Crete VLF studies of Transient Luminous Events (TLEs)

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  • TLE morphology, the medium, QE and EMP field effects, ionospheric VLF waves, lightning-induced VLF signatures

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  • Summary and concluding comments
Transient Luminous Events *TLEs*

Lightning-related phenomena, electric energy coupling between the troposphere and the upper atmosphere

**TLE properties**

- **Sprites**  
  Altitude: $\sim 40 - 85$ km  
  Lifetime: tens of ms

- **Halos**  
  Altitude: $\sim 70 - 85$ km  
  Lifetime: 5 ms

- **Elves**  
  Altitude: $\sim 75 - 105$ km  
  Lifetime: $< 1$ ms

- **Blue jets**  
  Altitude: $\sim 40 - 50$ km  
  (giant jets up to 90 km)  
  Lifetime: $\sim 250$ ms
Transient Luminous Events \textit{TLEs}

The hosting medium is the \textit{D region} of the ionosphere, thus \textit{TLE} effects can be studied with \textit{VLF electromagnetic waves}.
The D region

- Solar (Lyman-α, EUV, X-ray) and cosmic ray radiation
- At daytime from ~50 km
- At night-time from ~80 km

Electron density

\[ N_e(z) = 1.43 \times 10^7 e^{-0.15h'} e^{[(\beta - 0.15)(z - h')]}. \]

At night: \( N_e < 1 \text{ cm}^{-3} \) at 70 km; \( N_e \sim 500 \text{ cm}^{-3} \) at 90 km
D-region chemistry — electron production and loss

**Continuity equation**
\[
\frac{\partial N_e}{\partial t} = Q - L - \nabla(N_e \mathbf{v})
\]

**Q ~ L**

**Electron production term – Q**
- Photoionisation, corpuscular ionisation
- Detachment
  \[X^- + M \rightleftharpoons X^+ + e + M\]

**Electron loss term – L**
- Dissociative recombination
  \[XY^+ + e \rightarrow X + Y\]
- Three-body attachment
  \[e + O_2 + M \rightarrow O_2 + M\]
## D-region chemistry — constituents

### Neutral constituents

- **Main:** $\text{N}_2$, $\text{O}_2$
- **Minor:** $\text{O}$, $\text{O}_2$, $\text{NO}$, $\text{NO}_2$, $\text{CO}_2$, $\text{H}_2\text{O}$
- **Metals:** Mg, Si, Na, Fe (from meteors)

### Charged constituents

- **Electrons:** Exponential increase with height
- **Hydrated positive ions:** $\text{H}_3\text{O}^+$, $\text{H}_5\text{O}^+$, $\text{H}^+(\text{H}_2\text{O})_n$ (below $\sim 70 \text{ km}$)
- **Positive ions:** $\text{NO}^+$, $\text{N}_2^+$, $\text{O}_2^+$ (above $\sim 70 \text{ km}$)
- **Negative ions:** $\text{HCO}_3^-$, $\text{NO}_3^-$, $\text{CO}_3^-$, $\text{CO}_4^-$, $\text{O}_2^-$ (up to $\sim 80 \text{ km}$)
**Crete VLF studies of TLEs**

**VLF waves in the Earth-ionosphere waveguide**

VLF (very low frequency) waves: $f = 3 - 30$ kHz, $\lambda = 100 - 10$ km

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**Waveguide modes**
- TE and TM modes
- Energy propagates in a limited nr. of modes
- Cutoff frequency: $f_{cm} = mc/2h$
- Earth-ionosphere waveguide: QTE and QTM modes

**Reflection height**

Collisions dominant, magnetic field effects neglected:

$$\omega \sim \omega_p^2/\nu_e, \sim 82 - 85 \text{ km}$$

$$\omega_p = \sqrt{\frac{N_e e^2}{m_e e_0}} - \text{plasma freq.}$$
VLF signals

Types of VLF radiation

Natural
- Sferics: EM radiation from lightning
- Whistlers: Sferic energy escaping into the magnetosphere

Artificial
- VLF transmitters: Man-made transmitter signals
VLF transmitter signals

VLF transmitters
- For communication and navigation
- Penetrate the sea water ($\delta \sim 2.5$ m at 10 kHz)
- Low attenuation, 2 – 3 dB/Mm

Narrowband VLF recordings
- Diurnal variation
- Daytime: stable propag. conditions
- Night-time: ionospheric sensing possible
Lightning-generated sub-ionospheric VLF Perturbations

Crete VLF station recordings - November 15, 2005

Narrowband VLF signal time series and perturbations. It allows one to study indirect and direct lightning effects in the upper atmosphere lower ionosphere.
Lightning-generated VLF signatures

VLF perturbations

**LEP** Indirect effect, whistler – radiation belt electron interaction, secondary ionisation by precipitating 50 – 500 keV electrons.
- Onset delay: $\sim 0.6$ s
- Onset duration: 1 – 2 s
- Recovery: 10 – 100 s
- Size: 1000 km x 500 km

**Early/fast** Direct effect
- Onset delay: $< 20$ ms
- Onset duration: $< 20$ ms
- Recovery: 10 – 100 s
- Size: about 100 – 150 km

Figure and text is from Stanford group publications
Early VLF perturbations due to scattering from irregularities in conductivity

VLF Scattering

**narrow angle forward scattering**
caused by a horizontally extended region of perturbed electron density \((l > \lambda, h< \lambda)\)
*Wait (1964); Poulsen et al. (1990, 1993)*

**wide angle scattering**
by induced currents from an assembly of conducting vertical structures \((d << \lambda)\).
*Wait (1995); Rodger et al. (1997, 1999)*

D-region conductivity

\[
\sigma \approx \frac{e^2 N_e}{m_e \nu_{en}}
\]

\[
\nu_{en} = [43 + 4.18 \ln(T_e^3/N_e)]N_e T_e^{-3/2}
\]

\(\sigma\) changes due to change in:
- Electron density (ionisation) – last 10 to many 100 s
- Collision frequency (heating) – last < 1 s

**Observations imply:**

Most Early VLF events are likely due to laterally extended regions of electron density enhancements in the upper D region
Crete VLF studies of TLEs (Sprites and Elves)

Generation mechanisms
Crete VLF studies of TLEs (Sprites and Elves)

Generation mechanisms

Sprites  QE fields – sudden charge rearrangement due to a CG discharge, 5 – 100 ms
Elves  EMP (sferic) radiated by the lightning, <1 ms

Electric energy coupling to the medium

Coupling via electron acceleration and electron–neutral collisions:
- Few eV: vibrational and rotational states are excited
- Higher energies: electronic states are excited ⇒ light emissions (∼7.5 eV for N₂)
- Even higher energies: ionisation (∼15.57 eV for N₂)

Breakdown electric field (890 V/m at 60 km, 5 V/m at 90 km):

\[ E_k(z) = 3.2 \times 10^6 \frac{N(z)}{N_0} \]

When breakdown occurs light emission increases markedly
Electric field relaxation

Dielectric relaxation time:
\[ \tau_r = \frac{\varepsilon_0}{\sigma(z)} \]
Typical values: \( \sim 0.1 \) s at 60 km, \( \sim 4 \) ms at 70 km, 15 \( \mu \)s at \( \sim 80 \) km, and \( \sim 0.2 \) \( \mu \)s at 90 km

QE field generation

1. Charge accumulation takes many tens of seconds ⇒ shielding efficient, strong fields only inside the cloud
2. Sudden charge neutralisation by a discharge ⇒ electric field (few 100 V/m at 60 km) due to the unpaired charge ⇒ heating, optical emissions \( \text{N}_2(1\text{PG}) \), breakdown, ionisation, sprites and/or halos
3. Space charge rearrangement
QE fields/Sprites II.

QE fields
- Quasi-static electric dipole with the image charge in the ground
- Maximum field right above the discharge:

\[ E_{\text{max}} = - \frac{1}{4\pi \varepsilon_0} \frac{4Q(t)Z_d}{(h + Z_d)^3} \]

- Decisive parameter: \( M = QZ_d \) (charge moment)
- +CG: larger charge moments than -CG
The EMP mechanism/Elves I.

<table>
<thead>
<tr>
<th>Return stroke EMP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elve/EMP theory before their discovery (1995)</td>
</tr>
<tr>
<td>- Strongest current during the return stroke, lasting $\sim 50 - 100 \ \mu s$</td>
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<tr>
<td>- EMP released by the varying current, peak spectral content in VLF, below 10 kHz</td>
</tr>
<tr>
<td>- 85 – 100 km: mean free path large $\Rightarrow$ electron acceleration, optical emissions, $N_2(1PG)$, and ionisation</td>
</tr>
</tbody>
</table>
The EMP mechanism/Elves II.

EMP from CG and IC lightning

- Electric field:
  
  \[ E_\theta = \frac{\mu_0}{4\pi} \frac{\beta cl_0}{r} \frac{\sin 2\theta}{1 - \beta \cos \theta}, \]

  where \( \beta = \frac{v}{c} \)

- **Vertical (CG) discharge:**
  - Null at: \( \theta_{v_{\text{min}}} = 0 \); Maximum at: \( \theta_{v_{\text{max}}} \approx 45^\circ - 41^\circ \)
  - Doughnut-shape, expanding at \( v > c \), emissions for <1 ms
Crete VLF Studies of TLEs
VLF Measurements in Crete (started July 18, 2003)

The Stanford VLF receiver

Stanford VLF receiver on Crete
- North-south oriented 1.7 \times 1.7 \, \text{m}^2 \, \text{loop antenna}
- Records TX signal amplitude and phase with 50 \, \text{Hz} \, \text{resolution (20 ms)}
EuroSprite campaigns

Instruments

- Optical cameras
- Lightning detection systems: Météorage, SAFIR
- Broadband and narrowband VLF receivers
- Pulsation magnetometers
- ISUAL (FORMOSAT-2)
EuroSprite campaigns

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Coupling of Atmospheric Layers - EU / RTN
HAIL Software (Analysis of Narrowband VLF recordings)
More work is needed

Narrowband VLF time series

VLF Wavelet analysis
More work is needed

Narrowband VLF time series

VLF Wavelet analysis

Broadband VLF time and frequency domain analysis
Crete VLF / TLE Studies  (PhD Thesis, Agnes Mika) *

Investigated topics

**Topics/Questions**
- What is the relation between sprites and early/fast VLF events?
- Which scattering mechanism is more important?
- Can sprites cause backscatter?
- What is the role of continuing currents and IC lightning in sprite generation?
- What can be inferred from early VLF perturbation recoveries about the electron densities?
- Are all early VLF events early/fast?
- Is there ionisation produced during elves?
- What can we infer from modelling VLF scattering from sprites?
- Is there a unique ULF sprite signature?
- Can previously reported contradictions in observations be due to instrumental differences?

Relation between Early VLF events and sprites

Sprites and VLF perturbations – previous studies

Very few and contradictory results.

Conclusions – Stanford
- Sprite-related E/F events constitute only a small subset
- Strong forward scattering from smooth, large disturbances

Conclusions – Otago
- One-to-one relationship between sprites and early VLF events
- Wide-angle scattering from structured, small-scale \( a \ll \lambda_{\text{VLF}} \) ionised regions
Early VLF Events and Sprites

July 21, 2003, storm 02:00 - 03:15 UT: 28 sprites
Sprite related “Early/Slow” and LEP VLF Signatures

Sprite at 02:38:40.640 UT
A large amplitude Early VLF event
2003 July 21 storm

- 27 sprites, early VLF events accompanied 24
- 1273 -CGs and 207 +CGs, but no VLF events without sprites
- ⇒ One-to-one relationship
- Tested and validated on more storms
Early VLF events and Sprites: *EuroSprite 2007*


3 VLF links (HWU, NAA, HWV) have identical GCPs
Early VLF and Sprites: “one to one” relation


- 14 Sprites, 12 +CGs, 14 Early VLF events accompanied, 100 %
- 1 Early event (with +CG causative) but no sprite
- 664 -CGs and the rest (190) +CGs had NO Early-like VLF signature
Sprites and early VLF perturbations – conclusions

Conclusions

- Virtually one-to-one relationship between sprites and early VLF events \( \Rightarrow \) Proxy?
- Sprites are nearly always accompanied by ionisation production in the D region
- VLF event recoveries: 20 – 150 s \( \Rightarrow \) ionised region above 75 km
- Forward scattering

Need for more work
Wide-angle scattering in relation to sprites I.

2003 July 21–24 storms
- 21 July storm at 100 – 200 km to Nançay
- 22–24 July storms at 230 – 500 km
- Early VLF events at Nançay for 5 out of 38 sprites
- All during the 21 July storm
- 3 more storms at >300 km from Nançay also examined – no perturbations

Conclusions
- 5% of the sprites relate to backscatter ⇒ less important than forward scatter
- Cause might also be propagation effects
- Importance of wide-angle scattering not clear

Need for more work
Sprites and causative CG discharges I.

Sprites and +CGs
- Widely accepted: sprites initiate a few ms after a +CG
- Relation unclear, e.g. long-delayed sprites >30 ms after +CG
- Use VLF and lightning data to investigate the sprite – +CG delays

103 sprites:
- 70% short-delayed
- 30% long-delayed up to 220 ms
Sprites and causative CG discharges II.

Sprites, +CGs, and sferics
- Short-delayed: sferic activity during sprite occurrence
- Long-delayed: only IC sferic activity during the CG-to-sprite period

Explanation: continuing currents, requires significant IC activity
Importance of long-delayed sprites (30%) underestimated before

Need for more work
The role of IC lightning in sprite generation I.

Data
- 23–24 July 2003 15 sprites observed from Pic du Midi, 8 carrot, 5 column, and 2 undefined
- Sferic detection using the Nançay receiver
- Different IC lightning activity for column and carrot sprites
The role of IC lightning in sprite generation II.

Column sprites

- Sprite→CG delay up to 27 ms ⇒ short-delayed
- No significant IC activity
The role of IC lightning in sprite generation III.

Carrot sprites
- Sprite→CG delay from 18 to 205 ms ⇒ mostly long-delayed
- Significant IC activity

Carrot sprites associate with longer-lasting continuing currents ⇒ breakdown field exceeded for a longer time, more time for growth

Need for more work
Early/slow events: a new category I.

Early/slow VLF perturbations
- E/F: onset duration < 20 ms
- 73 early VLF events examined, clear events selected: 27
- 15 (55%) E/S, 8 E/F, 4 complicated onsets
- E/S onsets up to ~2 s ⇒ new discovery
“early/slow” vs “early/fast” VLF events
Early/slow events: a new category II.

Insight into the origin of E/S events
- Complex sferic activity during the E/S onset duration of \( \sim 1 - 2 \) s
- Origin: IC discharges
- Absent during E/F events
Early/slow events: a new category III.

Origin of the sferic activity

- Sferics seen at <150 km
- Sferics not observable at ~2000 km

⇒ Source: IC discharges
Early/slow events: a new category IV.

Terminology: \(E/F\) and \(E/S\), thus better call \textit{Early VLF events}.

Proposed mechanism:

- \(\sim60\%\) of early VLF events are \(E/S\)
- Secondary ionisation build-up in the \(D\) region
- Cause: IC discharge EMPs energise the sprite-produced electrons further
- Test: sensitive cameras/photometers to detect associated optical emissions

Need for more work
Elves and early VLF perturbations I.

**Motivation**
- Theory predicts ionisation at \(\sim 85 - 95\) km, but no experimental proof available
- Elve-related perturbations would constitute proof of ionisation
Elves and early VLF perturbations II.

**EuroSprite 2003 observations**

- 5 elves observed, initiated by CGs of $>100$ kA
- All associated with VLF perturbations having 20 ms – 2 s onsets and 2 – 3 min recoveries
Elves and early VLF perturbations III.

**ISUAL observations**
- Elves are more easily observed from space
- ISUAL – payload on FORMOSAT-2
- October, 2004 – March, 2005: 18 elves observed over Europe, 3 with E/F events

Typical Early VLF signature. Recovery time $\sim 200$ s
Elves and early VLF perturbations IV.

ISUAL Observations

July 2004 - July 2005
282 Elves over US/Mexico

45 elves and VLF data

No VLF-perturbations
Elves and early VLF perturbations

Conclusions

- Existence of VLF perturbations $\Rightarrow$ clear proof of ionisation changes, corroborating EMP-theory predictions
- VLF event recoveries in the 24.0 and 37.5 kHz signals longer than those in the 18.3 kHz $\Rightarrow$ higher frequency waves, reflecting at higher altitudes, detect the upper, longer-lived regions of ionisation changes
- Recovery times place the disturbed region above about 85 – 90 km

Need for more work
Modeling the relaxation of Early VLF events

Early VLF event recoveries range from several seconds to several tens of seconds mostly between 20 s and 200 s what can we learn?
Modelling the relaxation of early VLF events I.

**Motivation, basics**

- Early VLF event relaxation times are similar to those of LEPs, LEP model used here [Glukhov et al., 1992]
- Four constituents: electrons $N_e$, positive single ions $N^+$, negative ions $N^-$, positive cluster ions $N^+_x$
- Six processes:
  - Attachment: $\beta = 10^{-31} N_{O_2} N_{N_2} + 1.4 \times 10^{-29} \left( \frac{300}{T} \right) e^{-\frac{600}{T}} N_{O_2}^2 \text{ s}^{-1}$,
  - Detachment: $\gamma = 3 \times 10^{-18} N \text{ s}^{-1}$,
  - Dissociative recombination: $\alpha_d = -3 \times 10^{-7} \text{ cm}^3\text{s}^{-1}$,
  - Recombination with $N^+_x$: $\alpha_d^c = 10^{-5} \text{ cm}^3\text{s}^{-1}$,
  - Ion-ion recombination: $\alpha_i = 10^{-7} \text{ cm}^3\text{s}^{-1}$,
  - Conversion of $N^+$ into $N^+_x$: $B = 10^{-31} N^2 \text{ s}^{-1}$
Modelling the relaxation of early VLF events II.

Model equations

\[ \frac{dN_e}{dt} = I + \gamma N^- - \beta N_e - \alpha_d N_e N^+ - \alpha_d^c N_e N_x^+ \]

\[ \frac{dN^-}{dt} = \beta N_e - \gamma N^- - \alpha_i N^- (N^+ + N_x^+) \]

\[ \frac{dN^+}{dt} = I - BN^+ - \alpha_d N_e N^+ - \alpha_i N^- N^+ \]

\[ \frac{dN_x^+}{dt} = -\alpha_d^c N_e N_x^+ + BN^+ - \alpha_i N^- N_x^+ \]
Modelling the relaxation of early VLF events III.

**Ionisation production**

- ODES solved first using ambient profiles and the production term: \( I = \nu_i N_e \);

\[ \nu_i = F(E_r) \text{ and } E_r = E_{r0} \left( \frac{t}{T_r} \right) \exp\left( -\frac{t}{\tau_r} \right) \]

- The resulting number densities for the four constituents are the initial conditions for the recovery calculation, using \( I = 0 \)
Modelling the relaxation of early VLF events V.

\[ \frac{N_e}{N_{e0}} = 10^2 \quad \frac{N_e}{N_{e0}} = 10^3 \quad \frac{N_e}{N_{e0}} = 10^4 \]

Best fit at

- **Short recovery**<br>  < 50 s<br>  75 km

- **Medium recovery**<br>  \( \sim \) 100 s<br>  80 km

- **Long recovery**<br>  > 200 s<br>  85 km

*Need for more work*
Modelling the relaxation of early VLF events VI.

Conclusions

- Short recoveries of <50 s: $N_e/N_{e0} \approx 10^4$ at \( \sim 75 \text{ km} \)
- Recoveries of \( \sim 100 \text{ s} \): $N_e/N_{e0} \approx 10^3$ at \( \sim 80 \text{ km} \)
- Long recoveries of >200 s: $N_e/N_{e0} \approx 10^2$ at \( \sim 85 \text{ km} \)
- Strong QE fields cause breakdown and large ionisation at lower altitudes (since increased conductivity shields higher altitudes), attachment and recombination are efficient
- Weaker QE fields cause ionisation higher up, slower decay since attachment is negligible and recombination will be slower ($N_e^2$ dependency)

Need for more work
Summary of new findings – I.

1. Virtually one-to-one relationship between sprites and early VLF events – Proxy?
2. Backscatter from structured sprite bodies possible, but weak and rare (~5%)
3. Long-delayed sprites are more frequent than thought (~30%) ⇒ continuing currents
4. IC lightning determines sprite morphology (carrot sprites) ⇒ QE fields exceeding breakdown threshold for longer time
5. Ionisation enhancements are about $10^2 - 10^4 \times N_{e0}$ situated at 75 – 85 km altitudes (upper diffuse sprite regions and/or halos)
Summary of new findings – II.

1. New category of VLF events: *early/slow* ⇒ secondary ionisation build-up due to EMPs from IC discharges
2. Elves sometimes relate to VLF perturbations ⇒ first proof for ionisation production

3. VLF scattering from sprites is omni-directional and highly complex
4. There is no unique ULF signature associated with sprites ⇒ disproves previous claims
5. Reported observational differences might be partially instrumental
Sub-Ionospheric VLF events

There is now a good deal of understanding. But there are remaining problems/questions and need for more work.

The **AWESOME** network offers new opportunities-possibilities for more VLF-lightning research, also with **EuroSprite, TARANIS** and **ASIM** projects.
6-Tutorials on Ionospheric physics topics

Tutorial by U. S. Inan on: Lower and middle atmospheric electrodynamics

http://isea12.physics.uoc.gr/
Numerical results

- **Left:** lower altitudes
  Weak dependence on initial $N_e$, attachment dominates

- **Right:** higher altitudes
  Strong dependence on initial $N_e$, recombination dominant
  Larger initial $N_e \Rightarrow$ faster recovery since recombination
  $\sim N_e^2 (N^+ \approx N_e)$