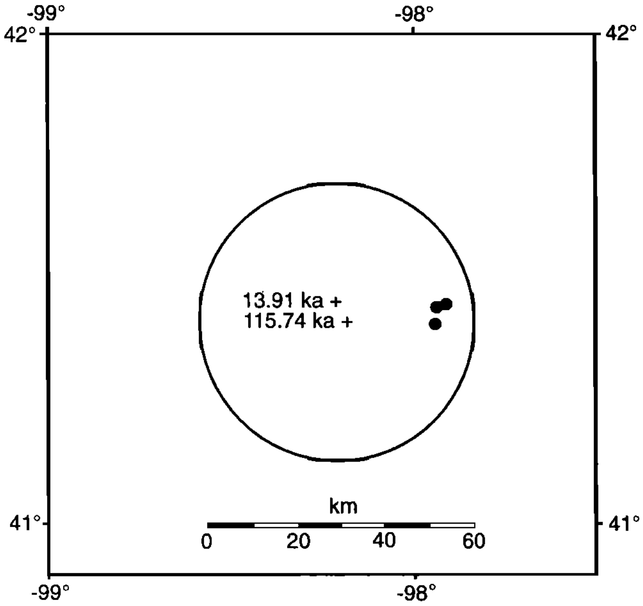

Figure 5. August 18, 1999, 0428:09.682 UT, sprite halo and sprite event map, showing the location of the sprite (solid circles), the +115.74 kA and +13.91 kA NLDN strokes, and a 33 km radius circle around the triangulated halo center point. Note that the center of the halo is displaced from the flash by only 2.8 km, while the sprite is ~20 km away.

~65 km. The first millisecond frame showing the halo (59) also shows some faint discrete structures which grew both upward and downward, evolving from c-sprites into two carrot sprites. These structures were located 11 and 15 km from the NLDN location, with a top altitude of 81.3 km. When the other smaller sprite elements which developed were included, the mean distance from the NLDN flash was 17 ± 8 km.

3.4. The 0419:27.868 Event: August 18, 1999

This event was caught only by the narrow field of view TV system at Bear Mountain and the medium FOV TV at WIRO, so we cannot tell the sequence of events with millisecond resolution. Figure 8 shows the TV frames from Bear Mountain (top row) and from WIRO (bottom row). The left TV frames show the halo and a group of c-sprites protruding below the bright halo. The right frames, 67 ms later, show that the c-sprites have evolved into carrot shapes. The triangulated center of the halo is at 75 km altitude. The triangulated tops of the sprite forms range from 73.5 -81.4 km, with a mean altitude of 77.8 km. There is no obvious NLDN flash that corresponds with this event. The nearest +CG flash is at a distance of 240 km. There are two small (16 kA) negative CG strokes 65 km from the center of the halo. However, the three discrete sprite elements are displaced from the halo center by 25, 25, and 16 km.

3.5. The 0649:54.898 Event: August 18, 1999

There was no high-speed imager coverage of this sprite halo and multiple sprites event, shown in Figure 9. The center of the halo was triangulated at an altitude of 84 km and at a distance of 7.7 km from a NLDN +125.97 kA flash. The three sprites have a top altitude of 85 km and are located at distances of 9.3, 19.4, and 32.5 km from the flash.

4. Spectrum of Sprite Halos

During a short 1995 campaign on Mt. Evans, Colorado, the first spectra of sprites were recorded and identified as $N_2$1P [*Hampton et al.*, 1996]. It is now recognized that a spectrum of a sprite halo was also obtained. Figure 10 shows the spectrum of the halo recorded June 22, 1995, 0710:49 UT, uncorrected for the system response and atmospheric transmission. This can be compared with a synthetic spectrum [from *Green et al.*, 1996] and a sprite spectrum, both corrected for system and atmospheric transmission. There is no indication of ionized N_2 in the spectrum, and the corrections would not change that result.

The halo, well resolved on the TV field, preceded a group of sprites, and similarly, the spectrograph recorded wide horizontal emissions, which were dim compared to the narrow emissions that correspond to the sprites. The halo spectrum observation is 17 ms integrated. However, the halo itself is of only a few milliseconds duration, and no sprite is observed to emit in the same video field, so the integration time is not affecting the observed neutral to ionized emission ratio. *Armstrong et al.* [1998] and *Suszcynsky et al.* [1998] present observations of a brief initial ionized component to sprites. Upon further investigation into more events, it became apparent that some sprites have much stronger initial ionized emissions and some sprites have very little, or an undetectable, ionized component, *Armstrong et al.* [2000]. Indeed, the July 24, 1996, 0358:23.9768 event presented in Figure 2b of *Suszcynsky et al.* [1998] has been studied with TV rate (17 ms resolution) spectroscopy by the authors of this paper, and strong evidence of ionized emissions is present in the 17 ms spectral observation, making that sprite one of the most strongly ionized to be observed [*Morrill et al.*, 1998, Figure 2a].

The observations presented in the paper agree with earlier theoretical predictions of the ratio of neutral to ionized emissions. Specifically, *Pasko et al.* [1997, Figure 17b] predict a ratio between the total N2(1PG) emissions and N2+(M) emissions to

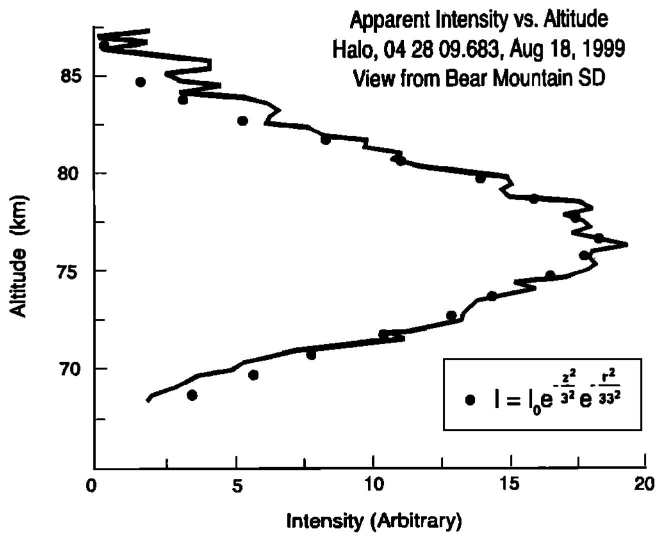

Figure 6. August 18, 1999, 0428:09.682 UT sprite halo apparent brightness versus altitude and the best Gaussian fit to the observed halo. The thickness and width from 1/*e* points are 6 km and 66 km, respectively. When the 2 km vertical motion of the halo, obvious in Figures 3c-3f, is accounted for, the thickness is 4 km.

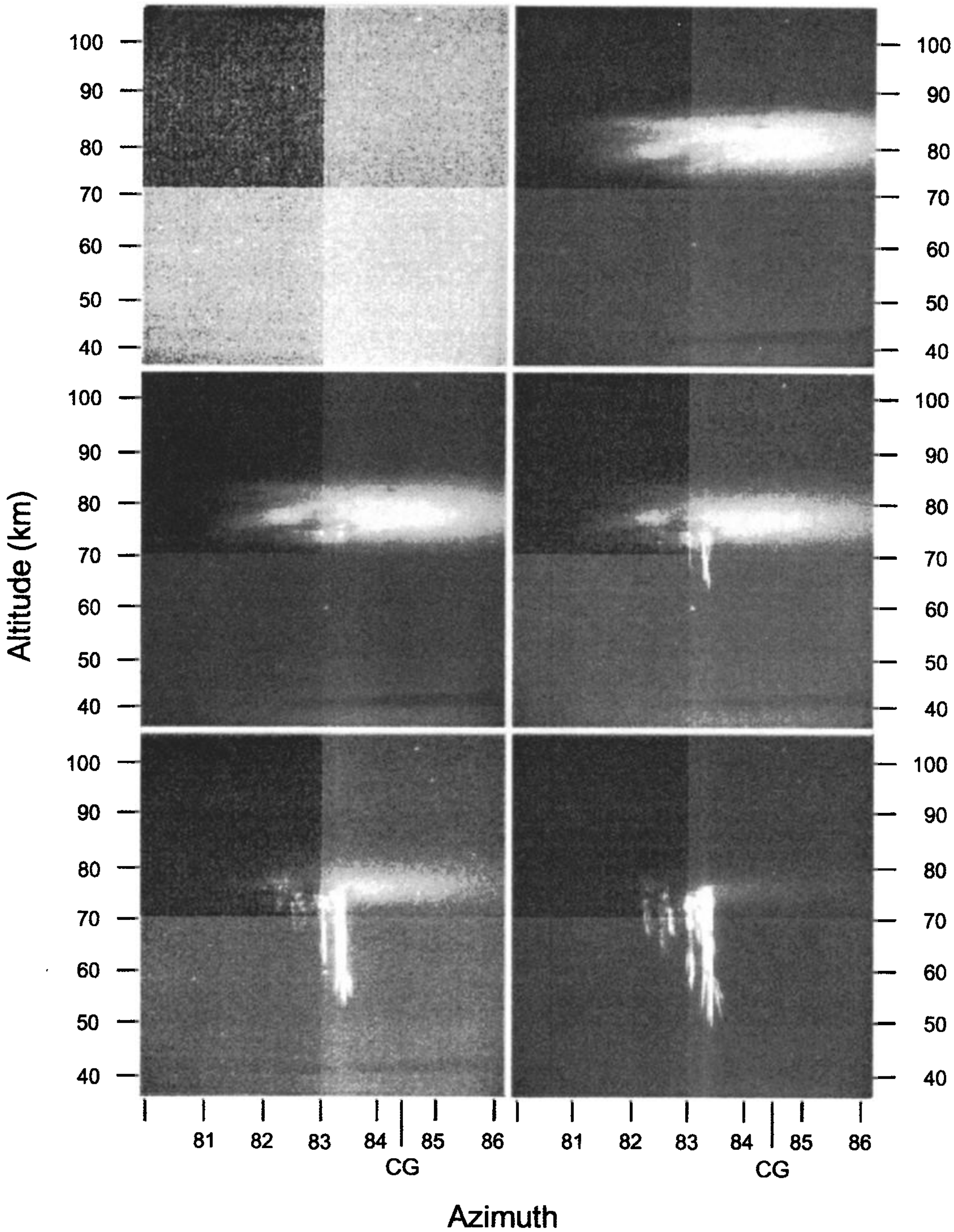

Figure 7. High-speed imager frames 1 ms apart (top left, top right, middle left, middle right, bottom left, bottom right) of sprite halo at 0441:10.746, August 18, 1999. There was only one positive 50.98 kA CG flash at 0441:10.746 UT followed by a sprite halo with some faint discrete structures (frame 58), which grew both upward and down-ward, evolving from c-sprites into two carrot sprites. The center of the halo was triangulated at 78 km altitude, located 9.8 km from the stroke. The apparent diameter of the sprite halo is ~65 km. The top of the carrot sprites was found to be at 81.3 km.

be three orders of magnitude at ~75 km and even greater at other altitudes. The observations presented in Figure 10 show no N2+(M) emissions, and the sensitivity of the measurement is not as good as one part in one thousand.

5. Summary

During August 1999 the University of Alaska operated two optical sites in Wyoming and South Dakota. Images from narrow and medium field of view low light level TV systems running at 60 fields per second (fps) were used to triangulate on many sprites and on four diffuse horizontal glows that we now call sprite halos. Sprites, elves, and sprite halos that were recorded at WIRO with a 1000 fps high-speed imager have been compared with the causative NLDN lightning flashes. In some of the halos the altitude dropped in time. This effect has been observed by *Barrington-Leigh et al.* [2001] and attributed to modification of the electric field by the enhanced ionization produced by the

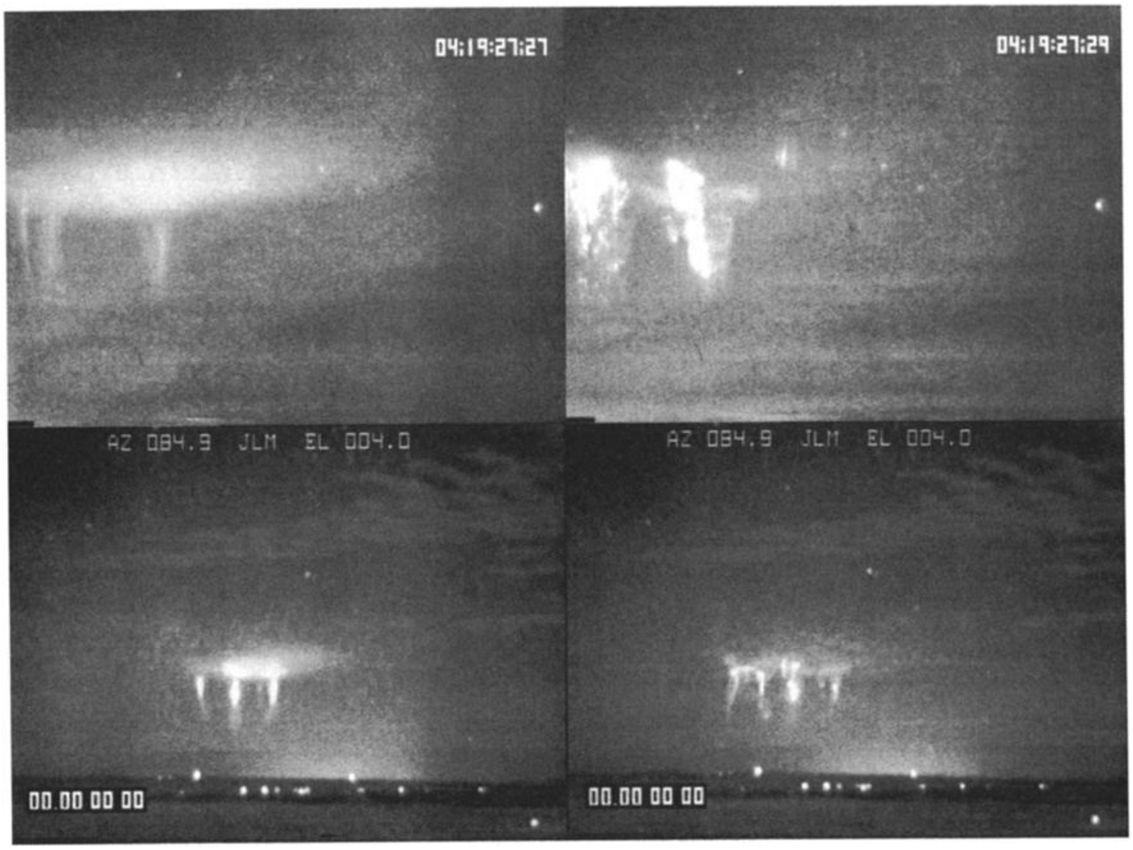

Figure 8. Sprite halo event at 0419:27.868, August 18, 1999, from the narrow field of view TV systems at (top) Bear Mountain, and (bottom) WIRO. The first TV frames (left) show the halo and a group of c-sprites protruding below the bright halo. The right frames show that the c-sprites have evolved into carrot shapes. The triangulated center of the halo is at 75 km altitude. The triangulated tops of the sprite forms range from 73.5 to 81.4 km, with a mean of 77.8 km altitude. There is no obvious NLDN flash that corresponds with this event. The nearest + CG is at a distance of 240 km. There are two small (16 kA) negative strokes at 65 km from the center of the halo.

halo. The mean altitude of the four triangulated sprite halos was found to be 78 km with a standard deviation of 3.7 km. This contrasts with the estimated altitude of an elve of 100 km. The estimated altitude of the elve is based on centering it over the NLDN + CG flash. In several other cases where there was no obvious NLDN flash on which to base estimates, the elve was always higher in elevation than the following halo. In a direct comparison of the total amount of light emitted by a sprite halo and a preceding elve, the halo was brighter by a factor of 100 to 84 in 1 ms. As the halo lasted more than 5 ms, it emitted ~5 times as many photons in total as the elve.

The spectrum of a sprite halo was obtained during observations from Mt. Evans, Colorado, in 1995 and is essentially identical to spectra of sprites. *Barrington-Leigh et al.* [1999b, 2001] propose that halos are a different phenomenon than elves and are caused by the vertical charge moment changes of CG lightning flashes. Theoretical models by *Pasko et al.* [1995; 1997; 1998] show that the electric field responsible for the quasi-electrostatic heating, ionization, and optical emissions of sprites is caused by the charge moment changes associated with the movement of large thundercloud charges during either +CG or –CG discharges. These models predict a diffuse region near the top of sprites, which can now be identified with the observations and triangulation of halos reported in this paper. No spectra of elves have been obtained to date.

São Sabbas [1999] and *São Sabbas et al.* [1999] have studied the relationship between sprites and lightning from the associated storms and found a significant proportion of sprites that were not associated with +CG flashes. *Barrington-Leigh et al.* [1999a] presented evidence that sprites may be triggered by negative CG lightning discharges as well as positive CG flashes. The significance of these studies is in regard to the runaway electron model that has been proposed as a mechanism for sprites [*Roussel-Dupree et al.*, 1996, 1998a, 1998b] which depends on a +CG lightning stroke for initiation; this model is clearly not capable of explaining the occurrence of "negative sprites." Either the model must be revised to explain –CG initiation or some mechanism other than the runaway electron must be responsible at least for these –CG associated sprites.

The three triangulated halos which could be associated which a positive NLDN flash were nearly centered on the NLDN flash location. The mean distance from the center of these halos to the flash was 4.6 km with a sigma of 2.7 km. On the other hand, the triangulated sprites following these three halos were almost never centered over the NLDN +CG flash. Thirteen discrete sprites were located at a mean distance of 25.2 km with a standard deviation of 18.8 km. A fourth halo was accurately triangulated, but there was no NLDN flash reported which could be a probable cause of the halo. However, if we assume that the center of the halo is the proper reference, we find that the radial distances to

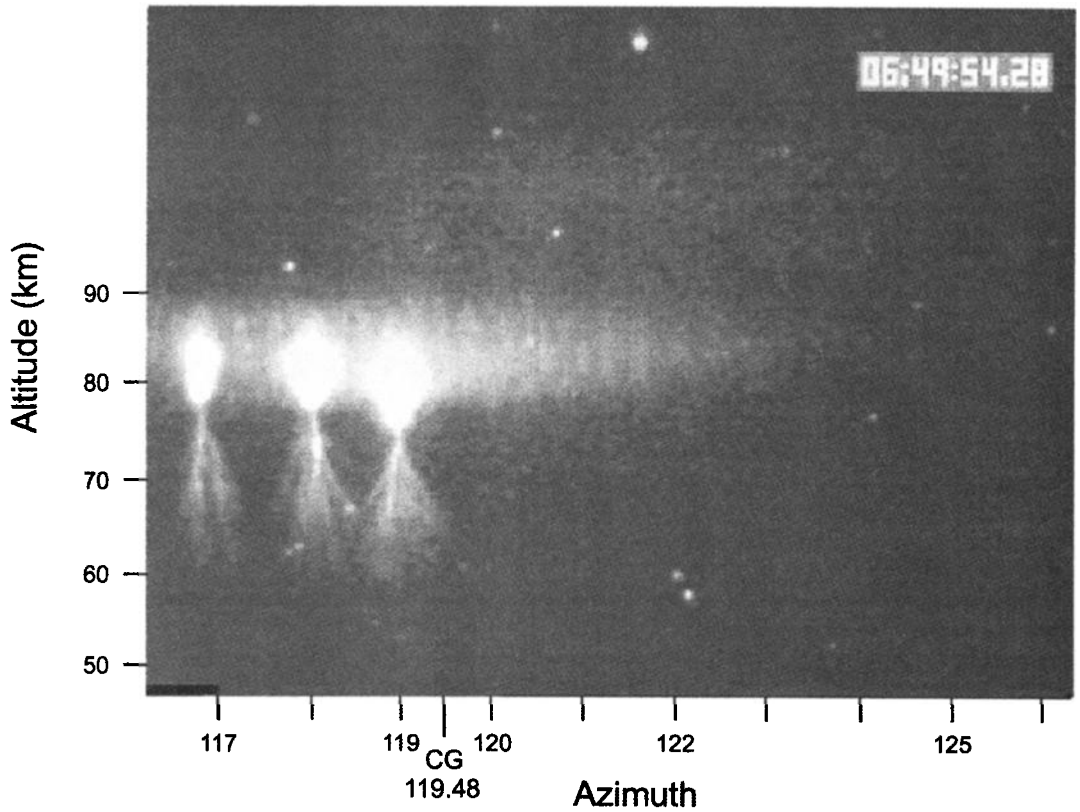

Figure 9. August 18, 1999, 0649:54.898, sprite halo and sprites from the narrow field of view TV at Bear Mountain. The center of the halo was triangulated at an altitude of 84 km and at a distance of 7.7 km from a NLDN +125.97 kA flash. The azimuth of the NLDN flash at 119.48° is shown. The top of the sprite at the right is at 85.2 km.

the three following discrete sprite forms are 25, 25 and 15.7 km, which have a mean value of 21.9 km, consistent with the other 13 triangulated sprite distance values.

6. Discussion

The identification and triangulation of sprite halos poses several questions: Why do some halos occur without a following sprite, some sprites without a preceding halo, and some large sprites with a nearly simultaneous halo? *Barrington-Leigh et al.* [2001] have discussed halos in the context of photometric observations, high-speed imager frames and VLF sferics, and theoretical quasi-electrostatic (QE) modeling. Our triangulation of halos raises another question: Why do halos seem to be centered over the causative NLDN flash location but sprites are scattered widely around, up to 50 km from the flash? It would be very desirable to have many more examples of triangulated halos and sprites to improve the statistics, but we have done as much as is possible with what is available.

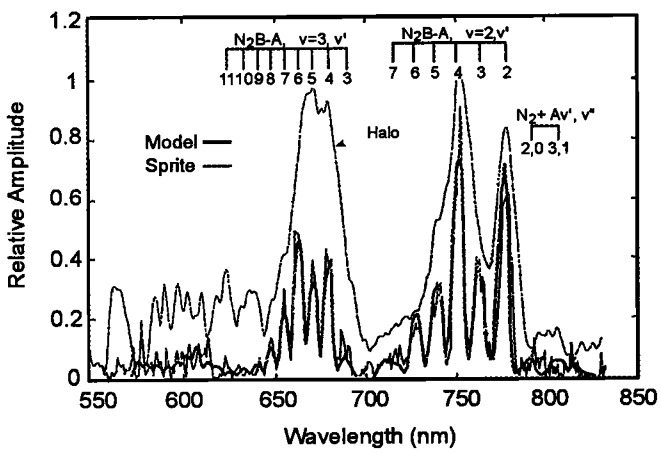

Figure 10. Spectrum of a halo recorded June 22, 1995, 0710:49 UT with a sprite spectrum and synthetic spectrum [from *Green et al.*, 1996].

We would like to speculate about answers to these questions, which involve the triggering process of sprites. In the QE model explanation for sprites, obviously the magnitude of the charge transfer from cloud to ground, and the length of time the electric field is present in the sprite region, is important, whether the field is upward or downward. It must take a minimum electric field to excite the N_2 molecules near 77 km to produce the uniform glow that is the sprite halo. The halo is centered over the lightning. What happens afterward can be divided into several cases:

1. If the electric field is large enough to excite N_2 via impact excitation by electrons accelerated in the electric field but not so large as to produce streamers, which appear as c-sprites, and there is no random ionizing perturbation, nothing more happens, and sensitive instruments detect only a halo. Streamers as defined by *Raizer* [1991] and related to the spatial structure of sprites by *Pasko et al.* [1998] are narrow filamentary plasmas driven by highly nonlinear space charge waves.

2. If the electric field is not large enough to produce streamers by itself, but a random ionizing trigger occurs in the region near 70 to 80 km during the time when the electric field is large enough, streamers appear and develop into sprites, which are

located where the random ionizing event occurred, not centered over the lightning flash.

3. If the electric field is much larger, the process develops immediately into a large sprite even without a random trigger, guided by preexisting irregularities in the region.

We suggest that the random trigger could be a micrometeor of sufficient mass to cause an ion trail as it encounters the atmosphere. *Muller* [1995, p. F105] postulated that "the mesosphere behaves like a triggered spark chamber" and that "the breakdown occurs only when the lightning event is roughly coincident with the arrival of an ionizing event." Even though a meteor does not enter the atmosphere vertically, as soon as ionization occurs, the electrons will move vertically in the direction of the electric field, thus producing the path for the streamer. Since the meteor is a random event within the excited region, the location of the sprite will also be at a random distance from the center over the lightning flash. *Nilsson and Southworth* [1968] show the cumulative flux of particles to the Earth's surface versus particle mass. The particles of interest are those of mass 10^{-6} to 10^{-2} g, which can be detected by radio techniques because they produce an ionized trail but are not visible. The flux of these ionizing particles into a circular area of radius 25 km is 19/s. The mean radar echo duration of meteor trails is ~400 ms [*Hadjuk*, 1968], so there would usually be a preexisting ion perturbation. The maximum ion production is at 93 km [*Manning and Eschelman*, 1959]. The visual meteors of larger mass could also provide the trigger, but they are a negligible fraction of the flux except during meteor showers. *Suszcynsky et al.* [1999] reported the observation of a visual meteor recorded with a low light level TV which seemed to trigger a sprite.

Cosmic rays are the main source of nighttime ionization in the *D* region, and we considered the suggestion by *Muller* [1995] that heavy nuclei cosmic rays could be a source of trigger events. However, the cosmic ray flux [*Smart and Shea*, 1985] is much too large to provide isolated random events at a rate low enough to account for the small fraction of sprites relative to +CG events. Instead, such cosmic rays represent a steady background drizzle of ionization.

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