



Early VLF perturbations caused by lightning EMP-driven dissociative attachment

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[1] We propose a new mechanism for lightning-induced perturbations to VLF transmitter signals known as Early VLF events. This mechanism involves electron density changes due to electromagnetic pulses (EMP) from successive in-cloud lightning discharges associated with cloud-to-ground discharges (CGs), which are likely the source of continuing current and much of the charge moment change in CGs. Through time-domain modeling of the EMP we show that a sequence of pulses can produce appreciable density changes in the lower ionosphere, and that these changes are primarily electron losses through dissociative attachment to molecular oxygen. Modeling of the propagating VLF transmitter signal through the disturbed region shows that perturbed regions created by successive horizontal EMPs create measurable amplitude changes. **Citation:** Marshall, R. A., U. S. Inan, and T. W. Chevalier (2008), Early VLF perturbations caused by lightning EMP-driven dissociative attachment, *Geophys. Res. Lett.*, *35*, L21807, doi:10.1029/2008GL035358.

1. Introduction

[2] “Early/fast” events are perturbations to VLF transmitter signals caused by lightning-induced effects in the lower ionosphere [e.g., Inan *et al.*, 1995]. A number of mechanisms for these perturbations have been proposed in the past decade. Dowden *et al.* [1994] suggested scattering of the VLF signal from the body of sprite columns, including backscattering, while Inan *et al.* [1996] demonstrated that the disturbances scatter VLF largely in the forward direction (later confirmed by Johnson *et al.* [1999]). Mika *et al.* [2006] showed examples of VLF scattering associated with elves, while Moore *et al.* [2003] used a full-wave electromagnetic model to show that in the altitude regions at which sprite halos occur, the heating and ionization produced by the combined quasi-electrostatic (QE) field and the lightning electromagnetic pulse (EMP) from a large cloud-to-ground (CG) discharge may be the underlying cause of some early/fast events.

[3] Haldoupis *et al.* [2004] showed a one-to-one correlation between sprites and early/fast events in Europe, suggesting they are caused by the quasi-electrostatic (QE) field as proposed by Pasko *et al.* [1997], while Marshall *et al.* [2006] showed that about 61% of Early/fast events over four years in the USA are accompanied by sprites. Haldoupis *et al.* [2006] demonstrated a different type of event, labeled “early/slow” due to the slow (~ 1 s) rise to full perturbation (prompting a

reclassification of these types of direct ionospheric perturbation events as “Early VLF” perturbations) and explained these Early/slow events via in-cloud lightning activity, suggesting that such activity would cause a slow buildup of secondary ionization through collisions between neutrals and QE-heated electrons. In this paper, we present a new mechanism, involving electron density changes due to the EMP fields of repeated in-cloud discharges, often associated with sprites as “spider” lightning. This differs from the mechanism of Haldoupis *et al.* [2006] in that the QE field is not a factor in our mechanism, and thus the correlation with sprites is not necessary.

2. VLF Perturbations Due to Dissociative Attachment

[4] The proposed mechanism is as follows: in-cloud lightning discharges associated with cloud-to-ground discharges serve to provide “continuing current” to the CG discharge by tapping a large horizontal area of the cloud for charge. These discharges, often reported as “spider lightning” and frequently associated with sprites [Stanley *et al.*, 1999], appear in VLF data as spheric bursts [Marshall *et al.*, 2007]. Each of these horizontal discharges radiates an EMP preferentially upwards, unlike CG discharges which have a null in the vertical direction. The radiation pattern and the ground reflection yield similar effects in the ionosphere from a horizontal discharge of ~ 3 times lower magnitude than a vertical discharge. Furthermore, these horizontal pulses typically occur in large numbers (~ 100 or more [Proctor *et al.*, 1988]) over a ~ 1 – 3 second duration, rather than the most typical CG with a single return stroke, meaning effects in the ionosphere will accumulate. Note that electron density changes at 80–90 km have recovery times of ~ 10 – 100 seconds, dominated by three-body electron attachment to O_2 and N_2 (via the catalyst O_2) and dissociative attachment to O_3 [Sentman *et al.*, 2008], so that no real recovery occurs in the time span of these bursts.

[5] Dissociative attachment to molecular oxygen ($O_2 + e^- + 3.6 \text{ eV} \rightarrow O^- + O$) is the dominant endothermic electron loss process in the lower ionosphere [Pasko, 1996]. It should be noted that the energy required for attachment (~ 5 eV) is much less than that of N_2 optical emissions often seen in sprites and elves (7.5 eV) and N_2 and O_2 ionization (15.6 eV) [Haldoupis *et al.*, 2006], which implies that attachment would occur alone more often than in combination with optical emissions and ionization.

3. Three-Dimensional Model of the EMP

[6] To test this mechanism, we use a 3D Finite-Difference Time-Domain (FDTD) fully-kinetic model of the

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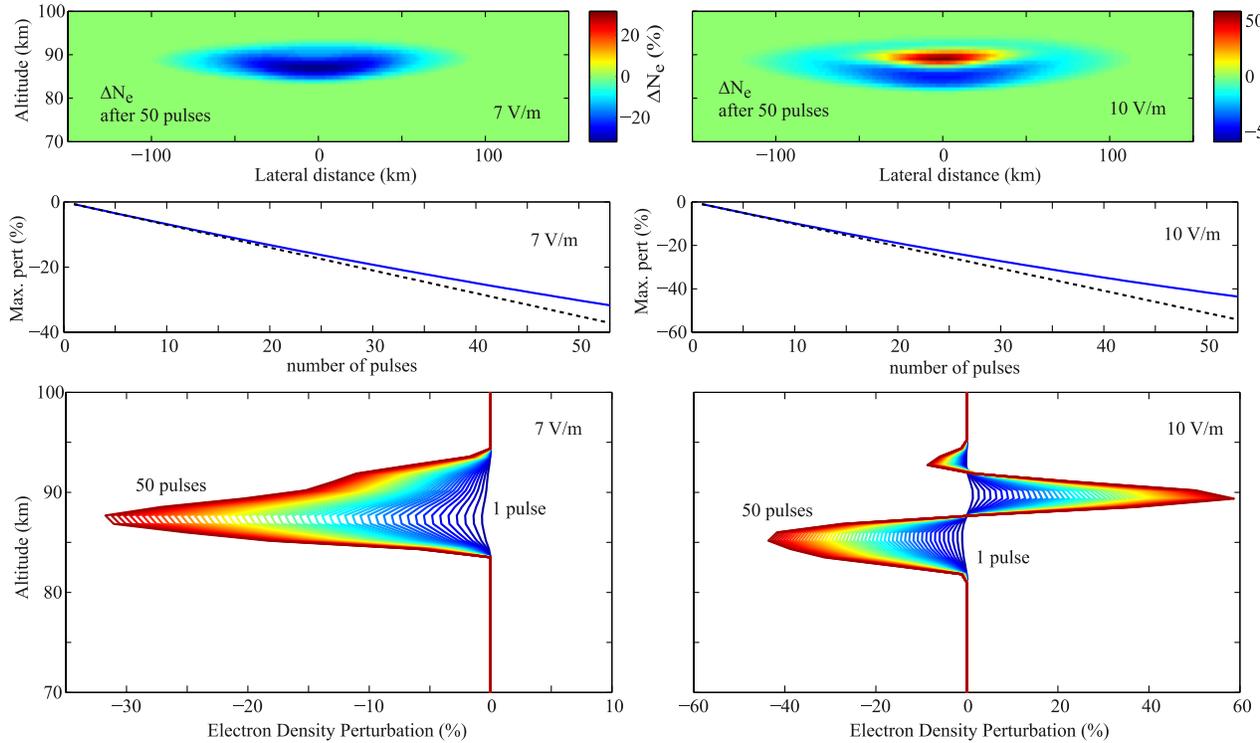


Figure 1. EMP model results. (top) 2D x-z slice through the 3D density perturbation for $E_{100} = 7$ and 10 V/m. (middle) Maximum perturbation versus number of pulses, demonstrating a nearly linear (dashed line) relationship. (bottom) Vertical slice through the center of the perturbed region.

interaction of the EMP pulse with the ionosphere. This model is a 3D extension of the model used by *Taranenko et al.* [1993]. We input a pulse with a current of the form $I_0 e^{\alpha t}/(1 + e^{2\alpha t})$ at an arbitrary altitude using analytical Hertz dipole radiation equations. This field is propagated into a realistic ionospheric plasma, representing all of the inelastic losses in air, while field propagation is implemented using the TRISTAN algorithm of *Buneman* [1993]. At each point in time and space, collision frequencies, ionization, attachment, and optical emissions are calculated using the models described by *Pasko* [1996].

[7] Figure 1 shows a 2D slice of the 3D density perturbation after 50 successive horizontal pulses with $E_{100} = 7$ V/m (left) and 10 V/m (right) located at 5 km altitude with $\alpha = 10^5 \text{ s}^{-1}$ (pulse duration of $\sim 20 \mu\text{s}$). These parameters are consistent with in-cloud discharges reported by *Proctor et al.* [1988] and others, and results in a discharge slow enough to allow the use of stationary cross sections of *Taranenko et al.* [1993]. The lightning literature does not yet have amplitude measurements for spider-lightning discharges, nor reliable E_{100} values for IC lightning, and so we estimate these amplitudes using VLF data as follows: a simple 2D FDTD simulation (including a realistic ground) shows that the fields at ≥ 100 km along the ground due to a horizontal discharge at 5 km altitude are reduced by a factor of ~ 20 compared to a CG on the ground. Analysis of the VLF data reported by *Marshall et al.* [2007], comparing the amplitudes of sferic bursts with those of CG sferics, shows that the typical sferic burst is a factor of 20–40 lower in amplitude than CG sferics. Using the more conservative factor of 40 here and the factor of

20 difference in propagation, this leaves a factor of 2 decrease at the source. Hence, a 75 kA CG discharge corresponds to $E_{100} = 20$ V/m, and so sferic burst pulses can be estimated to have a relative source amplitude $E_{100}^{\text{ic}} \approx 10$ V/m.

[8] The results show that 7 V/m pulses indeed create a loss of electron density without increases due to ionization. When the amplitude is increased to 10 V/m, ionization appears at 85–90 km, but over a much smaller volume. The total electron change in the 7 V/m case is -8.30×10^{19} electrons in one pulse; at 10 V/m, despite density increases of 1.32% and decreases of -1.02% at the center, the total volumetric change in electrons is -1.31×10^{20} electrons in one pulse. So, even when ionization does occur, the loss of electrons due to attachment dominates due to the larger volume affected. Note that *Cho and Rycroft* [2001] also showed results of a 3D EMP model, but did not focus on the effects of attachment. The middle plots in Figure 1 show the very nearly linear (dashed line) density change with number of pulses; hence, an event with hundreds of pulses may produce huge electron density changes (although of course the linear relationship must break down as the loss approaches 100%).

4. Transmitter Propagation Model

[9] To demonstrate that the density reduction due to attachment as calculated above can cause measurable perturbations of VLF transmitter signals, we employ a 2D Finite-Difference Frequency-Domain (FDFD) model of the VLF signal propagation through a disturbed region. This model is described in full by *Chevalier et al.* [2008] and

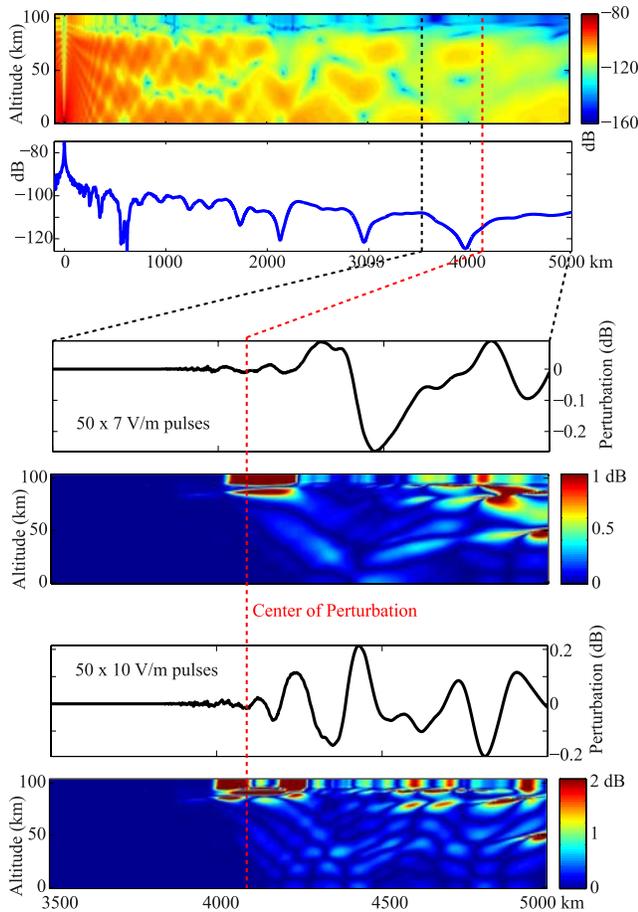


Figure 2. FDFD Model results demonstrating feasibility of attachment-caused VLF perturbations. (top) Ambient VLF H_x field at 24 kHz in 2D and along ground. (bottom left) ambient and perturbed ionospheric profiles used. (bottom right) 2D and along-ground perturbed H_x fields.

uses a Segmented Long Path (SLP) method to simulate large spaces. In the model runs shown here, we use a space of 110 km in altitude (z) and 5000 km in length (x). The model grid spacing is $\Delta x = \Delta z = 0.5$ km. We use a transmitter frequency of 24 kHz, corresponding to the NAA transmitter in Maine, on whose path many Early VLF events have been seen [e.g., Marshall *et al.*, 2006]. The path length of 5000 km was chosen so that the perturbation could be located a realistic distance from the “receiver” (~ 200 – 900 km away) while avoiding interference nulls along the ground in the signal pattern (as observed near 4000 km in this example), which create artificially high dB perturbations.

[10] Results are shown in Figure 2. The top two plots show the 2D ambient H_y -field and its amplitude along the ground. These results have been shown to match those of the Long-Wave Propagation Capability (LWPC) code. The bottom plots show the 2D scattered field in dB that would be observed by a receiver, for both perturbations shown in Figure 1. For a receiver at ~ 4500 km, a -0.2 dB perturbation is observed for the 7 V/m case. While this is a small value compared to typical measured early/fast perturbations (~ 0.2 – 1.0 dB), it must be noted that this perturbation, with

a 30% decrease in electron density at its maximum, occurs for only 50 pulses, which is as many pulses as we have simulated in the EMP model for reasons of computation time. Fifty pulses is a small number when compared to events measured by Lightning Mapping Arrays (LMAs); for example, events reported by Noble *et al.* [2004] typically have hundreds of VHF pulses, and Proctor *et al.* [1988] reports flashes with a mean of over 100 Q-bursts over not more than 2–3 seconds, which may be the sources of VLF spheric bursts [Marshall *et al.*, 2007]. The linear relationship in Figure 1 shows that more pulses will cumulatively increase the density perturbation. Figure 2 shows that the sequence of fifty 10 V/m pulses from the EMP model results in a perturbation of ± 0.2 dB at various possible receiver locations. Note that these successive pulses occur in a very short time compared to the relaxation time of Early VLF events.

5. Associations With Optical Events

[11] Logical reasoning shows that the proposed mechanism is able to explain the correlations between TLEs (sprites, halos and elves), Early VLF perturbations, and spheric bursts described by Marshall *et al.* [2006, 2007]. Spheric bursts and Early VLF events are seen in one-to-one correlation [Johnson and Inan, 2000], and we are arguing here for their common cause. Sprites are not seen in one-to-one correlation by Marshall *et al.* [2006] but are present in work by Haldoupis *et al.* [2004]; in either case, the two are strongly connected. This is simply because sprites usually require large continuing currents to remove enough charge from the cloud to generate a substantial QE field, and this continuing current is sourced by in-cloud lightning discharges. Hence, the two will often be seen together when the charge moment is substantially comprised of continuing current; if the impulsive charge moment change (first ~ 2 ms) is dominant, and little IC activity is present, Early VLF events may not appear.

[12] In the case of elves, which are the optical signature of the vertical CG EMP impinging on the ionosphere, we note that optical emissions imply attachment (due to the lower energy threshold) but not ionization (higher threshold). Simulation results show that even for a very large vertical EMP ($E_{100} = 25$ V/m, or a peak current of 92.5 kA), a single pulse will only create a density change of a few percent, likely not enough for noticeable perturbations. However, some cases do have correlated Early VLF events [Mika *et al.*, 2006], which could be explained by some combination of (i) appreciable attachment in the single CG pulse, (ii) a pulse large enough to create appreciable ionization, and/or (iii) coincident in-cloud lightning activity and thus spheric bursts. These cases need to be further analyzed to determine the exact scenario.

6. Polarity of Early VLF Events

[13] One consequence of our hypothesis is that Early VLF events caused by attachment-depleted regions would more typically have *positive* perturbation amplitudes, due to less VLF signal absorption in the reduced density region. Waveguide mode interference and coupling is of course always present, arising through scattering and absorption of

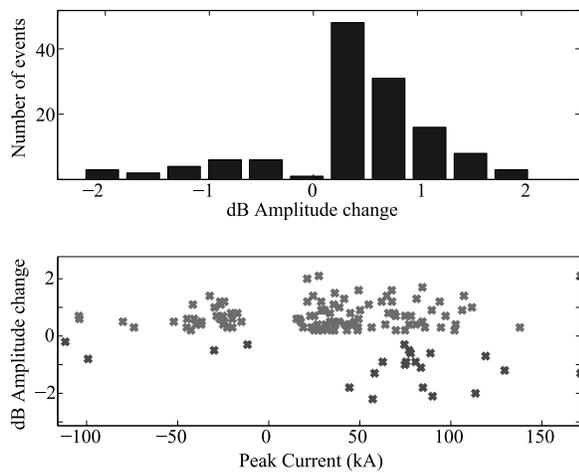


Figure 3. Histogram of dB perturbation amplitudes of early VLF events from 15 July 1995, 18 August 1999, and 22 July 2000. See the text for discussion.

each mode independently, and leading to perturbation events of both polarities. Over a large data set, however, *statistically* the perturbations should more often be positive, if indeed the overall effect is a reduction in electron density. This is especially true when the perturbation is far from the transmitter (a few Mm), as in the results of *Marshall et al.* [2006], as only a few propagating modes remain and interference is less prominent.

[14] Previously published data confirms our hypothesis: in work by *Inan and Rodriguez* [1993], all 33 Early/fast events were positive perturbations, while all 22 lightning-induced electron precipitation (LEP) events had a negative amplitude perturbation. Precipitating energetic electrons produce purely an increase in electron density (see, e.g., *Peter and Inan* [2005] through secondary ionization from relativistic electrons. *Inan et al.* [1993] showed data for different dates, with the same results - every LEP event has a negative amplitude change, while every early/fast event has a positive change. Similarly, *Inan et al.* [1996] reported about 29 positive VLF perturbations versus 10 negative events. Note that the results cited here provide a variety of transmitter–receiver paths, so the result is not specific to a particular combination.

[15] Figure 3 shows histograms of Early VLF events from 15 July 1995, 18 August 1999, and 22 July 2000, presented and discussed by *Marshall et al.* [2006]. Many of the largest Early VLF events are negative perturbations (bottom plot); indeed, a quick inspection of Figures 4 and 8 of *Marshall et al.* [2006] seems to signify a prevalence of large negative perturbations (some of which are actually LEP events). However, there are far more small positive perturbations; the large negative perturbations may arise in the rare cases when the causative CG lightning stroke is strong enough to create ionization, through either EMP or QE effects.

[16] Despite the overwhelming predominance of positive-polarity Early VLF events in the data, the simulation results do not seem to agree with this trend. Rather, the results in Figure 2 back up the argument of significant modal interference, and show that the received amplitude (and presence or lack of a registered “event”) strongly depends on the

relative locations of the transmitter, disturbance, and receiver. However, such conclusions can not be made reliably from these two simulations; further investigation is needed to determine if this positive-polarity argument will be consistent with modeling.

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