Sprites in low-frequency radio noise

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Received 18 February 2013; revised 22 March 2013; accepted 22 March 2013; published 30 May 2013.

1Low-frequency radio noise is the electromagnetic background radiation which is compared here to the luminosity of 39 sprites recorded with a low-light video camera. It is found that the sprite luminosities coincide with ~10–30 ms long sudden enhancements of the electromagnetic background radiation ~6–8 µV m−1 Hz−1/2 (~6–9 dB) with a relative maximum near ~125 kHz as measured with a wideband (~1–400 kHz) digital radio receiver. The sprites cluster in 10 groups of 2–5 consecutive sprites which are paralleled by up to ~1 s long slowly varying enhancements of the electromagnetic background radiation ~4–5 µV m−1 Hz−1/2 (~2–4 dB). The observed electric field strengths place an upper bound on the low-frequency radiation from the electron multiplication associated with the exponential growth and branching sprite streamers predicted by Qin et al. (2012a). This upper bound corresponds to a maximum of ~300–5000 sprite streamers at ~40 km height above thunderclouds. Some part of the observed electromagnetic background radiation might result from the superposition of low-frequency radiation emanating from the quick succession of numerous horizontal lightning strokes and/or stepped leaders inside thunderclouds which would constitute a fundamentally novel quasi-static discharge process inside thunderclouds radiating slowly varying low frequency radio noise. Citation: Füllekrug, M., A. Mezentsev, S. Soula, O. van der Velde, and T. Farges (2013), Sprites in low-frequency radio noise, Geophys. Res. Lett., 40, 2395–2399, doi:10.1002/grl.50408.

1. Introduction

2. Observations

3. The predicted low frequency electromagnetic radiation from sprite streamers scales with the total number of streamers such that it is suggested to investigate particularly bright sprite occurrences [Qin et al., 2012a]. An exceptional sequence of 10 spectacular clusters of sprites is used for analysis which occurred above a mesoscale convective system in the Mediterranean during the early morning hours from 00:55 to 02:17 UTC on 31 August 2012. The parallel stratiform mesoscale convective system [Parker and Johnson, 2000] was initiated by unstable air masses off the south-eastern Spanish coast over the Mediterranean and it propagated south-eastward toward northern Africa until it reached a horizontal extent ~330 × 140 km2 shortly after midnight. Numerous lightning discharges occurred in the convective core of the mesoscale convective system (Figure 1, left) and some particularly intense positive lightning discharges in the stratiform region caused the 10 spectacular clusters of sprites which included 39 individual sprites, i.e., ~32% of all the 122 sprites observed during that night. Each sprite cluster comprises 2–5 consecutive sprites which occur within ~120–960 ms, with time differences between consecutive sprites of ~80–620 ms. These sprites comprise numerous luminous sprite elements, some of which exhibit significant deviations from the vertical direction (Figure 1, right) which is indicative of a superposition of the forcing electric field with the preceding electric field decay [Neubert et al., 2011]. Several of these sprites show trolls, palm trees, or secondary jets; all of which are very rare phenomena named secondary transient luminous events (TLEs) [Lee et al., 2012; Marshall and Inan, 2007].

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near Bath in south-west England (51.4°N, 0.3°E) consequently averaged from The decadic logarithms of the spectral amplitudes are sub-
secutive spectra with a temporal resolution of 1 ms. away from the sprites. The recordings are used to calculate 
the derived 1 ms logarithmic mean in insensitive to con-
1 ms long modulation of the entire spectrum. Note that /EM minor fraction /STX 3 kHz /STX 400 kHz
[CAN] /EM. These impulsive lightning strokes are known as sferic clusters which can cause sprites [van der Velde et al., 2006; Ohkubo et al., 2005]. Yet, after the impulse from a lightning stroke, the intensity of the electromagnetic background radiation observed here falls back to the level of the background radiation before the lightning stroke, similar to sferic bursts in the frequency range ~3–30 kHz [Marshall et al., 2007]. This background radiation varies only slowly on time scales ≥10 ms when compared to the impulsive lightning strokes (Figure 2, top image of left panel). The influence of lightning strokes is therefore removed by only using the smallest 1 ms value within each 10 ms long time interval. This minimum value is finally used to characterize the electromagnetic background radiation with a temporal resolution of 10 ms. This background radiation exhibits a sudden enhancement at the onset of the sprite cluster which was initiated by a positive lightning discharge with a peak current +117 kA at 01:12:59.420 UTC (Figure 2, top image of left panel). A more detailed analysis of this sudden enhancement of the background radiation shows that all spectral amplitudes from 1–400 kHz exhibit a relative enhancement by a factor of ~2–4 after the onset of the sprite cluster (Figure 2, right). The largest relative enhancement is found to be ~1 order of magnitude near ~125 kHz. On the other hand, the background radiation does not show any enhancement at the onset of a halo [Qin et al., 2012b] which was initiated by a negative lightning discharge with a peak current of –160 kA at 22:50:21.313 UTC (Figure 2, bottom image of left panel). It is interesting to note that this negative lightning discharge is accompanied by many more and stronger impulsive lightning strokes than the positive lightning discharge. Yet, all these impulsive lightning strokes have virtually no effect on the electromagnetic background radiation.

The sprite luminosity is inferred from the images recorded with the low-light video camera at a temporal resolution of 20 ms for comparison with the electromagnetic background radiation. The sprite luminosity typically lasts for ~1–2 images. This luminosity is quantified by counting the number of pixels above a threshold near the higher end of the distribution function of the observed luminosities present in a normal video image without any sprites. This threshold is roughly half the maximum luminosity in one pixel (140 out of 256 possible values). The sprites observed here are easily detected with this method because the sprites are so bright that they often saturate the chip of the camera. The sprites also appear to be relatively large in the recorded images (typically ~0.1–1% of 288 × 720 pixels) such that the logarithm of the number of pixels above the chosen threshold describes the sprite luminosity very well (Figure 3). The sprite luminosity coincides with the ~10–30 ms long sudden enhancements of the electromagnetic background radiation ~6–8 µV m⁻¹ Hz⁻¹/² (~6–9 dB). One sudden enhancement of the background radiation at

Figure 1. A mesoscale convective system in the Mediterranean produces numerous sprite clusters. (left) The mesoscale convective system in the Mediterranean reaches a horizontal extent ~330 × 140 km² during the early morning hours from 00:15 to 00:35 UTC on 31 August 2012. The negative lightning discharges mainly occur in the center of the convective core (circles) while positive lightning discharges also occur in the parallel stratiform region (white crosses) as reported by the Météorage lightning detection network. Three positive lightning discharges initiate sprites during this time interval (red crosses). (right) Two examples of the 10 sprite clusters which are observed with a video camera on Pic du Midi in southern France (42.9°N, 0.1°E, 2877 m). Both sprite clusters illuminate a substantial volume of the atmosphere. Note the deviations of the sprite luminosity from the vertical direction which indicates an influence of the electric fields associated with preceding sprites.
3. Discussion

The observed sprite luminosities coincide with sudden enhancements of the electromagnetic background radiation \( \sim 6–8 \mu \text{V m}^{-1} \text{Hz}^{-1/2} \) \( \sim 6–9 \text{ dB} \) with the largest enhancement occurring near \( \sim 125 \text{ kHz} \). Sprite streamers at \( \sim 70–75 \text{ km} \) height have a median width of \( \sim 300–500 \text{ m} \) before splitting [McHarg et al., 2010, Figure 5] which reduces to \( \sim 3–5 \text{ m} \) at \( \sim 40 \text{ km} \) height by using a scaling of \( \sim 1/100 \) derived from the similarity laws for sprites associated with the varying neutral density. The \( \sim 3–5 \text{ m} \) long current element develops over a time scale of \( \sim 5–10 \mu \text{s} \) [Qin et al., 2012a, Figure 3, lower panel]. Similarly, the growth rate of sprite streamers \( \sim 10^4 \text{ s}^{-1} \) at \( \sim 70–75 \text{ km} \) height increases to \( \sim 10^5 \text{ s}^{-1} \) at \( \sim 40 \text{ km} \) which corresponds to frequencies of \( \sim 100 \text{ kHz} \). This growth rate and the time scale of the sprite streamer development \( \sim 5–10 \mu \text{s} \) imply a radiated magnetic field of \( \sim 10^{-17}–10^{-16} \text{ T} \) at a distance of \( \sim 600 \text{ km} \) [Qin et al., 2012a, Figure 4]. The corresponding electric field strength \( E \) of the radiation from one sprite streamer is

\[
E = Z_0 H \approx 3–30 \text{ nV m}^{-1},
\]

where \( Z_0 = (\mu_0/\varepsilon_0)^{1/2} \approx 120\pi \Omega \) is the free space wave impedance. The electric field strength is further reduced to \( \sim 1.6–16 \text{ nV m}^{-1} \) by an attenuation of \( \sim 5.3 \text{ dB/Mm} \) [Füllekrug et al., 2009] during the subionospheric propagation to the radio receiver \( \sim 1400 \text{ km} \) away. The number of sprite streamers is then calculated to be \( \sim 300–5000 \) by using the ratio of the observed electric field strengths \( \sim 5–8 \mu \text{V m}^{-1} \) to the theoretically predicted value \( \sim 1.6–16 \text{ nV m}^{-1} \) for one streamer. The more continuous smaller enhancement of the background radiation \( \sim 4–5 \mu \text{V m}^{-1} \text{Hz}^{-1/2} \) \( \sim 2–4 \text{ dB} \) suggests an \( \sim 1 \text{ s} \) long persistence of weaker background radiation, possibly from sprite streamers at lower heights above the thundercloud. The optical detection of these streamers remains a substantial challenge as a result of the strong absorption of optical wavelengths in the atmosphere.

[6] Although the experimental results lend support to the theory of Qin et al. [2012a], it is intuitively tempting to
associate the observed electromagnetic background radiation with ordinary lightning strokes inside thunderclouds, even though there is not much experimental evidence for it. For example, sprites are usually initiated by positive lightning discharges [Boccippio et al., 1995] and this is confirmed here for 36 out of 39 sprites by broadband electric field measurements with a dipole antenna [Farges and Blanc, 2011] near Rustrel (43.9°N, 5.5°E) ~600 km away from the sprites. Yet, the sprites coinciding with the sudden enhancements of the electromagnetic background radiation at ~01:12:59.602, ~01:47:11.741, and ~01:47:12.401 are not initiated by intense positive lightning discharges as evidenced by the absence of corresponding vertical electric field signatures recorded with the dipole antenna near Rustrel and the absence of lightning strokes recorded by the Lightning Network (LINET) and the Météoré Lightning Detection Network. In addition, impulsive lightning strokes typically discharge the electric field inside thunderclouds on time scales ~0.1–1 ms [Rakov and Uman, 2003, p. 8 and 215] which have virtually no effect on the observed electromagnetic background radiation even if many more and stronger lightning strokes occur (Figure 2, bottom image of left panel). As a result, it is difficult, if not impossible, to understand the observed electromagnetic background radiation as the superposition of many individual lightning strokes with varying intensity inside the thundercloud. Finally, the absence of any luminosity in video observations does not necessarily imply the absence of streamers above thunderclouds as a result of the strong absorption of optical wavelengths in the atmosphere. In fact, the larger sensitiv-

ity of radio measurements to electric current in comparison to optical measurements might actually help to quantify the density of visual and subvisual streamers above thunderclouds which is an important parameter for sprite modeling [Pasko, 2010].

On the other hand, it is currently not possible to exclude any doubt that the superposition of low-frequency radiation from numerous horizontal lightning pulses, e.g., stepped leaders inside thunderclouds, might produce the electromagnetic background radiation reported here. For example, sferic bursts are thought to result from numerous lightning pulses which coincide with bursts of stepped leaders inside thunderclouds and can last up to ~1 s [Marshall et al., 2007; Marshall and Inan, 2007; van der Velde et al., 2006; Ohkubo et al., 2005]. In this picture, the quick succession of consecutive lightning pulses from radiating stepped leaders might blend into the slowly varying background radiation observed here, possibly assisted by wave propagation effects. However, to the best of our knowledge, there is currently no scientific rationale to describe the transition from Poisson-distributed lightning return stroke intensities [Chrisian and Fraser-Smith, 2003] or stepped leaders to smoothly varying low frequency background radiation. On the other hand, the mere absence of such kind of theory does not exclude the possibility of this blending process to occur. But this hypothetical theory would definitely describe a fundamentally novel quasi-static discharge process inside thunderclouds which radiates slowly varying low frequency radio noise.

In summary, it is concluded that the observed electric field strengths from the slowly varying low frequency electromagnetic background radiation place an upper bound on the predicted low frequency radiation from sprite streamers with a potential contribution from horizontal lightning strokes and/or stepped leaders which remains to be quantified in future studies. From an experimental point of view, it seems therefore vital to investigate the relationship between low frequency radio noise, stepped leaders inside thunderclouds and sprite streamers above thunderclouds in much more detail than previously thought.

4. Summary

Sprite luminosities coincide with ~10–30 ms long sudden enhancements of the electromagnetic background radiation ~6–8 [$\mu$V m$^{-1}$ Hz$^{-1/2}$] in the frequency range ~1–400 kHz with a relative maximum near ~125 kHz. The sudden enhancements are superimposed on ~1 s long enhancements of the electromagnetic background radiation ~4–5 [$\mu$V m$^{-1}$ Hz$^{-1/2}$] (~2–4 dB). The observed electric field strengths place an upper bound on the predicted low frequency radiation from the electron multiplication associated with the exponential growth and branching of sprite streamers. This upper bound corresponds to a maximum of ~300–5000 sprite streamers at ~40 km height. Some part of the observed electromagnetic background radiation might result from the superposition of low-frequency radiation from numerous lightning strokes and/or stepped leaders inside thunderclouds which would constitute a fundamentally novel quasi-static discharge process inside thunderclouds radiating slowly varying low frequency radio noise.
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