GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 24, PAGES 3461-3464, DECEMBER 15, 1995

VLF signatures of ionospheric disturbances associated with sprites

U.S. Inan, T.F. Bell, and V.P. Pasko
STAR Laboratory, Stanford University, Stanford, California

D.D. Sentman and E.M. Wescott
Geophysics Institute, University of Alaska, Fairbanks

W.A. Lyons
ASTeR, Inc., Ft. Collins, Colorado

Abstract. VLF perturbations on signals propagating along great-circle-paths (GCP) through electrically active midwest thunderstorms are associated with luminous high altitude glows (referred to as sprites) observed from aircraft or ground. The data constitutes the first evidence that the physical processes leading to sprites also alter the conductivity of the lower ionosphere.

Introduction

Sprites provide dramatic new evidence of electrodynamic coupling between tropospheric lightning and the overlying mesosphere/lower ionosphere [*Sentman and Wescott*, 1993; *Lyons*, 1994; *Sentman et al.*, 1995; *Wescott et al.*, 1995]. Earlier evidence of direct disturbances of these regions by lightning were in the form of 'early/fast' subionospheric VLF perturbations [*Inan et al.*, 1988; 1993]. These perturbations were suggested to signify ionization changes resulting from the heating of the lower ionosphere by electromagnetic pulses (EMP) from lightning [*Inan et al.*, 1991; *Taranenko et al.*, 1993] or ionization columns associated with cloud-to-ionosphere discharges [*Dowden et al.,* 1994]. VLF perturbation events were also found to be sometimes associated with anomalous optical events [*Li et al.,* 1991]. Heating of ambient electrons by quasi-electrostatic (QE) thundercloud fields was suggested to produce both sprites and large ionization changes [*Pasko et al.*, 1995].

Sprites typically occur in association with intense (estimated peak currents of >50 kA) positive polarity cloud-to-ground (+CG) flashes [*Boccippio et al.*, 1995; *Winckler et al.,* 1995]. While the 'early' VLF events are always accompanied by intense radio atmospherics, only a subset of them are associated with CG flashes [*Inan et al.*, 1993]. In this paper, we provide the first evidence (initially presented by *Inan et al.* [1995*a*]) that the physical processes initiated by intense CG flashes which produce sprites also alter the lower ionospheric conductivity, leading to VLF perturbations.

Paper number 95GL03507
0094-8534/95/95GL-03507$03.00

Description of the Experimental Data

Data reported was collected in an aircraft-based campaign conducted by the University of Alaska between June 29 and July 12, 1994, and a ground-based program conducted by ASTeR, Inc., extending from 28 June through 7 September 1994, aimed at observations of mesoscale thunderstorms and associated sprites respectively in the midwest and High Plains.

VLF data consisted of narrowband (24.0±0.15 and 21.4±0.15 kHz) observations at Stanford and at San Diego of the magnetic field components (vertically deployed 1.7 m^2 square-loop antennas) of the signals respectively from the NAA and NSS transmitters in Maine and Maryland (Figure 1). Data were recorded at 10-ms resolution typically during 0000-1200 UT.

The University of Alaska observations were made with Jet Commander and Westwind 2 aircraft at flight altitudes of 12.2-12.8 km at speeds of 790 km/hr. Identical wide angle, low-light-level silicon-intensified-target monochrome TV cameras were used on each aircraft, and a low-light-level color camera on the Westwind 2, with GPS systems used to track aircraft position and to synchronize the various cameras [*Sentman et al.*, 1995].

ASTeR, Inc. observations were made at Yucca Ridge Field Station (104°56′24″ W, 40°40′06″ N), using two Xybion model ISS-255 low-light imagers, sensitive from 400 to 900 nm, with a broad peak from 550 to 750 nm. Unfiltered lenses were used, including a Cosmicar f1.4 with 12.5 mm focal length and a nominal 48° horizontal field of view, and a zoom lens [*Winckler et al.,* 1995]. The sensing system had a face plate illumination sensitivity of 10^{-6} foot-candles. The EIA RS/170 video was recorded on SHVS, with the camera strapped to produce successive, independent 16.7 ms fields with IRIG-B time stamping from a GPS source.

VLF Events, CG Lightning and Sprites

An example of the association between VLF perturbations, CG lightning, and sprites is shown in Figure 1. The NAA-SD GCP passes through an active storm center, with the CG lightning activity (i.e., time of occurrence and estimated peak current in kA) recorded by the National Lightning Detection Network (NLDN) [*Orville*, 1991]. Only *positive* flashes are shown since

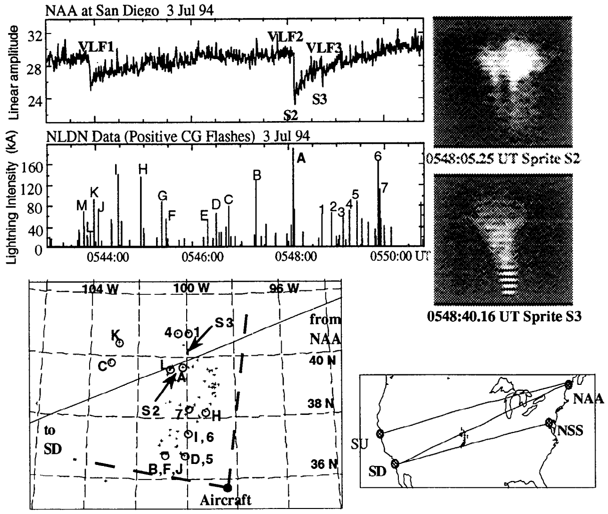

Figure 1. The top two panels show the amplitude of the NAA signal observed at San Diego and NLDN data on intensity and time of positive CG flashes. Relatively intense (>40 kA) CG flashes are identified by letters (A, B, C, etc.) or numbers (1,2,3, etc.) and their positions with respect to the VLF great circle path are shown in the lower panel. The two sprites shown were recorded on the Jet Commander aircraft.

the lightning rate was extremely high (~200/min), and also since sprites tend to be associated with positive CG flashes [*Boccippio et al.*, 1995]. Three VLF amplitude changes (VLF1, VLF2, and VLF3) are observed (with no detectable phase changes), associated respectively with CG flashes L, A and 1. No negative CG flashes occurred within ±150 ms of the onsets of VLF1 and VLF3.

Expanded records in Figure 2 indicate that the onset of VLF2 is simultaneous ($\leq$ 10 ms) with the largest CG flash A, confirming that the VLF event is of the 'early' type [*Inan et al.*, 1993], and thus signifying a sudden change in ionospheric conductivity produced directly by the energy released in the CG flash. The VLF perturbation does not appear to be 'fast' (onset duration is ~ 500 ms); however, this is likely due to the CG flashes A1 through A5 which follow the main flash A and which continue to alter the ionospheric conductivity.

The 178 kA CG flash A (CG-A) is one of the closest to the NAA-SD path. The ~30 kA CG flash L is also similarly located and is accompanied by VLF1. Other marked CG flashes were at distances of >100 km from the NAA-SD path, with the next closest being CG flash 1, which is accompanied by the relatively small VLF3. It appears that the proximity of the flash location to the path is the primary determinant (probably more important than flash intensity, as long as it is above a certain threshold) of whether or not a VLF perturbation is observed. By implication, the other large positive CG flashes may have produced similar ionospheric disturbances, which would have caused VLF perturbations had they been closer to the VLF path.

University of Alaska low light TV (LLTV) image data (available only from Jet Commander aircraft, see field-of-view in Figure 1) showed only two sprites S2 and S3 during this period, the times of which are coincident respectively with CG-A and CG-1, and thus the onsets of VLF2 and VLF3. The intensities of the two sprites at the brightest portions of the images were > 600 kR. CG-L occurred during an aircraft left turn so that the sprite altitudes were below the camera field of view; it is also likely that this relatively weak flash (~30 kA) did not lead to a detectable sprite.

If the highest altitude extent of S2 and S3 were 88 km (statistical average derived from dual aircraft measurements [*Sentman et al.*, 1995]), the locations of S2 and S3 would be as shown in Figure 1. The differences in the shapes of S2 and S3 are well within the range of typically observed variabilities [*Sentman et al.*, 1995].

During June 30 to July 12, 1994, (mostly in 0300-0600 UT), hundreds of sprites were recorded in the University of Alaska LLTV images. NAA and NSS signal data from San Diego and Stanford were available for this entire period. No other cases of VLF events were found during times of sprites recorded by the University of Alaska. NLDN data indicated that CG lightning flashes were within ±50 km of a monitored VLF path only in two other cases in which the flashes were coincident (within ±60 ms) with aircraft-based recordings of sprites, as discussed below.

On July 12, 1994, two 116 kA CG flashes (at 0429:41. 478 and 0436:52.260 UT) occurred within ~ 25 km NSS-SD GCP and led to sprites noted as 'bright', with no detectable changes on the NSS-SD signal. These two CG flashes would be expected to lead to 'early' VLF events on the NSS-SD signal based on past work [*Inan et al.*,1993]; however, subionospheric VLF response to a localized ionospheric disturbance is dependent on many factors, including the signal frequency, position of the disturbance along the GCP and the ambient ionospheric profile [*Poulsen et al.*, 1993].

On July 4, 1994, two <60 kA CG flashes at 0358:11.59 2 and 0503:29.373 UT occurred respectively within ±50 km of the NAA-SD and NSS-SD paths. The sprites observed coincident with these two flashes were not particularly noteworthy in terms of intensity or size, and no detectable VLF perturbations were observed.

Figure 3 shows the only three additional VLF events observed during 30 June to 12 July 1994, marked VLF4, VLF5, and VLF6, and associated with CG flashes X, Y, and Z, occurring within ~ 50 km of the NAA-SD path.

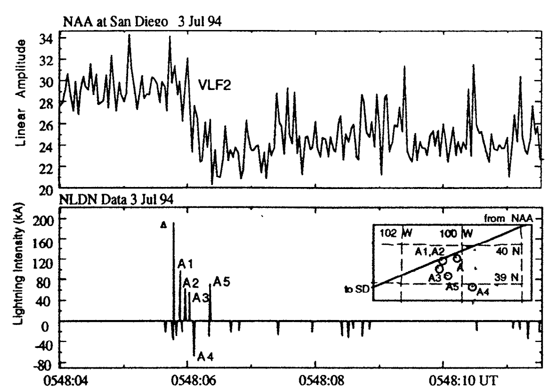

Figure 2. The NAA-SD signal amplitude is shown on the top panel, whereas the CG flashes (including negative ones) are shown in the middle panel. The locations of various flashes are indicated on the map.

Other CG flashes such as N, Q, R, and S, of comparable or higher intensity but located at distances > 100 km from the path, do not produce any VLF events. No negative CG flashes were recorded within ±200 ms of the onsets of VLF events or sprites.

During this period, the ASTeR, Inc. LLTV cameras recorded three large sprites, marked S4, S5, and S6 in Figure 3, occurring at the times respectively of the CG flashes X, Y, and Z. Assuming that they occur above the associated CG flashes, S4 and S5 extend from ~39 km to ~90 km altitude and are ~75 km across at their widest, while S6 extends from 39 km to 91 km altitude, and is slightly smaller in size [*Winckler et al.*, 1995]. All three sprites were bright enough to saturate the imager. S4 and S5 each persisted for 5 video fields (16.7 ms each), with the first field being the brightest. S6 had a number of small but intense bright spots within the larger luminous structure and persisted for 9 video fields, with the brightest being the 5th or 6th field, suggesting some complex internal dynamics.

The sky above the intense flash N (which did not lead to a VLF event) was just outside the camera field-of-view (see Figure 3); an intense sky brightening was observed at the time of N [*Winckler et al.*, 1995], probably due to a large sprite event just outside the field-of-view.

VLF Diffraction Pattern

The VLF events in Figures 1 and 3 represent the superposition of the unperturbed signals at the receiver and those which are scattered by the disturbance [*Poulsen et al.*, 1993]. The scattering of VLF signals by typical lower ionospheric disturbances is largely in the forward direction, with the angular pattern determined by the disturbance size and location [*Poulsen et al.*, 1993].

To quantify the VLF diffraction pattern for the NAA-SD GCP Figure 4 shows the computed amplitude change

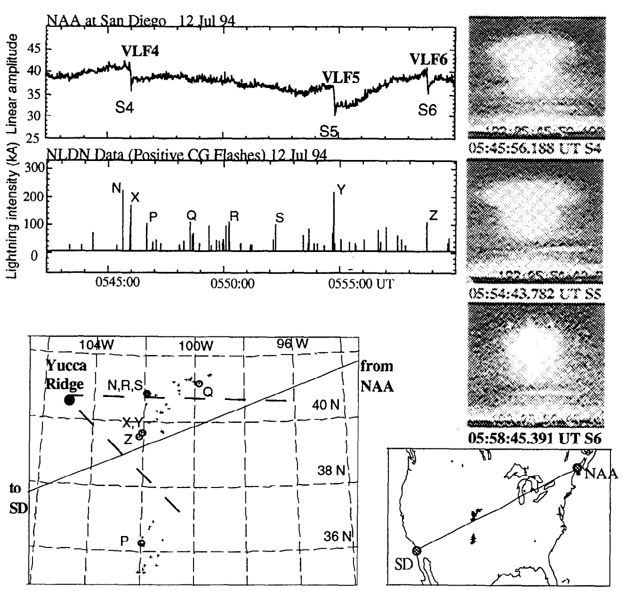

Figure 3. Top two panels show the amplitude of the NAA-SD signal and the NLDN data on intensity and time of positive CG flashes. The positions of selected flashes are shown in the same format as Figure 1. The images of the three sprites marked S4,S5, and S6 were acquired by ASTeR, Inc., at the Yucca Ridge Field Station, with field-of-view of being as indicated on the map.

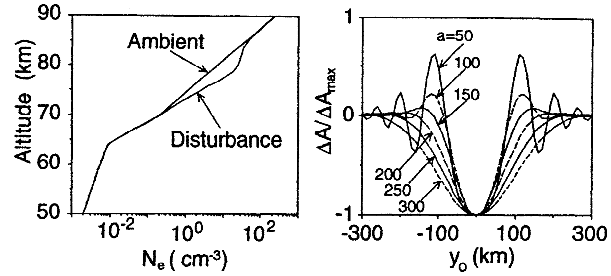

Figure 4. Right: Predicted change in the amplitude of the NAA-SD signal due to the appearance of a disturbance having a Gaussian shape ($e^{-(2r/a)^2}$) in the radial (r) direction, for different values of a, and as a function of the transverse distance y_o between the center of the disturbance and the VLF path. Left: The ambient and disturbed ionospheric ionization profiles used in the model calculations.

ΔA (in dB) of the NAA-SD signal as a function of disturbance size and location transverse to the path, computed using a new 3-D model of subionospheric VLF propagation and scattering [*Poulsen et al.*, 1993]. For simplicity, the disturbance is assumed to have a Gaussian shape in the transverse direction, with the altitude profile of the ionization change being that which is produced due to heating by QE fields released by a CG flash removing 200 coulombs from 10-km altitude in 1 ms [*Pasko et al.*, 1995]. Conductivity changes above the nighttime reflection height (~85 km) have virtually no effect on the VLF signal. The diffraction pattern is only weakly dependent upon the actual conductivity profile and is determined predominantly by the horizontal scale of the perturbation [*Poulsen et al.*, 1993].

Figure 4 indicates that the ionospheric disturbances in the cases of Figures 1 and 3 had transverse extents of ~100-150 km. Smaller disturbance sizes (e.g., 50-km) are not likely since disturbances at distances of 200-km from the propagation path (e.g., CG flashes K or 7 in Figure 1 or Q in Figure 3) would then have led to large ΔA due to the prominent side lobes. In this respect, our findings are not consistent with the interpretation by *Dowden et al.* [1994] of VLF events as scattering from few km wide ionization columns. Similarly, disturbance sizes > 150 km are not likely since the main beam of the pattern would then have been wide enough to include these distant CG flashes.

Summary and Discussion

We presented the first experimental evidence of an association between 'early' subionospheric VLF events and sprites, indicating that the physical processes that lead to the production of sprites alter the electrical conductivity of the lower ionosphere.

The observation of only a few examples of VLF events time-correlated with sprites is likely due to the 'viewing' limitations of the VLF method, which, for the path geometry in hand, requires the disturbed ionospheric regions to be within ±50 km of the path. Since the associated sprites shown in this paper were in the upper 10 percentile in terms of intensity and size, it is possible that electrical conductivity changes commonly occur in association with intense sprites, and would lead to measurable VLF perturbations, depending on the availability of measurements on a nearby VLF path, and also to some degree on the VLF propagation and scattering conditions. In this connection, we note that examples were observed of sprites associated with CG lightning near the paths with no detectable VLF events. Thus, the extent of the association between sprites and early VLF events needs to be further assessed.

The VLF events shown in Figures 1 and 3 literally constitute *all* of the events (defined as a sudden (< 1 s) amplitude change of > 0.2 dB recovering back to pre-event levels in 10-100 s) observed at San Diego during 29 June to 12 July 1994. However, it is not clear whether early VLF events are necessarily accompanied by sprites. 'Early' VLF events are observed with both positive and negative CG flashes with intensites as small as 20 kA [*Inan et al.*, 1993], although sprites are typically associated with positive and relatively intense (> 60 kA) CG flashes [*Boccippio et al.*, 1995]. It is thus more likely that only a subset of VLF events are accompanied by detectable sprites. However, it remains to be determined whether weaker sprites, possibly below the threshold of presently used LLTV cameras, may more often accompany VLF events, as would be expected on theoretical grounds [*Pasko et al.*, 1995].

The nature of the association between early VLF events and NLDN recorded CG flashes is similar to those reported in previous work [*Inan et al.*, 1993]. The apparent requirement of the proximity of the causative CG lightning to the GCP indicates that the transverse extent of the affected ionospheric regions is likely $\sim$100-150 km, substantially larger than the transverse size of the associated sprites.

If sprites are produced as a result of the heating of ambient electrons by intense QE thundercloud fields [*Pasko et al.*, 1995], and given that their red color is primarily due to excitation of the N_2 first positive band (excitation threshold $\sim$7-8 eV) [*Mende et al.*, 1995; *Hampton et al.*, 1995], it is difficult to imagine that the size of regions of enhanced ionization, produced by impact of electrons with energy $>\sim$15.6 eV, could be larger than the observed size of sprites. Alternatively, the ionization changes could be depletions produced via dissociative attachment to O_2, which occurrs at ~ 6 eV. However, model calculations indicate that the size of both ionization and attachment regions produced as a result of heating by QE fields are small, typically $<$50 km [*Inan et al.*, 1995*b*].

Acknowledgments. The Stanford University component of this research was supported under ONR grant N00014-94-1-0100. We thank Dr. J. Ferguson of NOSC for housing and operation of our equipment in San Diego. The University of Alaska effort was supported by NASA Grant NAGW5-5019 and by NSF Grant ATM-9217161 while the ASTeR, Inc., work was partially supported by NASA/KSC, SBIR Phase II Contract NAS10-12113. We appreciate the contributions of W. J. Trabucco, A. Slingeland, T. E. Nelson, I. T. Baker, and E. Williams. We thank the MSFC DAAC for providing access to NLDN lightning data.

References

Boccippio, D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. Baker, and R. Boldi, Sprites, ELF transients and positive ground strokes, *Science, 269*, 1088, 1995.

Dowden, R. L., C. D. C. Adams, J. B. Brundell and P. E. Dowden, Rapid onset, rapid decay (RORD), phase and amplitude pertubations of VLF subionospheric transmissions, *J. of Atmospheric and Terrestrial Phys., 56,* No. 11, pp.1513-1527, 1994.

Hampton, D. L., M. J. Heavner, E. M. Wescott, and D. D. Sentman, Optical Spectra of Sprites, *Geophys. Res. Lett.*, (in press), 1995.

Inan, U. S., D. C. Shafer, W. Y. Yip, and R. E. Orville, Subionospheric VLF signatures of nighttime D-region perturbations in the vicinity of lightning discharges, *J. Geophys. Res., 93,* 11455, 1988.

Inan, U. S., T. F. Bell, and J. V. Rodriguez, Heating and ionization of the lower ionosphere by lightning, *Geophys. Res. Lett., 18,* 705, 1991.

Inan, U. S., J. V. Rodriguez, and V. P. Idone, VLF signatures of lightning-induced heating and ionization of the nighttime D-region, *Geophys. Res. Lett., 20*, 2355, 1993.

Inan, U. S., T. F. Bell, V. P. Pasko, D. D. Sentman, and E. M. Wescott, VLF sprites as evidence of ionization changes associated with red sprites, *EOS, 76*, S64, A31E-1, 1995*a*.

Inan, U. S., A. Slingeland, V. P. Pasko, and J. Rodriguez, VLF signatures of mesospheric/lower ionospheric response to lightning discharges, *J. Geophys. Res.*, (in review), 1995*b*.

Li, Y. Q., R. H. Holzworth, H. Hu, M. McCarthy, R. D. Massey, P. M. Kintner, J. V. Rodriguez, U. S. Inan, and W. C. Armstrong, Anomalous optical events detected by rocket-borne sensor in the WIPP campaign, *J. Geophys. Res., 96*, 1315-1326, 1991.

Lyons, W. A., Characteristics of luminous structures in the stratosphere above thunderstorms as imaged by low-light video, *Geophys. Res. Lett., 21,* 875, 1994.

Mende, S. B., R. L. Rairden, G. R. Swenson, and W. A. Lyons, Sprite spectra: N_2 first positive band identification, *Geophys. Res. Lett., 22* 2633, 1995.

Orville, R. E., Calibration of a magnetic direction finding network using measured triggered lightning return stroke peak currents, *J. Geophys. Res., 96*, 17135, 1991.

Pasko, V. P., U. S. Inan, Y. N. Taranenko, and T. F. Bell, Heating, ionization and upward discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields, *Geophys. Res. Lett., 22,* 365, 1995.

Poulsen, W. L., T. F. Bell, and U. S. Inan, The scattering of VLF waves by localized ionospheric disturbances produced by lightning-induced electron precipitation, *J. Geophys. Res., 98*, 15,553-15,559, 1993.

Sentman, D. D., and E. M. Wescott, Observations of upper atmospheric optical flashes recorded from an aircraft, *Geophys. Res. Lett., 20*, 2857, 1993.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, M. J. Heavner, Preliminary results from the Sprites94 campaign: Red Sprites, *Geophys. Res. Lett., 22*, 1205, 1995.

Taranenko, Y. N., U. S. Inan and T. F. Bell, Interaction with the lower ionosphere of electromagnetic pulses from lightning: heating, attachment, and ionization, *Geophys. Res. Lett., 20*, 1539,1993.

Wescott, E. M., D. Sentman, D. Osborne, D. Hampton, and M. Heavner, Preliminary results from the Sprites94 aircraft campaign: 2. Blue jets, *Geophys. Res. Lett., 22,* 1209, 1995.

Winckler, J. R., W. A. Lyons, T. Nelson, and R. J. Zemzek, New high-resolution ground-based studies of cloud-ionosphere discharges over thunderstorms (CI or Sprites), *J. Geophys. Res.*, (in review), 1995.

(received September, 1995; revised , 1995; accepted , 1995.)