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“Early/slow” events: A new category of VLF perturbations observed in relation with sprites

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[1] Analysis of subionospheric VLF transmissions, observed in relation with sprites, has led to the identification of a new category of VLF perturbations caused by the direct effects of tropospheric lightning on the overlying lower ionosphere. They constitute a large subset of the so-called “early/fast” events where now the term “fast,” which implies rapid onset durations less than $\sim$20 ms, does not apply. In contrast with early/fast, the perturbations have a gradual growth and thus “slow” onset durations ranging from about 0.5 to 2.5 s; thus these events are labeled herein as “early/slow.” They are indicative of a new physical process at work which, following a sprite-causative cloud-to-ground discharge, leads to a gradual buildup of conductivity changes in the lower ionosphere which must be responsible for the long onset durations of the observed perturbations. Analysis of broadband VLF sferic recordings, made with a two-channel receiver near the sprite producing storms, shows that the growth phase of an early/slow event coincides with the occurrence of complex and dynamic lightning action. This is composed of a few sequential cloud-to-ground lightning strokes and clusters (bursts) of sferics which are attributable to intracloud lightning. We postulate that the long onset durations are due to secondary ionization buildup in the upper *D* region below the nighttime VLF reflection heights, caused mainly by the impact on sprite-produced electrons of sequential electromagnetic pulses radiated upward from horizontal in-cloud discharges.

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1. Introduction

[2] Following the description of *Johnson et al.* [1999], “early/fast” (E/F) events are abrupt perturbations in the amplitude and/or phase of subionospheric very-low-frequency (VLF) transmissions. They occur within 20 ms of a causative cloud-to-ground (CG) lighting discharge (i.e., early) and have rapid onsets (<20 ms, i.e., fast) followed by relatively long signal recoveries ranging from about 10 to more than 100 s. They are rare relative to the large number of potentially causative CG discharges that occur during a thunderstorm. Although the early VLF perturbations have been studied extensively over the last 15 years, mostly by the VLF group at Stanford University [e.g., see *Inan et al.*, 1993; *Johnson and Inan*, 2000; *Moore et al.*, 2003], and also by *Dowden et al.* [1996a, 1996b], the complexity of their properties is not yet fully explored.

[3] The key property of E/F is their “early-ness” which implies a direct energetic coupling process between lightning discharges and the lower ionosphere. This distinguishes E/F from the well-known “trimpis,” or lightning-induced electron precipitation (LEP) events, whose onsets are delayed by $\sim$1 s relative to their causative CG lightning discharges [e.g., see *Burgess and Inan*, 1993; *Rodger*, 2003, and references therein]. This delay is a characteristic time-scale of an indirect coupling process between the tropospheric discharges and the ionosphere, involving the interaction between lightning-produced whistler waves and radiation belt electrons, which are forced to undergo pitch angle scattering into the loss cone and precipitation into the lower ionosphere. This magnetospheric process leading to LEPs lasts for $\sim$0.5 to 1.0 s which manifests itself in their slow onset duration.

[4] In contrast to LEP, and in addition to being “early,” E/F events are known to have rapid onset durations comparable to the short lifetimes of the causative lightning discharges. In the present study we provide evidence showing that a sizable group of sprite-related E/F perturbations do not display a “fast” onset; instead they have slow onset durations of $\sim$1 to 2 s. These are labeled here as “early/slow” (E/S) events. Their existence is intriguing and demands attention and further study.

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[5] This work comes as a continuation of recent studies based on observational campaigns in Europe aimed at studying transient luminous events, like sprites and elves [e.g., see *Neubert et al.*, 2005]. Initial investigations of early VLF perturbations observed during EuroSprite-2003 in close association with sprites were presented by *Haldoupis et al.* [2004] and *Mika et al.* [2005]. Although the identification of E/S events was reported briefly in these papers, there was no detailed analysis or thorough study of their properties. The present work complements the previous studies by focusing on the E/S VLF perturbations. We also aim to draw attention to the regular occurrence of these phenomena and offer some ideas for their interpretation.

2. Experiments and Measurements

[6] The present analysis is based on EuroSprite-2003 and -2005 summer observations. The experimental setup included: (1) a computerized sprite detection camera system with a minimum exposure image time of 20 ms, operating from the Observatoire du Pic du Midi, France (42.90°N; 0.09°E), (2) a narrowband VLF receiver in Crete, Greece (35.31°N, 25.08°E), which operated also as a single-channel broadband receiver in the 2005 campaign, (3) a dual broadband VLF receiver situated at Nancay, France (47.38°N, 2.19°E), and (4) Meteorage, a company that manages the French lightning detection network, which provided CG lighting data with spatial and temporal accuracies of 1 km and 1 ms and about 90% detection efficiency. The operational aspects of these units and various experimental details are given elsewhere [e.g., see *Neubert et al.*, 2005; *Haldoupis et al.*, 2004; *Mika et al.*, 2005].

[7] Both VLF receivers are identical to those deployed in the Holographic Array for Ionospheric Lightning (HAIL) network [e.g., see *Johnson et al.*, 1999] that have been used in the Stanford University VLF studies. The Crete narrowband station applied a sampling interval of 20 ms to record several VLF links, most of them originating from military transmitters in Europe and a few in the United States. For their call signs, frequencies, and great circle paths (GCP) to the Crete receiver, see *Haldoupis et al.* [2004]. Of particular interest is the powerful HWU transmitter (1 MW, 18.3 kHz) located near Le Blanc, France (46.70°N, 1.26°E). This link has detected most of the early VLF perturbations analyzed in this study, apparently because of its high power and because the thunderstorms were located near its GCP to Crete. The wideband ($\sim$400 Hz to 50 kHz) receiver at Nancay is a dual-channel system that uses two right-isosceles triangular antennas aligned in the east-west (EW) and north-south (NS) directions. It recorded time series of VLF data with a sampling interval of 10 μs. In the present study the storms happened to be located near Nancay; thus the broadband receiver is sensitive to sferics from intracloud (IC) lightning during those storms.

[8] An important result of the EuroSprite campaigns was the establishment of a nearly one-to-one relationship between sprites and early VLF perturbations, holding up to $\sim$85 to 95% of the cases. This was reported first by *Haldoupis et al.* [2004], who studied a single 1-hour long thunderstorm that produced 30 sprites, and confirmed further by *Mika et al.* [2005] who tested this result with additional observations from two more storms with a total of 20 sprites. In the present study, we have identified a total of 73 early VLF events after inspecting a total of 85 sprites, 75 from four different storms in the 2003 campaign (during 21–24 July and 28–29 August) and 10 from a short storm on 29 July 2005 when broadband VLF recordings were also available in Crete.

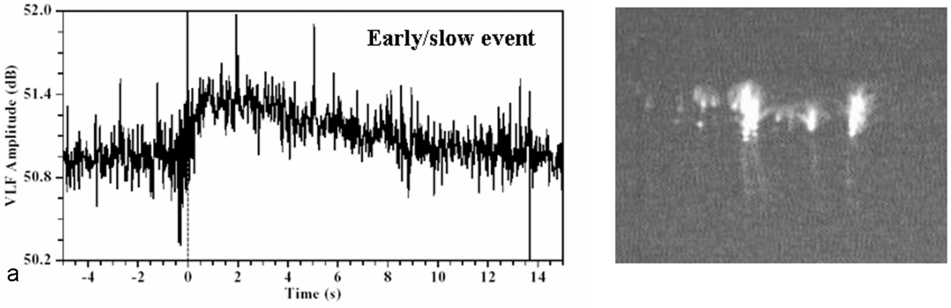
[9] Since the aim here was the characterization of early/slow events, we inspected high-resolution time series for all the sprite-related early perturbations to finally select and keep for analysis only those events whose onsets were clearly discernible. Most of the events were excluded because the background VLF noise level was almost comparable to the perturbation itself and/or it was heavily affected by intruding sferics so that the event's onset duration could not be estimated and categorized with certainty. Finally, the usable events were reduced to 27. These represented the strongest VLF perturbations with amplitudes ranging from about 0.4 dB to 1.7 dB that were "clear" enough to obtain objective estimates of their onset duration.

3. Observations of Early/Slow Events

[10] Out of the 27 strong VLF perturbations under consideration, at least 15, that is, about 55% of the cases, classified clearly as early/slow, eight events were early/fast, whereas the rest exhibited rather complicated onsets (a few associated with closely spaced sequential sprites), which made their categorization ambiguous. Figure 1 provides typical examples of the observed E/S and E/F perturbations which occurred in association with sprites. The zero time in the abscissa denotes the sprite onset marked there by the dashed line, whereas the optical image is shown to the right. Figure 1 shows the different nature of an E/S event in contrast to an E/F one. The latter displays an instant (fast) onset followed by the usual signal recovery of several tens of seconds. On the other hand, the E/S signature, shown in Figure 1a, has a slow onset duration, characterized by a gradual growth which lasts for $\sim$1.0 to 1.5 s. Next follows its recovery back to preonset signal levels, which is similar in duration to that of the E/F event (also that of LEPs).

[11] To substantiate further that E/S events do represent a distinct group of (sprite-related) early VLF perturbations, we provide Figure 2 with more examples of E/S events, having both positive (Figure 2a) and negative (Figures 2b and 2c) amplitude perturbations. All cases are characterized by a gradual growth of the perturbation which lasts somewhat more than 1 s. Surely these events cannot be classified as "fast," which are well known from past studies to have onset durations less than 20 ms [e.g., see *Johnson et al.*, 1999]. Note that VLF perturbations which were "early" but not "fast" with onset durations of $\sim$0.5 s were reported before, also in association with sprites, by *Inan et al.* [1995] who, however, did not investigate this aspect further. Finally, we need to mention that a few of our E/S events appeared to have their onset growth starting somewhat earlier than the sprite. The most convincing example of such "preearly" events is given in Figure 2a, showing clearly that the gradual growth of the perturbation started about 0.5 s prior to the sprite onset. Although the available number of such cases was not enough to categorize them as

Sprite at : July 21, 2003, 03:03:28.920 UT



Sprite at : August 29, 2003, 00:04:42.620 UT

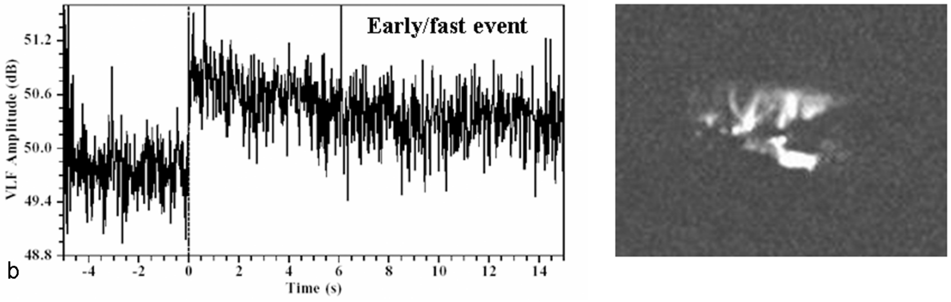


Figure 1. (a) A typical sprite-related early/slow VLF perturbation, characterized by a slow onset duration, is compared with (b) an early/fast event. The early/slow events, which have onset durations ranging from 0.5 to 2.5 s, occur regularly and represent a sizable group of early VLF perturbations observed in relation with sprites.

a separate subset, this possibility should be kept in mind and deserves to be examined in future studies.

[12] High-resolution broadband VLF recordings at Nancay were analyzed during E/S events, also in conjunction with Meteorage lightning data. The storms under consideration were located in central France at distances ranging between 100 and 400 km from Nancay. Our analysis revealed a recurring lightning pattern for E/S which is typified as follows: (1) Seen by Meteorage, there is a postonset sequence of a few individual CG discharges coming from the same area, suggesting that E/S events occur during a period of complex and dynamic thundercloud lighting action of charge removal and redistribution. (2) The CG discharges coincide with the strongest sferics at Nancay, but in addition there exist a large number of weaker and densely clustered sferics which are not seen by Meteorage, which are thus likely attributed to a packed sequence of IC lightning. (3) The latter may initiate before the sprite but most occur after it and always in coincidence with the E/S onset growth. (4) The clustering of IC sferics originates from about the same storm area.

[13] The situation just described is typified in Figure 3, which refers to a sprite-related E/S event with a long onset growth of about 2.5 s as depicted in Crete (see Figure 3d). Figure 3e displays the Meteorage CG lightning strokes, showing the sprite causative +CG discharge of 160 kA to be followed by three more positive discharges and two weak −CG ones, all occurring within about 1.0 s after onset. These discharges occurred at distances from Nancay between about 130 and 150 km to the southeast. The VLF broadband observations at Nancay are summarized in Figures 3a–3c. Figure 3c shows the signal waveform in nT induced in the EW Nancay antenna, which is combined with the one in NS antenna (not shown here) to compute the amplitude and direction of arrival of the sferic signal, shown in Figures 3b and 3a, respectively. As seen, there is a cluster of sferics that intensifies right after the sprite and the E/S onset, lasting for ~2–3 s in exact coincidence with the E/S onset duration. On the basis of Figure 3a, we infer that the aforementioned cluster of sferics comes from about the same directions, between 35° and 45° to the southeast, exactly from the thunderstorm under consideration, as evidenced by Meteorage. Previously, *Johnson and Inan* [2000] were the first to report characteristic wideband VLF sferic clusters attributed to IC lightning to be consistently associated with early VLF perturbations. Also more recently, *Ohkubo et al.* [2005] reported on enhanced VLF activity indicative of IC lightning in association with sprites.

[14] During EuroSprite-2005 the Crete VLF station operated also as a single-channel broadband receiver. This provided the possibility of testing if the cluster of sferics seen at Nancay simultaneously with the growth phase of E/S events is indeed caused by in-cloud discharges. This relies on the fact that IC lightning sferics are not expected to propagate at large distances [e.g., see *Johnson and Inan*, 2000]; thus they should not be seen in Crete, more than 2000 km away from the storms in France, under consideration.

[15] We have confirmed this by analyzing two E/S events from EuroSprite-2005, seen in the HWU-Crete link in relation with sprites over central France during a brief storm in 29 July 2005. The findings are summarized in Figure 4, which refers to a long-lasting (60 ms) sprite (marked by the

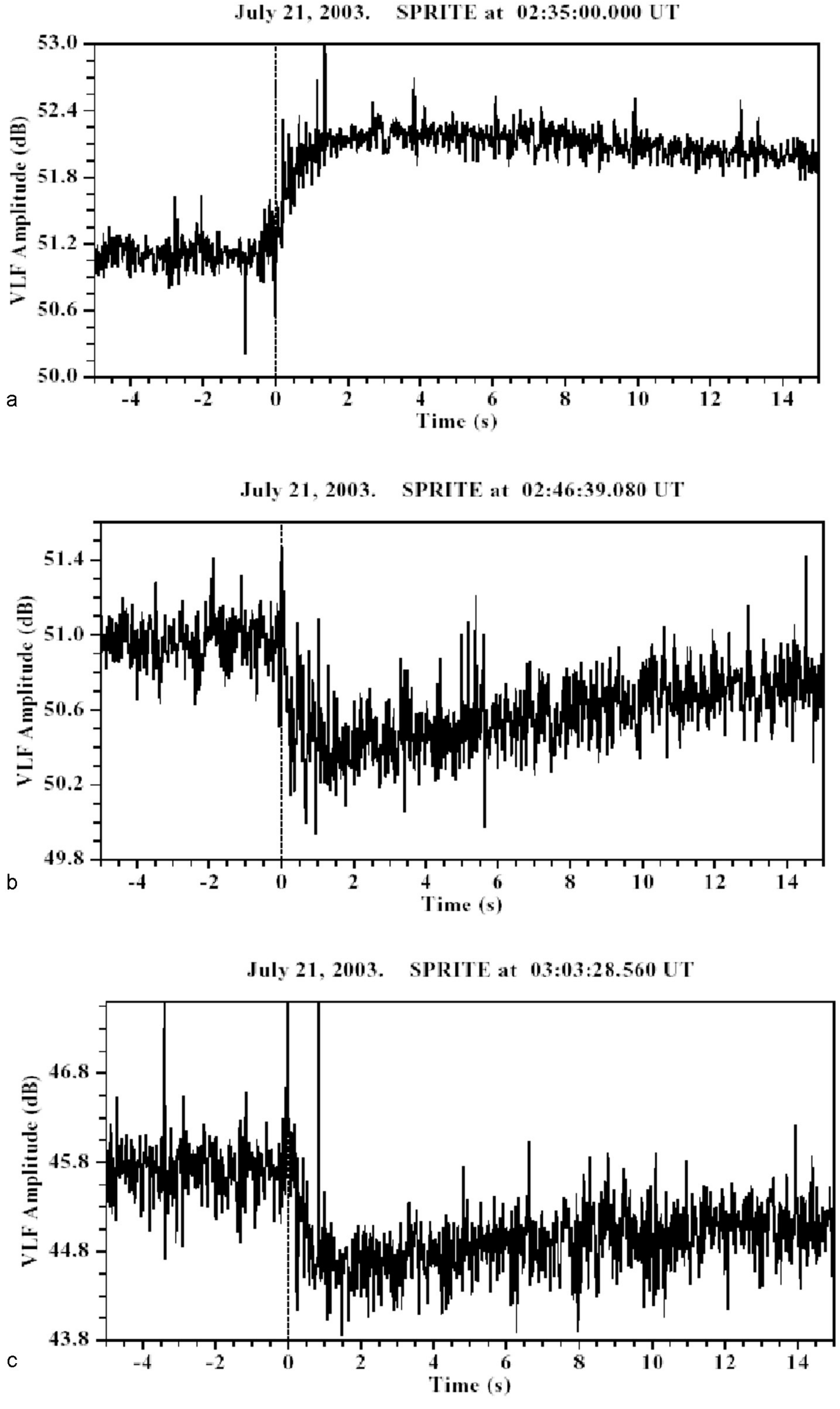


Figure 2. More examples of typical early/slow VLF perturbations observed in association with sprites.

dashed lines) following a +CG discharge of ∼100 kA. As seen in Figure 4d, Meteorage detected after the sprite-causative +CG discharge at least six more weaker +CG flashes packed over a time interval of 0.8 s, all originating from the same localized region. The accompanying E/S event seen in Crete, and shown in Figure 4c, started with the sprite but continued growing for about 2 s. This growth phase is also accompanied by a strong burst of numerous

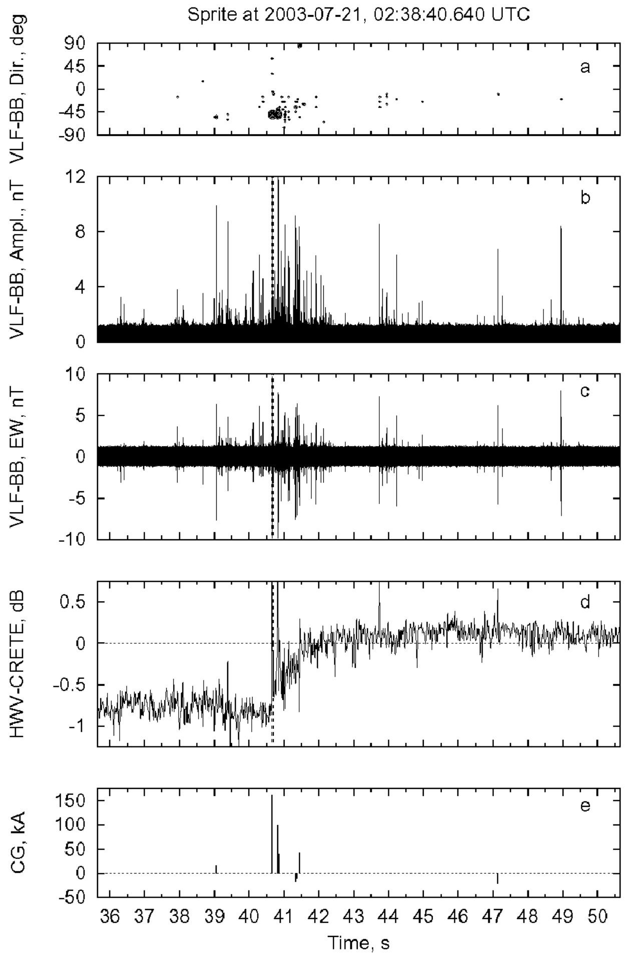


Figure 3. (d) The early/slow event seen in Crete, initiated by a sprite over a convective storm in central France, is compared with (e) CG lightning strokes and (a, b, c) wideband VLF sferic recordings in Nancay, France, at about 200 km northeast of the thunderstorm. The 2 s onset duration of the VLF perturbation coincides with a cluster of many sferics (Figure 3b) originating from the same storm area (Figure 3a), which are attributed to intense intracloud lightning currents. See text for more details.

sferics seen by the broadband VLF receiver at Nancay, as illustrated by the EW antenna waveform in Figure 3. Again the angle of arrival of these sferics (not shown here) comes from the same storm region under consideration. Comparison of the Crete broadband time series in Figure 4a, with the Nancay signal below and the Meteorage data, shows that Crete detects only a small number of discrete sferics all in relation to the CG discharges seen by Meteorage. Crete does not detect the clustered sferics seen at Nancay, apparently because these are due to IC lightning and thus cannot propagate at large distances, say larger than 500 to 800 km [e.g., see *Johnson and Inan*, 2000, and references therein].

[16] Finally, the few E/F events were also analyzed in the same manner to find out that their onsets were not accompanied by enhanced clusters of sferics as in the E/S cases. A representative example is shown in Figure 5. The VLF perturbation in Figure 5d, observed at 18.3 kHz in the HWU-Crete link, is a classic E/F event exhibiting an abrupt onset followed instantly by its recovery phase. This onset was coincident with the occurrence of a sprite that lasted for 40 ms, which apparently was triggered by the +CG discharge of 140 kA which was situated at about 330 km away from Nancay, followed by a much weaker positive discharge ~80 ms later. The broadband VLF records at Nancay are shown in Figures 5a–5c. Shown there are a few discrete sferics occurring after onset (e.g., see Figure 5b) but there is no significant clustering of sferics present as in E/S cases. The few discrete strong sferics over the next 3 s after onset are caused by negative CG discharges and appear to be unrelated and have no effect on the recovery of the perturbation. Also, their estimated directions of arrival, shown in Figure 5a, suggest their origins at different parts

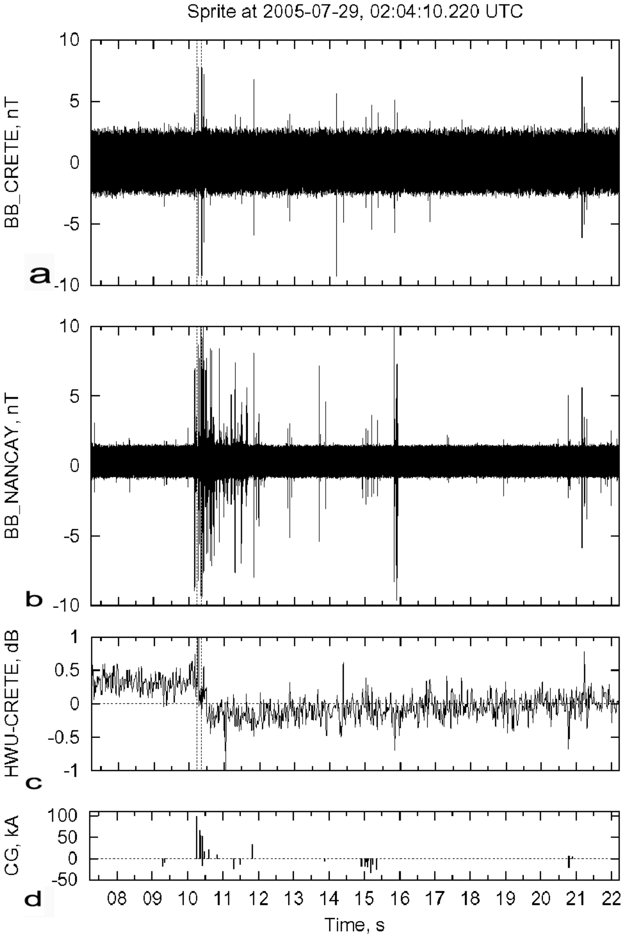


Figure 4. (c) An early/slow event seen in Crete, whose onset coincides approximately with a long-lived sprite, is compared with (d) simultaneous CG lightning strokes and broadband VLF sferic waveforms recorded (b) near the storm at Nancay and (a) about 2200 km away from the storm in Crete. As seen, the Nancay cluster of sferics, which coincides with the onset duration of the early/slow event, is not seen at 2200 km away in Crete, apparently because these are caused by in-cloud lightning. See text for more details. The two vertical dashed lines signify that the sprite is shown on two following images.

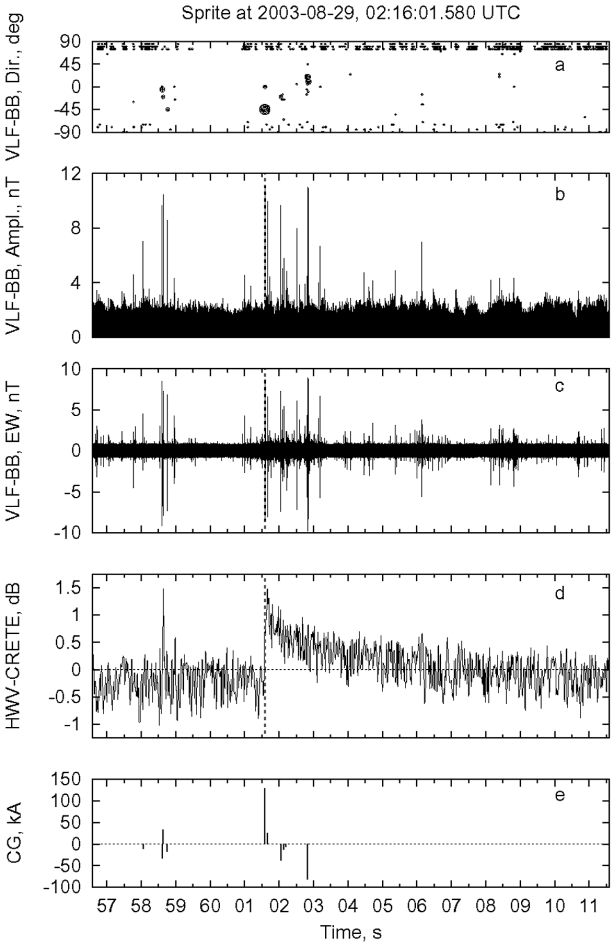


Figure 5. Same as Figure 3 but for a typical early/fast event. The broadband VLF recordings near the storm do not show much of postonset sferic clustering in contrast to early/slow events. The postonset discrete sferics appear to have no effect on the early/fast VLF perturbation, and to originate in different regions of the storm (see sferic directions of arrival in Figure 5a). See text for more details.

of the storm, rather far from the location of the sprite causative +CG discharge.

4. Recent Knowledge on Early VLF Events

[17] In view of the present findings, hereby we adopt the term "early VLF events" as representative of both the early/fast and early/slow perturbations. "Early" is the key word, meaning they are due to direct coupling of energy released by lightning discharges into the lower ionosphere. Next, we provide some background knowledge, which is to be used next in the discussion of possible interpretations for the observed growth, or long onset durations, of E/S events.

[18] Recently, there has been considerable progress in understanding the early VLF perturbations. As shown by *Johnson et al.* [1999], who used a dense array of identical VLF receivers in central United States, early VLF perturbations are caused by forward scattering (diffraction) of the transmitted signals from diffuse, lightning-induced ionospheric disturbances above thunderstorms. Such regions are found to be located near the GCP between the transmitter and the receiver, having typical lateral extents of ~100 km. The early VLF perturbations at the receiver come from the superposition of the direct signal and the scattered one and can be of negative or positive polarity depending on the phase (path) difference between the two signals.

[19] The findings of *Johnson et al.* [1999] can be accounted for by the theory of *Poulsen et al.* [1993] on VLF scattering from diffused ionospheric disturbances produced by lightning-induced ionization. We stress that this theory considers that the ionospheric disturbances responsible for early VLF events are perturbations in electron density (ΔN_e), expressed in their model by a cylindrically symmetric Gaussian distribution. In order to explain the observed perturbation amplitudes, one needs a region of enhanced electron density simply because it is the free electrons that scatter the incident wave. One should keep in mind, however, that electron attachment times in the lower ionosphere are short, e.g., <5 s at heights below 70 km [e.g., see *Clukhov et al.*, 1992], thus free electrons disappear quickly by forming negative ions. This means that the scattering ionization must be confined above ~70 km but below the VLF reflection heights at nighttime (~85 km), where electron lifetimes are comparable with the observed early VLF recovery times of 10–100 s. This important implication has been confirmed by the recent work of *Barrington-Leigh et al.* [2001] and *Moore et al.* [2003], with the identification of sprite halos and their close association with early VLF events. The sprite halos are briefly lived (a few ms) diffuse glows which are confined in the upper portion of the sprite body, in altitudes between ~70 and 90 km while their lateral extent is several tens of kilometers.

[20] *Barrington-Leigh et al.* [2001] analyzed high-speed image-intensified video sprite recordings to find that "sprite halos" are a normal component of the sprite electrical breakdown process caused by a quasi-electrostatic thundercloud field, in accord with the theory of *Pasko et al.* [1995]. Model estimates of the electron ionization produced in the high-altitude diffuse regions of sprite breakdown led *Barrington-Leigh et al.* [2001] to suggest that sprite halos are responsible for the early/fast VLF events. This proposition, which is in line with the work of *Johnson et al.* [1999] and the scattering theory of *Poulsen et al.* [1993], was verified later by *Moore et al.* [2003]. These authors used a model of VLF propagation and scattering in the Earth-ionosphere waveguide to reproduce accurately the measured amplitudes of strong E/F perturbations by using elevated N_e profiles in relation with sprite halos.

[21] Obviously, these results imply a close relationship between sprites and early VLF perturbations. This has been confirmed by the EuroSprite-2003 observations which suggested a nearly one-to-one relationship [e.g., see *Haldoupis et al.*, 2004; *Mika et al.*, 2005]. Note that the low-speed (standard) video camera of 20 ms frame time used in EuroSprite could not resolve the presence of sprite halos. Nevertheless, the observed long recovery times (20 to 150 s) of the early events suggest that the VLF perturbations accompanying the sprites can be due to diffuse regions of elevated electron densities which exist only in the upper

portions of the sprite displays and in sprite halos, that is, above ∼70 to 75 km and below VLF reflection heights.

[22] Finally, we note that although EuroSprite results and the observations of *Dowden et al.* [1996b] suggest a close relationship between early VLF events and sprites, there exist past observations when this was not the case [e.g., see *Inan et al.*, 1993, 1995]. To explain such cases, *Inan et al.* [1996] proposed a mechanism which relies on sustained ionospheric conductivity changes in the *D* region without involving ionization production. In this process, QE thundercloud fields above the storms are proposed to maintain the existing ionospheric electrons at a persistent (quiescent) level of heating above their thermal energy which can lead to conductivity changes sufficiently large to produce forward scattering and thus VLF perturbations. In this mechanism the long recovery times of 10 to 100 s of the perturbations do not represent electron lifetimes above 70 km, but characteristic recharging timescales of the thunderclouds. The mechanism of sustained heating, however, is difficult to account for VLF perturbations with amplitudes higher than 0.1 to 0.2 dB.

5. What Are the Early/Slow Events?

[23] Why is there a gradual onset growth for part of early VLF events that occur in relation with sprites? This is the key question of the present study. Next, we discuss possible ideas for an explanation by considering the existing knowledge and the present observational findings.

5.1. Secondary Ionization Buildup

[24] A mechanism behind the E/S events needs to explain why, soon after a sprite, the VLF perturbation undergoes, for about 1 to 2 s, a gradual growth to a maximum amplitude, instead of an abrupt jump to the same amplitude levels as is in E/F events. Given our present knowledge (outlined in the previous section), this points to a process of gradual ionization buildup at heights above ∼70 km which is initiated by a sprite breakdown. Such a possibility seems to be compatible with the present observations showing the onset duration of E/S events to be accompanied by a burst of lightning activity, composed of a few discrete CG return strokes and clusters of IC discharges. It is interesting that the VLF perturbation attains its maximum when the CG and IC activity ceases, which suggests the possibility that the induced QE and/or EMP fields provide the energy for the electron density to accumulate gradually in the upper *D* region.

[25] Following the suggestions of *Barrington-Leigh et al.* [2001] and *Moore et al.* [2003], we regard the strong early/fast VLF perturbations to be caused by scattering from sprite halos and the upper diffuse portions of sprites, caused by a QE field in the upper atmosphere which is capable of producing sprite breakdown and substantial ionization in the upper *D* region above ∼70 km. The abrupt (fast) onset in E/F is followed by a slow recovery phase which is defined by the lifetime of free electrons at these heights. The fast onset duration implies that any postonset lightning activity is not energetic enough to penetrate into an already conducting layer, and thus energize further, the ionized upper *D* region. These speculations seem to be in line with the broadband VLF and lightning detection data, suggesting that clear early/fast events are not followed by enhanced CG and IC activity.

[26] In extending this reasoning, we postulate the following scenario for E/S events: The sprite-causative +CG discharge and its associated charge moment changes set up a QE field above the thunderstorm that triggers sprite breakdown and some ionization production in the upper *D* region which, however, is now much less substantial than in the E/F cases. Next, the enhanced CG and IC lightning activity that follows the sprite onset generates QE and EMP fields, respectively, which can penetrate (also because the lower ionosphere is not now as conductive as in the E/F case) and thus energize further the electrons in the upper *D* region. In this way electrons can be accelerated to energies of many eV that suffice to produce additional (secondary) ionization through inelastic collisions with the neutrals. Since the times of interest (0.5 to 2.5 s) are much shorter than the lifetimes of the electrons at these heights, this process can lead to electron density accumulation which can be accountable for the growth phase, or the long onset duration, of the E/S events.

[27] In this scheme of secondary ionization buildup, IC lightning may play the key role especially if it relates to intense horizontal intracloud discharges known as "spider" lightning [e.g., see *Mazur et al.*, 1998]. Horizontal IC discharges act approximately as radiating dipoles which, because of their orientation, deposit most of the emitted energy directly above the discharge; thus these are optimal sources of vertical EMP heating of the upper *D* region. Also, and in accord with existing simulations [e.g., see *Rowland*, 1998], EMP fields can affect the upper *D* region, that is, above 70 km where elves and sprite halos do form, much more effectively than QE fields whose effects are more severe at lower heights. Furthermore, the absence of additional sprite displays in relation with the observed postonset +CG discharges, argues against important CG-induced breakdown effects in the overlying ionosphere. All this suggests that the EMP role for secondary ionization production, relative to that of QE fields, is possibly much more decisive.

[28] The effects of lightning EMP on the ionosphere have been modeled in several studies, mostly for the purpose of explaining elves (e.g., see review by *Rowland* [1998]). According to *Taranenko et al.* [1993], lightning-induced ionization by a single EMP is possible in the lower ionosphere and can lead to increases of a few percent, whereas a series of pulses during a period short enough that the ionization decay can be ignored (as in E/S events), could lead to severe accumulations in electron density. Similar results, applicable to upper *D* region altitudes were reported by *Barrington-Leigh and Inan* [1999] and *Rodger et al.* [2001], who found that lighting EMP events can lead to significant increases in electron density down to 75 km.

[29] On the basis of these findings, we believe the proposed mechanism of successive EMP-driven secondary ionization buildup in relation with E/S events is physically sound and feasible. This is consistent with the observation of enhanced clusters of IC discharges accompanying the growth phase of E/S perturbations. This mechanism can also explain why occasionally an E/S event can be "pre-early" (e.g., see example in Figure 2a), apparently because the EMP ionizing action may start earlier, as suggested at

times by the presence of enhanced sferic clustering prior to the sprite onset. The great majority of our events, however, are "early," meaning that the sprite, or its causative +CG discharge, plays a key role in initiating the E/S VLF perturbations. Note that in our scenario, a key assumption is that the sprite breakdown is needed for producing "seed" electrons in the upper *D* region, which then can be energized to produce additional (secondary) ionization under the action of subsequent EMP breakdown. This postulation, however, cannot be clarified by our data alone and remains to be proved.

[30] There is however a word of caution in regards to the proposed interpretation. This comes from the fact that the growth phase of E/S events appears in our data to not be accompanied by any optical emissions. Weak emissions would have been expected, however, because the excitation energies of key atmospheric constituents are smaller than the energies required for ionization. For example, the excitation of the most common emission in sprites, that is, the red emission from the molecular nitrogen first positive band N_2(1PG) electronic transitions, requires energies of 7.5 eV, whereas the ionization of N_2 needs an energy threshold of 15.6 eV. If the proposed secondary ionization buildup is mainly due to IC lightning-induced EMP effects, then there must be present a sequence of N_2(1PG) emissions as well, each one lasting, as in elves, for <0.001 ms. Since we do not see any reason for these emissions to be quenched, they should be there.

[31] It is likely, however, because we deal here with a relatively slow process, that such emissions besides being very short they are also extremely weak and thus very difficult to be captured from the ground, exactly as is with elves. Certainly, they could not be easily seen by the standard speed EuroSprite cameras yielding wide angle image frames integrated over 20 ms. For example, in the EuroSprite-2003 campaign, run more than 2 months, there were only two elves captured as compared to more than 130 sprites, whereas it is known from theory and satellite measurements that elves happen much more frequently than sprites [e.g., *Rodger*, 2003; R. R. Hsu, private communication, 2005]. In addition, one can use more arguments as to why these emissions are invisible, similar to those expressed by *Barrington-Leigh et al.* [2001] to explain why sprite halos are observed rarely while they are expected to be there regularly. In other words, the fact that the EuroSprite cameras did not detect any emissions during E/S onset growths does not mean that such emissions do not exist.

5.2. Quiescent Heating Buildup

[32] Finally, one cannot exclude the possibility that the quiescent heating mechanism of *Inan et al.* [1996] may also play a role in the slow growth of E/S events. This requires transient QE fields to exist at high altitudes above the thunderstorms that produce heating and conductivity changes and possibly sprites. In this mechanism, a situation of enhanced ionospheric QE fields can be maintained by the thundercloud charge distribution changes. These fields may sustain elevated electron heating levels at higher altitudes in regions with lateral extents of ~100 km, as long as the thundercloud discharging process continues through lightning. *Inan et al.* [1996] argued that such quiescent heating can cause conductivity disturbances which can scatter VLF transmissions to produce early VLF perturbations without ionization involvement. As for the slow VLF recoveries back to preonset levels, these were explained as corresponding to the characteristic times needed for the thundercloud to recharge to its predischarge configuration.

[33] In this process, a slow buildup of sustained heating caused by the postonset CG and IC discharging action may in principle be responsible for the slow growth of E/S perturbations. On the other hand, there appear to be difficulties with this mechanism which make its efficiency questionable. *Moore et al.* [2003] argued that this model cannot account for amplitude perturbations larger than 0.1 dB, whereas the early VLF perturbations under study were much stronger ranging between 0.4 and 1.7 dB. In addition, as *Rodger* [2003] comments in his review, if the quiescent heating mechanism were the case, early VLF events would have been very common and would be associated with the majority of the cloud discharging and recharging cycles, which certainly is not happening.

6. Summary and Concluding Comments

[34] The findings of this study are summarized as follows: (1) A sizable part of sprite-related early VLF perturbations exhibit a slow growth phase that leads to relatively long onset durations of about 1 to 2 s, thus these interesting events may be labeled as "early/slow." (2) Their occurrence is marked by a burst of dynamic thundercloud lightning action, characterized often by a sequence of few +CG flashes occurring shortly after the sprite onset and originating from the same localized region. (3) The early/slow onset duration, or growth phase, is accompanied also by clusters of weaker sferics attributed to packets of sequential IC lightning discharges. (4) The early/fast events seem to not be accompanied by enhanced bursts of sferics.

[35] Our study establishes the presence of a new type of sprite-related early VLF perturbations, which so far seems to have escaped attention. The gradual growth of these events soon after a sprite occurrence is an interesting new finding which contrasts with the abrupt onset of the well-known early/fast perturbations. The long onset durations of the early/slow perturbations are accompanied by a burst-like CG and IC lightning activity which seems to play the key role behind the physical processes involved in the generation of these events. We have speculated on some interpretative ideas, which however cannot be proved or disproved by our data alone. The most promising option, which is endorsed by broadband VLF recordings of sferics and lightning detection data, refers to a gradual buildup of secondary ionization production at higher *D* region heights where free electrons have longer lifetimes and can attain ionizing energies more easily. Although we cannot exclude a role for sequential +CG discharges soon after onset, we postulate that the key role in electron density buildup is played by a sequence of energetic EMP pulses radiated by clusters of horizontal IC lightning.

[36] The present paper is a first report of an intriguing new observation occurring in relation with transient luminous events in the lower ionosphere. This analysis is based on a limited number of events; thus there is need for more measurements in order to establish more reliable statistics and define better the properties of early/slow perturbations.

Also, there is a need for modeling results in order to quantify better the postulated process of secondary ionization buildup. A key implication of this interpretation is the production of diffuse regions of elve-like or halo-like optical emissions above the storm during the growth phase of early/slow events. This remains to be proved or disproved by carefully designed experiments. These need to deploy, along with high-resolution narrowband and broadband VLF receivers, also very sensitive, high-speed optical images and photometers. We hope that a new EuroSprite campaign will take all this into consideration.

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