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VLF Studies During TLE Occurrences in Europe: A Summary of New Findings

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Abstract The paper reviews the past few years' European efforts for characterising the effects of TLEs, in particular sprites and elves, on the lower ionosphere. A mostly experimental approach was applied for the analysis of data collected during the EuroSprite campaigns by optical cameras, very low frequency (VLF, 3–30 kHz) receivers and lightning detection systems. The new findings of these multi-instrumental studies can be summarised as follows: 1) A close relationship between sprites and early VLF perturbations was established which constitutes evidence of upper D-region electron density changes in association with sprites. 2) VLF backscatter from the sprite-affected regions exists but it occurs rarely. 3) Long-delayed sprites were present in a large percentage, contrary to previous reports; they occurred in relation to long-lasting continuing currents that contribute to the build-up of sprite-causative quasi-electrostatic fields. 4) Intracloud lightning was found to be the key-factor which determines the sprite morphological features. 5) A new subcategory of VLF events was discovered, termed *early/slow*, characterised by long onset durations from 100 ms up to $\sim$2 s. The slow onsets, which were attributed to a gradual ionisation build-up, are driven by a dense sequence of intracloud electromagnetic pulses that accompany the sprite-causative discharge. 6) A D-region chemical model was applied to simulate the measured recovery phases of the early VLF perturbations. This led to estimates about the mean altitude and electron density enhancements of the sprite-related ionospheric perturbations. 7) Early VLF events were identified for the first time to occur in association with elves, providing evidence that corroborates theoretical predictions on lower-ionospheric ionisation production by lightning-emitted electromagnetic pulses.

Keywords D region · TLE · Early VLF perturbation

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1 Introduction

Lightning discharges radiate electromagnetic energy in a wide spectral range with the bulk of their power released in the very low frequency (VLF, 3–30 kHz) band. At these frequencies, electromagnetic waves can propagate large distances (many Mm-s) via reflections from the conducting Earth surface and the lower ionosphere at about 85 km altitude. These waves cause the electrons of the lower-ionospheric plasma to accelerate and thus can lead to heating, the optical emissions called ‘elves’ and the production of extra ionisation near the VLF reflection height. Elves belong to the family of the so-called transient luminous events (TLEs). They consist of a rapidly expanding ring of luminosity and can be observed for less than about 1 ms. In addition, the sudden charge rearrangement in the thundercloud which follows a cloud-to-ground (CG) discharge can set up strong quasi-electrostatic (QE) fields above the cloud tops. These can cause breakdown around 70 km altitude and lead to the spectacular optical emissions called sprites which last for about 10 to 100 ms.

The changes in ionospheric conductivity associated with the lightning-induced electric fields can affect the propagation of the powerful VLF transmissions of navigation beacons situated all around the globe causing perturbations in their amplitude and/or phase. These perturbations appear in the form of early/fast events which are sudden jumps in the recorded VLF time series (Johnson et al. 1999). They occur within 20 ms of a causative CG lighting discharge (‘early’) and have rapid onsets (<20 ms, ‘fast’, i.e. within one sampling interval of the receiver) followed by relatively long signal recoveries (10 to more than 100 s). 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 University of Otago researchers (e.g., Dowden et al. 1996b; Dowden et al. 1996a), their complex properties are still not well understood. Early VLF events were reported to occur in association with both negative and positive CG discharges and were observed to accompany a subset of sprites (Inan et al. 1995). Using data from an array of closely-spaced receivers, the ionospheric disturbances were seen to cause forward scattering of the incident VLF waves and were estimated to be diffuse regions having typical transverse extents of ∼100–150 km (Johnson et al. 1999). On the other hand, researchers from the University of Otago reported that sprites within about 500 km of the receivers were always accompanied by VLF perturbations, irrespective of their distance from the transmitter–receiver (TX–RX) great circle path (GCP). These events showed evidence of wide-angle scattering, often even backscatter towards the VLF transmitter (Dowden et al. 1996a). This requires structured ionised regions with scales smaller than the VLF wavelength, which were hypothesised to coincide with the ionised sprite columns (Hardman et al. 1998; Rodger et al. 1998b; Rodger et al. 1999). Recent Stanford analyses (Marshall et al. 2006) found only rare examples of backscatter, always in relation to the most spatially extended, usually multiple, sprites, thus apparently contradicting the findings of the Otago group. These controversial results strongly suggest that the relation between TLEs and VLF perturbations is highly complex. Therefore further experimental studies are needed to understand better the link between the TLE and VLF phenomena, that is, to learn more about the effects of lightning discharges on the overlying lower ionospheric plasma.

The present paper aims at summarising the European contributions to this intriguing field of research. VLF studies are presented which tackle a number of open questions. These include the effects of lightning-induced TLE-producing electric fields on the lower ionosphere and in turn on VLF wave propagation, the structure of the TLE-related ionisation changes (i.e. forward vs. backscatter), the role of intracloud discharges in the sprite generation process, and the magnitude of excess ionisation produced during sprite occurrences.

2 Instrumentation

In a response to the need for more experimental TLE studies, the Danish National Space Center has been organising the so-called EuroSprite campaigns each summer since 2000. The aim of these campaigns is to stimulate collaboration between a number of institutes and to deploy a variety of instruments to study the different aspects of the TLE phenomena (Neubert et al. 2005). The data used in the studies summarised in this review were collected during the EuroSprite2003 and EuroSprite2005 campaigns. The essential components of the observing system were two remote-controlled, low-light optical cameras, mounted on mountain tops, in the Observatoire du Pic du Midi in the French Pyrénees and on Puy de Dôme in the Central Massif in France. These provided the information on TLE occurrences. Data on the cloud-to-ground and intracloud (IC) lightning activity was provided by the French Météorage and SAFIR lightning detection systems. The core data used for the analyses presented herein were provided by VLF receivers. VLF observations were conducted at two sites, on the island of Crete in Greece (35.31°N, 25.08°E) and at Nançay, France (47.38°N, 2.19°E). The Crete receiver was recording the amplitude and phase time series of VLF navigation beacons operating at well-defined frequencies with a sampling frequency of 50 Hz. The Nançay receiver was recording the VLF background noise in the 350 Hz–50 kHz range with 100 kHz sampling frequency. It was possible to post-process this broadband signal and extract from it narrowband VLF transmitter signal time series (Bainbridge and Inan 2003).

3 Summary of New Results

3.1 Sprites and Early VLF Perturbations

As emphasised in Sect. 1, the relationship between sprites and VLF perturbations still constitutes an area of debate and ongoing research. The unique dataset of optical sprite observations, lighting detection data and simultaneous VLF recordings collected during the EuroSprite2003 campaign was exploited in an attempt to find out more about the nature of the association between these two phenomena (Haldoupis et al. 2004; Mika et al. 2005).

Figure 1 shows the locations of the +CG discharges produced by three thunderstorms occurring over central France on 21 (circles), 22 (triangles), and 23–24 July 2003 (crosses). The Pic du Midi cameras captured 27 sprites during a 70-minute period of the first storm when the Météorage system reported a total of 1273 −CG and 207 +CG discharges. There were only 2 sprites recorded during a short storm period on 22 July during which there were 108 −CG and 18 +CG discharges observed by the lightning detection system. During the last storm, the cameras observed 13 sprites during a period when 5148 −CG and 247 +CG discharges were detected. All the storms were situated at distances between ∼100 and 600 km to the southeast of the two French transmitters (HWV—18.3 kHz and HWU—20.9 kHz), more or less along their GCPs to Crete. Due to the proximity of the storms to the GCPs, these transmitter signals were likely to be perturbed by lightning-induced conductivity changes in the lower ionosphere above the storms.

Inspection of the sprite occurrence sequence and the VLF amplitude time series revealed a striking coincidence between the detected sprites and the onsets of abrupt amplitude

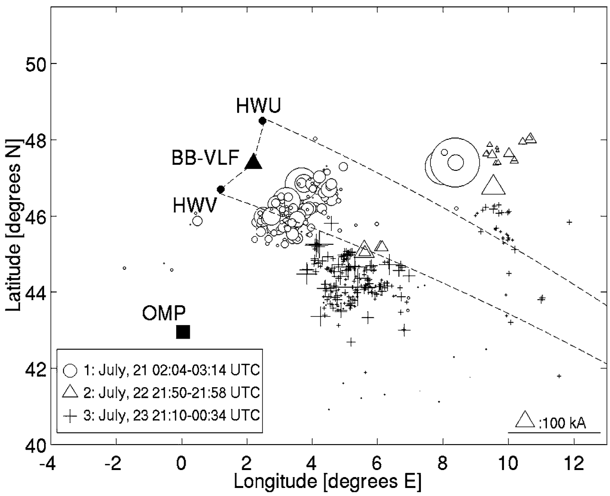

Fig. 1 Locations of the +CG discharges occurring during the 21–24 July 2003 sprite observation periods. The marker sizes are linearly scaled to the peak current intensities. The GCPs from the HWU and HWV transmitters to the Crete and Nançay (BB-VLF) receivers are shown by *dashed lines*. OMP marks the location of the optical cameras in the Observatoire du Pic du Midi in the French Pyrenées. From Mika et al. (2005)

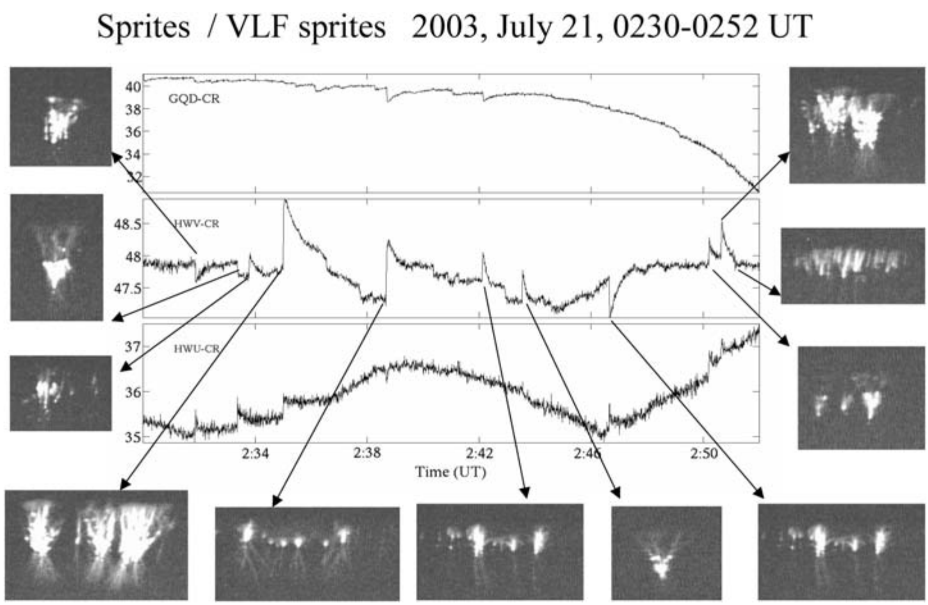

Fig. 2 VLF amplitude time series recorded on Crete and the optical images of 11 sprites captured from OMP during a 22-minute storm interval. All the sprites were accompanied by VLF perturbations. From Haldoupis et al. (2004). Copyright 2004 American Geophysical Union. Reproduced by permission of the American Geophysical Union

perturbations which were identified as early VLF events. This association is illustrated in Fig. 2, which corresponds to a storm interval on 21 July when 11 out of the 27 sprites were observed. The VLF time series display the signal amplitude in dB for the HWU–CR (HWU–Crete) and HWV–CR links traversing the storm region, and the 22.1 kHz GQD (Anthorn, Great Britain)–CR link north of the storm.

In total, 24 out of the 27 sprites observed during the 21 July 2003 storm coincided with an abrupt jump in VLF amplitude. High time-resolution plots showed that the perturbation onsets occurred within about 20 ms (time resolution of the data) relative to the sprite times. This signifies a sudden change in ionospheric conductivity produced directly by a process relating to the sprite-causative +CG discharge perturbations. There were no VLF events observed in relation to the numerous lighting discharges that did not produce sprites, which included 180 +CG and 1273 −CG flashes.

Inspection of the entire dataset for the two storms during 22–24 July 2003 revealed early VLF perturbations on the HWV signal amplitude in association with 12 out of the 15 observed sprites. On the other hand, there were also 10 cases of early-like VLF perturbations which were not accompanied by sprites. A re-examination of the optical images, which was unfortunately possible only for three out of these ten events, led to the discovery of one more sprite which, obviously, was missed originally, whereas for the other two cases the discharges were too low on the horizon for the cameras to capture a possible sprite.

Taking into account the entire dataset considered here, 37 out of the 43 sprites observed during 21–24 July 2003 were accompanied by VLF perturbations, that is, about 85%. On the other hand, there were 9 VLF events which did not relate to observed sprites. These results imply a close relationship between sprites and early VLF perturbations. The electron density changes occurring during sprite events located close to the TX–RX GCP seem to perturb VLF propagation in most cases, though they might not be the sole reason behind early VLF events.

The statistical properties of the sprite-related VLF signatures were also assessed using a sample of 26 selected events which had amplitudes higher than about 0.2 dB (since this is the minimum perturbation that is clearly discernible without significant data processing) and relatively low-level sferic contamination. Most of the perturbation magnitudes were between 0.2 and 1.0 dB in line with existing statistics for early/fast events (Johnson et al. 1999); there were also two events with magnitudes reaching values near 3.0 dB, departing considerably from the rest. The recovery times were mostly between 20 and 150 s, which compare well with those of early/fast events reported elsewhere (Strangeways 1996; Rodger 1999). An interesting new observational fact is that in 12 cases the perturbation onset durations (the time between the abrupt onset and the time of the maximum mean level of the amplitude perturbation) were larger than 100 ms and out of this subset 6 VLF events had onset durations greater than 500 ms reaching values up to about 2 s. These perturbations, termed 'early/slow', constituted a new category which had never been dealt with before. Results from studies examining their properties in more detail (Haldoupis et al. 2006) are presented in Sect. 3.5.

3.2 VLF Backscatter in Association with Sprites

The proximity of the 21–24 July sprite-producing storms at distances less than 500 km to the southeast of the broadband VLF receiver (e.g., see Fig. 1) and the controversy in the published observational results mentioned in Sect. 1 motivated a search for VLF backscatter perturbations in association with the observed sprites. In order to identify VLF backscatter signatures in the Nançay recordings, the HWV signal was extracted from the broadband time series by applying the same narrowband digital filter which is employed in real time at the Crete receiver and searched for sprite-related early VLF perturbations.

Inspection of the HWV–Nançay narrowband time series revealed only five cases out of the 38 sprites for which broadband data were available to be accompanied by weak early-like VLF perturbations having onsets coincident with the sprites. All five events occurred

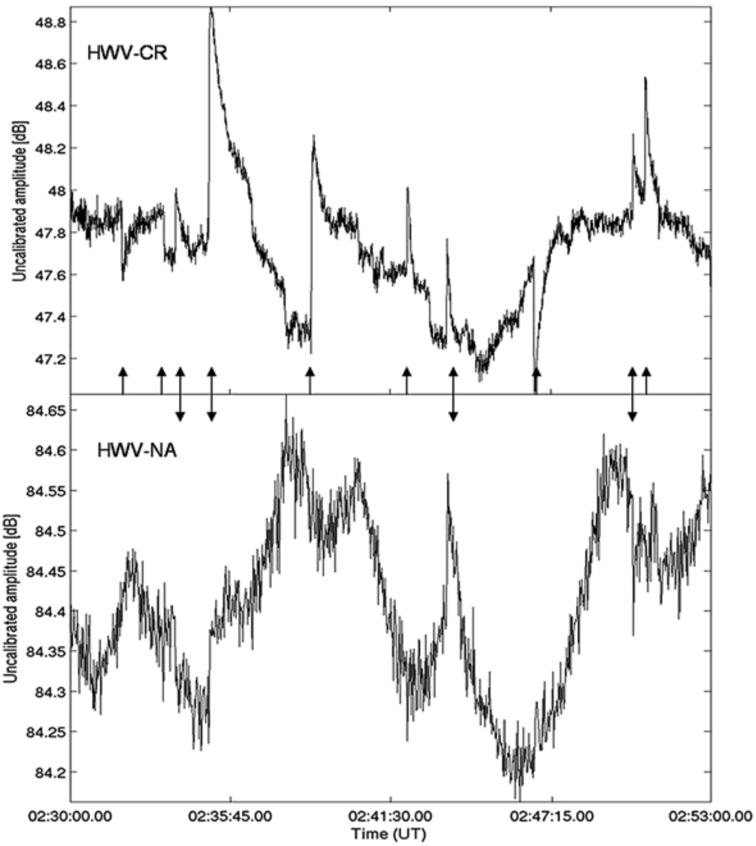

Fig. 3 Concurrent intervals of HWV signal amplitude time series showing sprite-related VLF perturbations (marked by *arrows*) received on Crete through forward scattering (*top*) and at Nançay possibly through backscatter (*bottom*) from conductivity changes in the lower ionosphere during sprite occurrences. From Mika et al. (2005)

during the storm of 21 July which was the nearest one to Nançay, at about 100 to 200 km to the southeast. No similar perturbations were identified to accompany the sprites captured during the 22–24 July storms, possibly because these were located further away from the receiver, at distances between about 230 and 500 km.

Figure 3 shows 23 minutes of recordings when 4 out of the 5 early VLF events were seen in the HWV–Nançay signal (bottom panel). Also shown for comparison in the top panel are simultaneous records from the HWV–Crete link. The sprite-related early VLF events are marked by arrows. As seen, there were 10 early VLF perturbations in the HWV–Crete time series, all in relation to sprites, but only four of these had counterparts in the HWV–Nançay signal. As evidenced by Fig. 3, the Nançay perturbations were considerably weaker than those observed at Crete, having magnitudes less than 0.2 dB. In addition, these few backscatter events did not appear to have any preference to either the early/fast or early/slow VLF perturbations. The HWV recordings were investigated for backscatter-like signatures also for the storms of 27 July, 22, 24, 25, and 28–29 August 2003, when broadband data was available for a total number of 47 sprites. During these storms, the +CG discharges detected by Météorage were located at distances larger than about 300 km from the HWV–

Nançay GCP. The results of the search were negative, there were no early VLF perturbations identified during the entire duration of the storms, probably due to their larger distances from the GCP.

In summary, considering the entire number of sprites recorded, only about 5% associated with identifiable backscatter-like VLF perturbations. Taking into account only those events which were located at distances less than about 500 km from the Nançay receiver this ratio becomes 7%, a figure which departs considerably form the one-to-one relationship reported by Dowden et al. (1996b). Note that the weak backscatter-like perturbations were observed during a single storm situated closer than 200 km to the Nançay receiver. In contrary to the findings of Marshall et al. (2006) there was no relationship between the sprite morphology (meaning here single sprites vs. large clusters) and the existence of backscatter. Alternatively, there might be another explanation for the presumed backscatter perturbations (substantiated by the findings of Mika et al. 2006 and also mentioned in Marshall et al. 2006). The distances of 100–200 km from the +CG location to the Nançay receiver can place these events in a disturbed ionospheric region associated with undetected sprite halos or elves (the possibility for the latter is examined in Sect. 3.7) that may overlap the receiver. Then, in this case, the early VLF signatures observed at Nançay may be the result of a direct change in the local propagation conditions (e.g. change in the reflection height) and thus not associate necessarily with VLF backscatter.

3.3 Long-Delayed Sprites

It is widely accepted that sprites initiate a few milliseconds after a +CG discharge accompanied by charge moment changes sufficiently large to set up a strong enough QE field in the upper atmosphere that is capable of causing locally an electrical breakdown. Despite this conviction, however, the nature of the relation between sprites and their causative +CG discharges is not yet clear and well understood. This is particularly true for the so-called long-delayed sprites, believed to represent a small percentage in which the sprite onsets are delayed relative to the +CG discharge by more than 30 ms (e.g., see Bell et al. 1998; Cummer and Füllekrug 2001). In the following, results from studies investigating the delays between sprites observed during the EuroSprite2003 campaign and the +CG discharges preceding their occurrence using lightning and VLF observations are presented (Mika et al. 2005).

First, the distribution of the time difference between the sprite occurrence and the time of the nearest +CG discharge preceding it up to ∼300 ms was investigated. A total of 103 sprites were used, observed during the storms of 21–27 July (44 sprites) and of late August 2003 (59 sprites). Since the sprite images were taken over 20 ms and their times were correct to within ±12 ms, +CG discharges preceding or following the sprite time by about 30 ms were taken to be nearly coincident, and considered as causative to the sprites. 64 out of the 103 sprites observed, that is ∼62%, were accompanied by +CG discharges occurring near their onset time. These were termed ‘short-delayed’ sprites. From the rest, 30 sprites (∼29%) were lagging the +CG discharge by times ranging from about 30 to 220 ms (termed herein ‘long-delayed’), whereas 9 sprites (∼9%) were not preceded by any +CG discharges up to at least 2.5 s prior to their occurrence. This means that nearly 40% of the observed sprites were either long-delayed or had no relation to a causative +CG discharge. Given that Météorage is a state-of-the-art lighting detection system having adequate coverage and a high detection efficiency of more than 90%, it is unlikely that it had missed such a high number of causative discharges. On the other hand, the software algorithms of systems such as Météorage are known to occasionally reject large lightning discharges with complex waveforms (typically +CGs), meaning that Météorage is more likely to miss sprite-associated CGs.

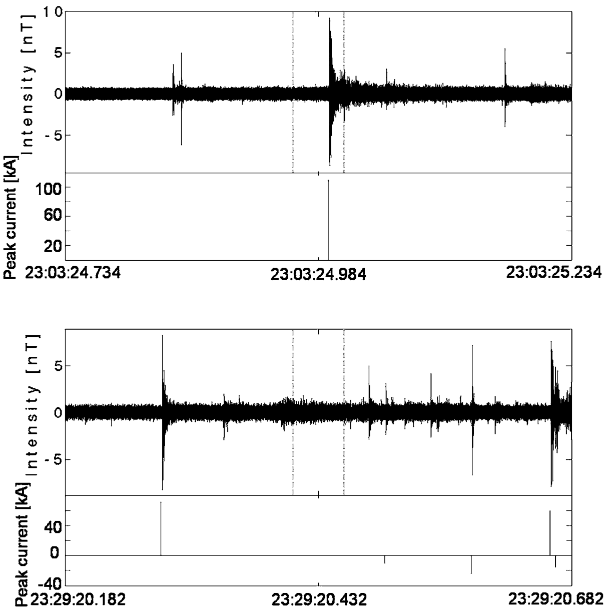

Fig. 4 Typical examples of broadband VLF data recorded at Nançay (*top*) 250 ms before and after a short-delayed (*left*) and a long-delayed (*right*) sprite. The sprite observation time is marked by *two vertical dashed lines* accounting for both the image exposure time of 20 ms and the time uncertainty of 12 ms. CG discharges recorded by Météorage are shown in the *bottom panels*. From Mika et al. (2005)

To further investigate the relation between sprites and preceding +CG flashes, the Nançay broadband VLF time series were inspected in order to assess the radio-sferic activity accompanying these events. VLF observations can more accurately link lightning activity to sprite occurrence, since all lightning discharges produce sferics and the receiver sferic-detection efficiency for CG discharges is precisely 1 at such short distances to the thunderstorm (from about 100 to 1000 km). Therefore, sferic detection could also identify the ∼9% of CG discharges which were apparently missed by the lightning detection network. Since broadband measurements were carried out from 21:00 to 03:00 UTC only, VLF recordings were available only for 51 short-delayed, 28 long-delayed, and 6 no +CG-related sprites. Close inspection of the Nançay VLF time series revealed the presence of a burst of sferic activity coincident with the +CG discharge always in relation to the short-delayed sprites. On the other hand, there was no significant level of sferic activity present in the broadband VLF signal during the observation times of the long-delayed sprites. Also, there were no additional sferics corresponding to potential causative CG discharges missed by Météorage which endorses that these events were indeed long-delayed sprites. As for the 6 sprites which, according to Météorage, were not preceded by a +CG discharge up to at least 2.5 s prior to their occurrence, the broadband VLF records revealed sferic clusters occurring simultaneously with all of them. This suggests that Météorage had indeed missed the causative discharges of these sprites. These data showed, for the first time, that the short- and long-delayed sprites occur with a ratio of about 2:1, which is much smaller than thought previously.

The radio-sferic and CG lightning activity for the short-delayed (left) and long-delayed (right) sprites is shown in Fig. 4. The left panel of Fig. 4 shows a strong burst of sferics in connection with the short-delayed sprite and its causative +CG discharge. The example in the right panel is representative of the long-delayed sprites showing only weak sferic activity during the sprite observation time.

An explanation put forward for the long-delayed sprites assumes the presence of long-lasting cloud-to-ground continuing currents flowing after the return stroke of the +CG discharge (Bell et al. 1998; Reising et al. 1999; Cummer and Füllekrug 2001) which neutralise charge on a relatively long timescale. This leads to a gradual build-up of the QE fields in the upper atmosphere which, when the field strength exceeds the air breakdown threshold, generate sprites. The VLF data used here cannot provide direct evidence either for or against this mechanism. On the other hand, in order to achieve such long-lasting continuing currents, a significant in-cloud component is required to feed the +CG discharge. In the next section, results from studies on the role of IC discharges in the sprite generation process are presented (van der Velde et al. 2006).

3.4 Intracloud Lightning Activity and Sprite Morphology

There exist a number of modelling studies (e.g., Valdivia et al. 1997; Rycroft and Cho 1998) and observations of spider lightning (Stanley 2000) accompanying sprites which suggest that IC discharges might play an important role in the sprite generating process. The existence of long-delayed sprites also substantiates this idea since it suggests a gradual build-up of the mesospheric electric fields due to long-lasting charge neutralisation by the continuing current and probably IC currents feeding it (Uman 2001, p. 171). Further observational evidence was provided by broadband VLF and ELF observations which revealed IC sferic clusters accompanying sprites (Ohkubo et al. 2005). It must be noted, that in the following, the term intracloud lightning is meant to describe all phases of lightning in the cloud or air involved in one flash event including leader activity accompanying a CG flash.

Sprite-producing thunderstorms traversed the area covered by the SAFIR lightning detection system, capable of detecting IC discharges (for a description of the shortcomings of interferometric systems see e.g., Mazur et al. 1998), on three nights during the EuroSprite2003 campaign. The best quality data were obtained during the night of 23–24 July 2003, when 15 sprites were observed from Pic du Midi. Broadband VLF observations were made by the Nançay receiver which was expected to detect sferics related to IC discharges occurring in the nearby (<500 km) thunderstorm. The sprite events were classified according to their morphology into two groups, column (narrow, straight, short, mostly uniform elements) and carrot (taller, irregular shapes, usually with well-visible streamers extending upwards and downwards from a bright body) sprites and their characteristics compared. Apart from their distinct shapes, these two groups seem to also be related to somewhat different physical processes. E.g., McHarg et al. (2007) observed that column sprites are initiated by downwards propagating (negative) streamers while in the case of carrot sprites upward moving (positive) streamer heads are also present.

Column sprites were found to associate with relatively few (3 to 8) very high frequency (VHF, 30–300 MHz) IC sources in a ±250 ms time interval (relative to the start of the video frame), as detected by the SAFIR system. They followed the +CG closely, with delays up to 40 ms, having an average value of 12 ms relative to the start of the video frame integration time of 20 ms. Thus these events classified as short-delayed sprites, in accord with the analysis presented in Sect. 3.3.

The average duration of VLF sferic clusters was about 25–30 ms for column sprites. Figure 5 shows the VLF and lightning data for a typical column sprite event. Both the broadband VLF time series (top) and the corresponding spectrogram (middle) show a short burst of VLF sferic energy (lasting for about 30 ms) in the time frame when the sprite occurred (marked by the two vertical dashed lines) corresponding to a +CG discharge detected by Météorage (bottom).

All carrot sprites associated with a relatively large number (between 17 and 88) of VHF IC sources. The delay between the +CG discharges and the sprites ranged from 18 to

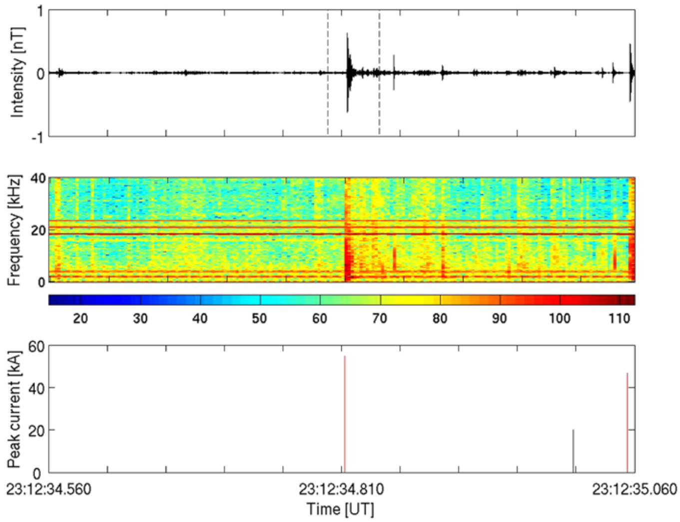

Fig. 5 East-west component of the broadband VLF signal intensity (*top*, in arbitrary units) and the corresponding VLF spectrum (*middle*, dB) 250 ms before and after a column sprite event. The *two vertical dashed lines* indicate the sprite observation time, accounting for the video frame integration time of 20 ms plus the timing uncertainty of 12 ms. The *bottom panel* shows the peak currents of CG discharges recorded by Météorage (*red*) and the VHF sources detected by SAFIR (*black*), the latter scaled arbitrarily. From van der Velde et al. (2006). Copyright 2006 American Geophysical Union. Reproduced by permission of the American Geophysical Union

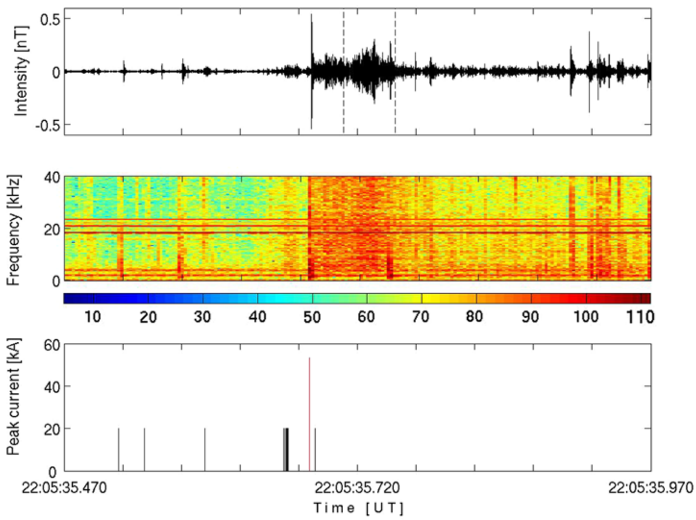

Fig. 6 Same as in Fig. 5 but for a carrot sprite event. From van der Velde et al. (2006). Copyright 2006 American Geophysical Union. Reproduced by permission of the American Geophysical Union

205 ms, with an average value of 63 ms thus carrot sprites classified, on average, as long-delayed sprites. This suggests that continuing currents are likely playing a role in the generation of carrot sprites. The duration of the VLF clusters was also longer, with averages of 100–110 ms. Figure 6 shows the VLF time series (top), the corresponding spectrogram (mid-

dle), the Météorage cloud-to-ground strokes, and the VHF sources detected by the SAFIR system (bottom) for a typical carrot sprite event.

The results presented in this section show that the IC phase of a lightning discharge plays an important role in the generation of carrot sprites but appears relatively unimportant for column sprites. The physics behind this role is far from being clear and needs to be further studied. These results seem to indicate that carrot sprites associate with longer-lasting continuing currents which help to build-up and sustain strong electric fields in the upper atmosphere for a longer time than in the case of column sprites.

3.5 An Explanation for Early/Slow VLF Perturbations

As described in Sect. 1, early/fast events are abrupt perturbations in the amplitude and/or phase of subionospheric VLF transmissions occurring within 20 ms of a causative CG lighting discharge (i.e., early) having rapid onsets (<20 ms, i.e., fast) followed by relatively long signal recoveries ranging from about 10 to more than 100 seconds. In this section, recent studies are summarised which provide evidence showing that a sizable group of sprite-related early VLF perturbations do not display a 'fast' onset, instead they have long onset durations of 100 ms to 2 seconds and thus were labelled 'early/slow' events (Haldoupis et al. 2006). The existence of slow onsets implies an underlying mechanism which causes a gradual build-up of ionisation following a causative CG discharge. Next, the observed characteristics of early/slow events are presented and the physical mechanism proposed in (Haldoupis et al. 2006) is described.

The analyses presented herein were based on data collected during the EuroSprite2003 and 2005 campaigns (see Sect. 2). VLF data of the 18.3 kHz transmitter, collected on Crete during 85 sprite events, 75 from four different storms on the nights of 21–24 July and 28–29 August 2003, and 10 from 29 July 2005 were analysed and lead to the identification of 73 early VLF events. From this dataset, only the VLF perturbations with clearly discernible onsets were kept for further inspection which reduced the number of usable events to 27. Out of these 27 VLF events, at least 15, that is, about 55% of the cases, classified clearly as early/slow, 8 events were early/fast, whereas the rest exhibited rather complicated onsets (a few associated with closely spaced sequential sprites), which made their categorisation ambiguous. Figure 7 displays typical examples of early/slow and early/fast perturbations along with the images of the sprites associated with them. The sprite onset is marked by the dashed line. The early/fast event (bottom panel) has an instant (fast) onset followed by the usual signal recovery of several tens of seconds. On the other hand, the early/slow signature, shown in the top panel, has a slow onset, characterised by a gradual growth which lasts for ∼1.0 to 1.5 s. The recovery back to pre-onset signal levels is similar in duration to that of the early/fast events.

The early/slow events were analysed in conjunction with high-resolution broadband VLF recordings made at Nançay and Météorage lightning data. The storms under consideration were located in central France at distances ranging between 100 and 400 km from the Nançay receiver which made the detection of sferics radiated by IC discharges possible. The analysis revealed a recurring lightning pattern for early/slow events which displayed the following characteristics: 1) Météorage recordings showed a post-onset sequence of a few individual CG discharges originating from the same area. 2) The Nançay VLF time series showed a large number of relatively weak and densely-clustered sferics which were not seen by Météorage and thus probably originated from IC discharges. 3) The sferic clusters sometimes initiated before the sprite but mostly occurred after it and coincided with the VLF perturbation onset growth. 4) The IC sferic clusters originated from about the same storm area.

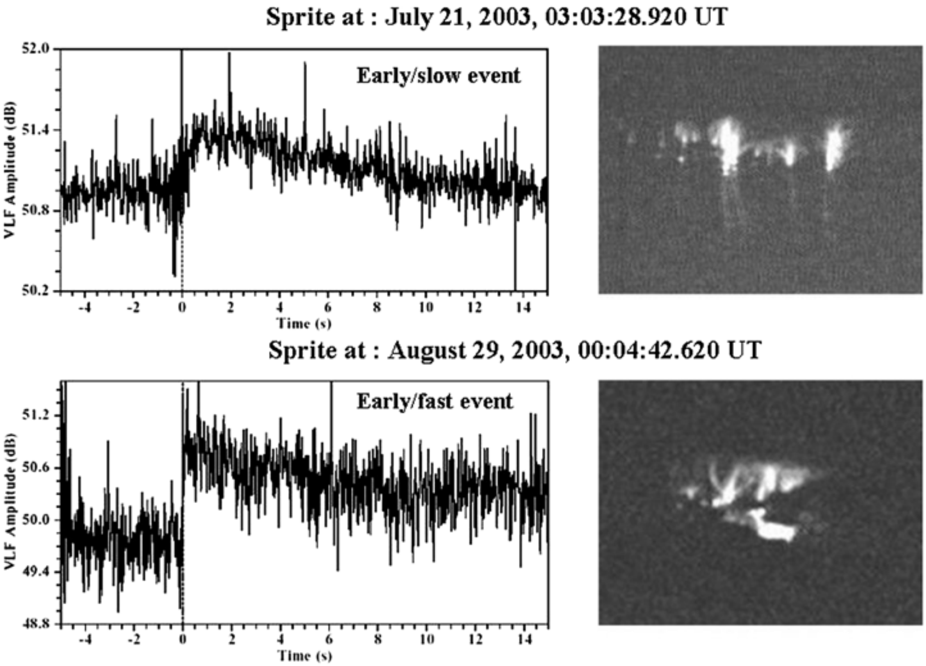

Fig. 7 Typical sprite-related early/slow (*top*) and early/fast (*bottom*) VLF perturbations. The optical images of the corresponding sprites are shown on the *right*. From Haldoupis et al. (2006). Copyright 2006 American Geophysical Union. Reproduced by permission of the American Geophysical Union

During EuroSprite2005 the Crete VLF station operated also as a single-channel broad-band receiver. This provided the possibility of testing if the cluster of sferics, observed at Nançay simultaneously with the growth phase of early/slow events, was indeed caused by IC 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 observable on Crete, more than 2000 km away from the storms in France. This was confirmed by analysing two early/slow events observed in relation to sprites during a brief storm on 29 July 2005. The findings are summarised in Fig. 8. As seen in the bottom panel, Météorage detected at least 6 +CG flashes following the sprite-causative +CG discharge, all originating from the same region. The related early/slow event shown in the third panel, started with the sprite and had a growth phase of about 2 s, accompanied by a strong burst of numerous sferics seen by the Nançay broadband VLF receiver (second panel). The angles of arrival of these sferics (not shown here) all pointed towards the storm region under consideration. The Crete receiver detected only a small number of discrete sferics all in relation to the CG discharges seen by Météorage. It did not detect the sferic clusters seen at Nançay, probably because these were due to IC lightning and thus could not propagate at distances larger than some 500 to 800 km (e.g., see Johnson and Inan 2000). In contrary, the onsets of the early/fast events were not accompanied by enhanced clusters of sferics.

A mechanism behind the early/slow 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 as in the case of the early/fast events. This suggests a process of gradual ionisation build-up initiated by the sprite breakdown which seems to be compatible with the presented observations showing the onsets of early/slow events to be accompanied

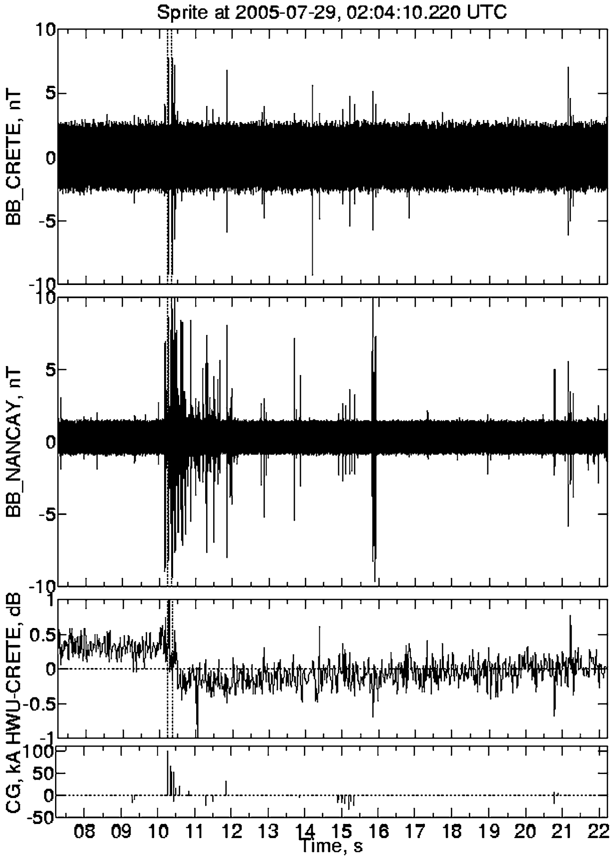

Fig. 8 An early/slow event seen on Crete (*third panel*) compared to CG lightning strokes (*bottom panel*) and broadband VLF data recorded near the storm at Nançay (*second panel*) and about 2200 km away from the storm on Crete (*top panel*). The *two vertical dashed lines* mark the occurrence of the sprite which was seen in two successive video frames. From Haldoupis et al. (2006). Copyright 2006 American Geophysical Union. Reproduced by permission of the American Geophysical Union

by a burst of lightning activity, comprised of a few discrete CG strokes and clusters of IC discharges. The following scenario was proposed for early/slow events: The sprite-causative +CG discharge and the associated charge moment change set up a QE field above the thunderstorm that causes electric breakdown, triggers the sprite and creates some extra ionisation in the upper D region. However, this ionisation production is not strong enough to raise the lower-ionospheric conductivity so much that it would prevent the electric fields related to further discharges from penetrating to higher altitudes. Next, the enhanced CG and IC lightning activity that follows the sprite onset generates QE and EMP (electromagnetic pulse) fields which penetrate in the upper D region and energise the electrons further, which leads to additional (secondary) ionisation. Since the times of interest (0.5 to about 2 s) are much shorter than the electron lifetimes at these altitudes, this process can lead to electron density accumulation which can account for the growth phase, or the long onset duration, of the early/slow events. In this scheme, IC discharges may play the key role as suggested by the VLF and lightning observations. The radiation pattern of horizontal IC discharge channels has a maximum of the emitted energy directly above the discharge and thus they are optimal sources of vertical EMP heating of the upper D region. Also, EMP fields can penetrate more easily to higher altitudes compared to QE fields because of their much shorter time scales due to which ambient conductivity shielding is much less severe. Furthermore, the absence of additional sprite displays in relation to the observed post-onset +CG discharges argues against important CG lightning-induced breakdown effects in the overlying ionosphere. All this suggests that the EMP role in secondary ionisation production is possibly much more decisive than that of QE fields.

The proposed mechanism is consistent with the observation of enhanced clusters of IC discharges accompanying the growth phases of early/slow perturbations. A key element is that the sprite breakdown is needed for producing seed electrons in the upper D region, which then can be energised to produce additional (secondary) ionisation under the action of subsequent EMPs. 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 since the energy thresholds for excitation are smaller than those required for ionisation. However, these would probably be weak and short-lasting (<1 ms), as in the case of elves. The existence of these weak emissions and thus the validity of the proposed interpretation remains to be proved or disproved by carefully designed experiments using high-speed optical imagers and photometers.

3.6 Estimating D-Region Electron Density Changes Related to Sprites

There are no conclusive measurements of sprite-related ionisation available to date, therefore any bit of independent information constitutes a valuable input for sprite-generation models and theoretical interpretations. Previous studies of modelling VLF scattering off the sprite plasma and comparing the results to VLF observations by Rodger et al. (1998a) estimated an increase in the D-region electron density of more than a factor of 10^4 at 75 km. Roussel-Dupré and Blanc (1997) observed HF (high frequency, 3–30 MHz) radar echoes attributed to reflection off the sprite plasma, requiring minimum electron densities of 6×10^4–10^5 cm^{-3} at 55–65 km altitudes, corresponding to relative electron density enhancements of about 7 to 8 orders of magnitude.

In the study presented in this chapter, a D-region chemistry model, originally developed for modelling the recovery times of lightning-associated VLF LEP (Lightning-induced Electron Precipitation) perturbations (Glukhov et al. 1992; Pasko and Inan 1994), was applied to estimate the electron densities involved in sprite events. The model accounts for four constituents: electrons (N_e), single positive ions (N^+), single negative ions (N^-), and positive cluster ions (N_x^+); and six different charge exchange processes: attachment, detachment, dissociative recombination, recombination of positive cluster ions, ion–ion recombination (mutual neutralisation), and conversion of positive ions into positive cluster ions, characterised by their rate coefficients: β, γ, α_d, $\alpha_\mathrm{d}^\mathrm{c}$, α_i, and B, respectively. The values of these coefficients can be found in Glukhov et al. (1992) and Pasko and Inan (1994). The time evolution of each of the four constituents obeys its own continuity equation, which together form the following system of ordinary differential equations (Glukhov et al. 1992):

$$\frac{\mathrm{d}N_\mathrm{e}}{\mathrm{d}t} = I + \gamma N^- - \beta N_\mathrm{e} - \alpha_\mathrm{d} N_\mathrm{e} N^+ - \alpha_\mathrm{d}^\mathrm{c} N_\mathrm{e} N_\mathrm{x}^+ \tag{1a}$$

$$\frac{\mathrm{d}N^-}{\mathrm{d}t} = \beta N_\mathrm{e} - \gamma N^- - \alpha_\mathrm{i} N^- (N^+ + N_\mathrm{x}^+) \tag{1b}$$

$$\frac{\mathrm{d}N^+}{\mathrm{d}t} = I - BN^+ - \alpha_\mathrm{d} N_\mathrm{e} N^+ - \alpha_\mathrm{i} N^- N^+ \tag{1c}$$

$$\frac{\mathrm{d}N_\mathrm{x}^+}{\mathrm{d}t} = -\alpha_\mathrm{d}^\mathrm{c} N_\mathrm{e} N_\mathrm{x}^+ + BN^+ - \alpha_\mathrm{i} N^- N_\mathrm{x}^+. \tag{1d}$$

Here I is the electron (and consequently positive ion) production term which can be expressed as $I = \nu_\mathrm{i} N_\mathrm{e}$, where ν_i is the ionisation rate which is a function of the electric field

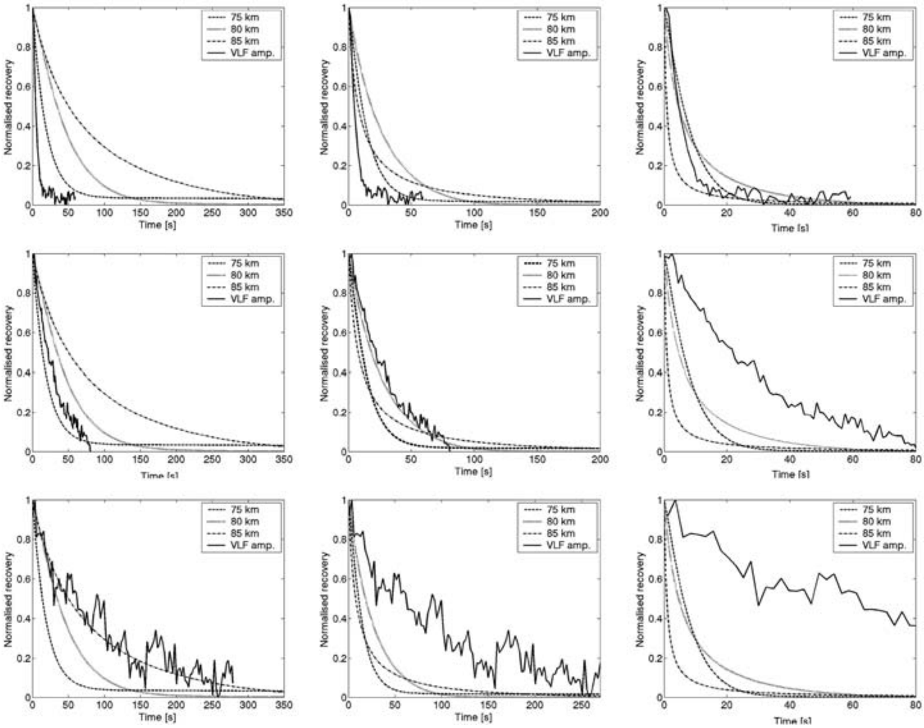

Fig. 9 Model fits of observed VLF perturbation recoveries. The *left panels* show recoveries from an initial electron density of $100 \times N_{e0}$, the middle ones from $1000 \times N_{e0}$, and the *right panels* from $10000 \times N_{e0}$. Each row corresponds to a different VLF event (*solid line*), representing short (*top*), medium (*middle*), and long (*bottom*) recovery durations for altitudes of 75 (*dashed*), 80 (dotted), and 85 km (*dash-dotted*)

(Papadopoulos et al. 1993). In order to model the relaxation of excess ionisation, the ordinary differential equation system (1) was solved numerically to produce the excess ionisation followed by the electron density relaxation. The ambient number densities of the four species, constituting the initial conditions for solving the equations, were extracted from their altitude profiles given in Glukhov et al. (1992). The model was set to produce different electron density enhancement levels N_e by manipulating the electric field properties (duration, peak amplitude) entering the electron and ion production term I. Then, by selecting values for the reaction rates corresponding to specific altitudes, it was possible to model the electron density relaxation at a given altitude.

Modelled electron density relaxation times were computed for altitudes of 75, 80, 85 km and initial electron densities of 100, 1000, and 10000 times the ambient values. The model results were then compared to observed VLF perturbation recoveries to provide some estimates on the electron density enhancements occurring during sprite events in the lower D region. Figure 9 shows three examples of early VLF events, representing short (∼30 s), average (∼100 s), and long (∼250 s) recovery times. The modelled curves were superimposed on the measured early VLF amplitude recoveries, and normalised to their maximum values.

Early VLF events with short recoveries (<50 s) could be modelled assuming regions of large electron density enhancements of up to about 10^4 times the ambient values confined at lower altitudes around 75 km. VLF perturbations with recovery times around 100 s could be reproduced by the model by considering electron density elevations around 80 km, having an initial value about 10^3 times the undisturbed electron density levels. Finally, long recovery early VLF events (>200 s) could be accounted for by taking relatively low electron density enhancements ($\sim 10^2$ times the ambient values) to be located at upper D-region altitudes, at ∼85 km. In the 75–85 km altitude range the key electron loss process governing the recoveries of the early VLF events is electron–ion recombination. Taking into account this and considering the dynamics of the sprite-producing QE fields a simple explanation can be put forward as follows. Strong and long-lasting QE fields are expected to exceed the breakdown threshold and produce large excess ionisation levels at upper D-region heights (say at ∼75 km) without significantly affecting higher altitudes because of drastic conductivity shielding effects. In this case, an early VLF event will have a short recovery phase not only because electron attachment is still effective at lower heights but also, and possibly mainly, because the electron–ion recombination losses will be higher there since the produced electron densities are high. On the other hand, a weaker QE field can penetrate to higher altitudes near the VLF reflection height before exceeding the breakdown threshold and produce some, relatively weak, ionisation. This may also result in an early VLF perturbation which now, however, will last longer (recover slowly) because electron attachment in this region is small to negligible, and the main electron loss process, that is, electron-ion recombination, will be slow since it depends strongly on electron density ($\sim N_e^2$), which is now lower at these heights.

The results described herein indicate that electron density enhancements related to sprites can vary over two orders of magnitude and can be concentrated at a range of altitudes from about 75 to 85 km. This, in addition to the observed strong forward scattering, suggests that the early VLF perturbations observed on Crete in association with sprites relate to electron density enhancements corresponding to the upper diffuse sprite regions and/or associated halos in line with the findings of Barrington-Leigh et al. (2001) and Moore et al. (2003).

3.7 Elves and Early VLF Perturbations

Electromagnetic pulses released by lightning discharges into the lower ionosphere can lead to momentary optical emissions called elves (e.g., see reviews by Rowland 1998 and Rodger 1999). These phenomena appear at altitudes between 75 and 105 km as a rapidly expanding ring of luminosity reaching lateral extents of about 500 km. Elves are visible for less than 1 ms, which makes their detection from the ground rather difficult. They can be captured from space more easily due to the much lower atmospheric attenuation rates and unobstructed viewing conditions (Chern et al. 2003). Theoretical models predict that in addition to optical emissions, impact ionisation of N_2 can also be caused by an EMP at 80–95 km altitudes, leading to electron density enhancements from a few to a few tens of per cent (Taranenko 1993). Successive EMPs can cause a density increase of many hundreds of per cent of the ambient values (Taranenko et al. 1993; Rodger et al. 2001), affecting a large area of $\sim 3 \times 10^5\,km^2$ (Barrington-Leigh and Inan 1999). At lower altitudes, where electrons are only mildly heated, dissociative attachment to molecular oxygen dominates, leading to decreases in the electron density of several per cent (Inan et al. 1996; Sukhorukov et al. 1996). The anticipated electron density enhancements due to ionisation and the depletions caused by dissociative attachment lead to a sharpening of the electron density profile in the upper D region. At elve-altitudes this ionisation is expected to be lasting for a few to many minutes (e.g., Rodger et al. 2001; Rodger and McCormick 2004) and may affect VLF radio wave propagation inside the Earth-ionosphere waveguide (Taranenko 1993). For instance, the name ‘elves’ was originally introduced by Fukunishi et al. (1996) as an acronym for 'Emissions of Light and VLF perturbations due to EMP Sources', although there were no reports of accompanying VLF perturbations. In his review, Rodger (2003) pointed out that, despite the efforts, experimental evidence in favour of elve-related ionisation was still lacking. Recently, Mende et al. (2005) presented indirect evidence of electron density enhancements in relation to an elve event observed by the ISUAL (Imager of Sprites and Upper-Atmospheric Lightning) instrument onboard the Taiwanese FORMOSAT-2 satellite. They combined multi-wavelength photometric observations and theoretical model results and estimated the average electron density to be ~210 electrons cm^{-3} over a circular region with a diameter of ~165 km at ~90 km altitude having an assumed vertical extent of 10 km. A direct evidence of elve-related ionisation changes would be the detection of VLF perturbations occurring in association with elves. However, this topic has received little attention so far and the few published studies referring to the topic (Hobara et al. 2001; Hobara et al. 2003; Dowden et al. 1996c) did not provide proof of ionisation production in relation to elves.

The study summarised herein and published in Mika et al. (2006) aimed at investigating the existence of elve-related VLF perturbations which would constitute direct evidence of electron density changes caused by the elve-generating lightning EMP. For this purpose, a large dataset comprising both ground- and space-based optical observations was used. Five elve events captured during the EuroSprite2003 campaign were analysed along with the largest dataset of elves used for VLF studies so far, collected by the ISUAL instrument of the FORMOSAT-2 satellite (Chern et al. 2003). VLF data for the elves observed over Europe were supplied by the Crete and Nançay receivers, while for those observed over North America data were obtained from various Stanford University VLF receivers located in the United States and Antarctica.

During the two month duration of the EuroSprite2003 campaign, six elves were captured by the optical cameras on Pic du Midi on the nights of 22–24 July 2003. The locations of the storms are shown in Fig. 1. VLF data were available for five events, from the Crete and Nançay receivers. The perturbation magnitudes varied from 0.15 to 0.4 dB and the onset durations were in the range of 20 ms–2 s, including both early/fast and early/slow type events, while the relaxation times were ~2–3 min. The elve-producing discharges were all located at ~1950 km from the Crete receiver, at distances <650 km from the TX–RX GCPs.

In order to get more insight into the nature of the relationship between elves and VLF perturbations, a large dataset of satellite-based elve observations was analysed in conjunction with VLF recordings. The dataset consisted of 18 elves observed over Europe between October 2004 and March 2005 and 282 captured over North America between July 2004 and July 2005 by the ISUAL payload of the Taiwanese FORMOSAT-2 satellite. Out of the 18 elves observed by ISUAL over Europe VLF data was available for 17 events from the Crete receiver. The GCPs of the transmitters monitored during this period to the Crete receiver are shown in Fig. 10 along with the locations of the elve-producing lighting discharges (marked by circles). Eight elves were situated at lateral distances less than ~300 km to the closest GCP, while the rest were located between ~550 and 1150 km. Six VLF perturbations were observed on multiple links in association with three elves (marked by numbered circles on Fig. 10) which were all located close (at <500 km) to the GCPs. The distances to the Crete receiver were ~400–950 km. All perturbations were of the early/fast type having onset durations of <50 ms and magnitudes in the range of 0.2–0.7 dB.

All three early VLF perturbations seen in the HWV transmitter (18.3 kHz) signal had relaxation times of ~2 min. The VLF events identified in the higher frequency NAA (24.0 kHz) and NRK (37.5 kHz) signals had a slower relaxation which was eventually masked by other variations in the signal level. This suggests that the higher frequency waves,

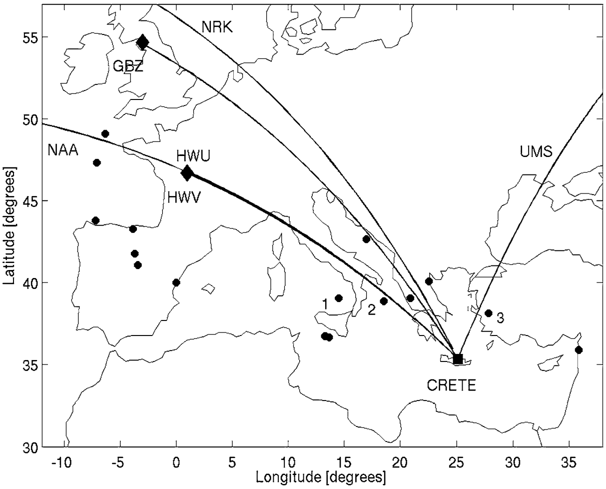

Fig. 10 Locations of the elves observed by the ISUAL payload over Europe (*circles*) during the October 2004–March 2005 period, along with the GCPs from the VLF transmitters to the Crete receiver. The elves accompanied by VLF perturbations are marked by *numbers*. From Mika et al. (2006)

which reflect from higher electron densities and therefore can penetrate to higher altitudes, detected the upper, and thus longer-lived, regions of the EMP-induced ionisation perturbations.

As for the 282 elves observed by the ISUAL over North America, VLF data was supplied by eight receivers, four of them being part of the Stanford HAIL (Holographic Array for Ionospheric and Lightning research) network (Johnson et al. 1999): Cheyenne, Boulder, Parker, and Las Vegas, while the other four being the Taylor, Boston, Arecibo receiver sites and Palmer station in Antarctica. The VLF receiver specifications were identical to those of the Crete station (see Sect. 2). Amplitude and phase time series from the NPM (21.4 kHz, Lualualei, Hawaii), NAA (24.0 kHz, Cutler, Maine), NLK (24.8 kHz, Arlington, Washington), and NAU (40.75 kHz, Aguada, Puerto Rico) VLF transmitters were recorded daily from 01:00 to 13:00 UTC, except for Palmer station which was operating synoptically (recording for only 10 minutes out of every hour). VLF data was only available for 51 elves out of the 282, in most cases for multiple TX–RX combinations. 42 out of the 51 elves were situated at lateral distances less than 500 km from the nearest GCP, whereas the distances of the elves from the receivers were >2000 km, that is, much larger than those found previously for the European sector (<1200 km). The amplitude and phase time series were thoroughly analysed for each receiver–transmitter combination, but no perturbations were found to accompany the elves.

In summary, all five elves captured during EuroSprite2003 were accompanied by VLF perturbations seen in the HWV and GQD signals. Out of the 17 elves observed by ISUAL over Europe three were accompanied by early/fast VLF perturbations seen on multiple transmitter–receiver GCPs. In contrary, there were no VLF perturbations accompanying any of the 51 elves observed by ISUAL over North America, which, however, occurred at rather large distances from the receivers. The occasional existence of early VLF perturbations accompanying elves constitutes a clear proof of electron density changes caused by the elve-generating lightning EMP.

The observations summarised here showed for the first time that the ionisation changes caused by the lightning EMP can occasionally be detected via VLF remote sensing. However, the possibility of detection seems to be highly dependent on the observing geometry. It is interesting that no VLF perturbations were observed in relation to the numerous elves captured over North America. One possible reason can be that these events were located at distances >2000 km from the receivers, while those observed over Europe were much closer. Theory and numerical calculations predict strong inter-modal scattering upon incidence on lower-ionospheric ionisation enhancements (e.g., see Nunn 1997). These modes can be attenuated over the long propagation distances to the receiver and thus the VLF perturbations can be masked by noise. Another reason can be the absence of ionisation during elves in cases when the EMP intensity is enough to excite optical emissions (the electron energy threshold is ~7.5 eV for the first positive band of N_2), but it is insufficient to produce ionisation due to the higher energies (15.6 eV for N_2) required for this process. This can be either due to the low intensity of the EMP or to high ambient electron densities. In the latter case, the electron mean free path is so short that the electric energy goes into excitation during the frequent collisions rather than ionisation which would require that the electrons attain higher energies by being accelerated by the electric field over larger distances.

4 Summary

The new contributions from the European VLF studies of TLE-related phenomena can be summarised as follows: 1) Sprites occurring close to a TX–RX GCP and also to the VLF transmitter are found to be nearly always accompanied by early VLF perturbations. This and more evidence from the observed recovery times of the perturbations are indicative of strong forward VLF scattering from a region of diffuse ionisation enhancement that develops during a sprite, generated by QE fields impacting on the upper D region above about 75 km. 2) Early VLF perturbations due to wide-angle VLF scattering (also backscatter) from conductive filamentary structures associated with the sprite discharges might also occur but are weak and infrequent relative to the strong forward scatter events. The VLF perturbations possibly due to backscatter were observed to accompany only about 5% of the sprites, a much smaller number than it is predicted by scattering theories. 3) Long-delayed sprites were observed to occur much more frequently than thought before, since about 30% of the sprites were delayed with respect to their causative +CG discharges by more than 30 ms up to 220 ms. Apparently, these sprites are caused by QE fields which build up slowly during long continuing currents and thus reach the levels needed for excitation and air-breakdown later compared to short-delayed sprites. 4) Sprite morphology appears to be affected by intracloud lightning. As evidenced by broadband VLF recordings and lightning detection measurements, carrot sprites are concurrent with bursts of sferics of intracloud origin, while such action is absent in column sprites. Moreover, carrot sprites seem to fall in the category of long-delayed sprites, while column sprites are on average short-delayed. This suggests that carrot sprites associate with IC discharge processes and long-lasting continuing currents, leading to electric fields which exceed the air breakdown thresholds for longer times. 5) A new category of early VLF perturbations in relation to sprites was discovered. These are characterised by a slow onset duration or growth. Their onset is nearly coincident with the sprite (early) but is followed by a slow growth lasting up to ~2.5 s. These events were named 'early/slow' in contrast to the well known 'early/fast' perturbations having short onset durations of about 50 ms or less. There is evidence suggesting that early/slow events are due to secondary ionisation build-up in the D region caused by subsequent intracloud discharges. 6) Lightning-induced electron density relaxation times were computed using a D-region model which accounts for charge exchanges between four types of charged particles and various electron loss mechanisms. Model results were fitted to early VLF event recoveries to infer estimates of electron density enhancements and their altitudes of occurrence. Early VLF perturbation recovery times from about 20 to more than 250 s could be explained by assuming electron density increases of ∼10^2 to 10^4 times the ambient values at altitudes between ∼75 and 85 km. 7) Elves, which are theoretically understood in terms of molecular excitation produced by strong EMPs impacting on the upper D region—lower E region of the ionosphere, are sometimes accompanied by early VLF perturbations similar to those seen with sprites. This implies the presence of ionisation production during elves providing experimental proof corroborating EMP theories.

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