Properties of Sprite Parent Lightning for a Storm on 6 August 2013

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Abstract. We analyze parameters of lightning discharges parent to sprites observed in Nýdek, Czechia and in Sopron, Hungary, during a storm over Central Europe on 6 Aug 2013. Magnetic field waveforms were recorded in Nový Kostel, Czechia. Locations and energies of lightning discharges were provided by the World Wide Lightning Location Network. We find that the mean energy of 11 sprite-parent lightning (28 kJ) is substantially larger than the mean energy of 91 non parent lightning discharges (18 kJ).

Introduction

A large multi-core mesoscale convective system occurred over Central Europe on 6 August 2013. Numerous lightning discharges and transient luminous events (TLEs) called sprites occurred in this storm. In this paper, we are focusing on extremely low frequency waves (ELF, between 3 Hz and 3 kHz according to convention used in atmospheric sciences) and very low frequency waves (VLF, between 3 and 30 kHz) emitted by lightning. These waves can propagate to large distances in the Earth-ionosphere waveguide [*Barr et al.*, 2000] which allows us to record electromagnetic signals from distant source discharges. Transient luminous events are also studied remotely using optical video recordings.

Sprites are branches (streamers) of red light which extend between altitudes of about 40 km to 90 km; sprite channels are weakly ionized [*Neubert*, 2003]. Halos are brief descending glows which are, just as sprites, produced mainly by quasi-electrostatic field of a storm cloud [*Pasko et al.*, 1997, *Barrington-Leigh et al.*, 2001]. The descent rate of a halo is roughly controlled by the local electrostatic relaxation time (the local permittivity divided by the local conductivity) [*Barrington-Leigh et al.*, 2001]. Sprites can be preceded by halos, but both halos and sprites can also occur independently. By recording sprites at two different sites, their location can be triangulated [*Młynarczyk et al.*, 2015, *Wescott et al.*, 2001]. Sprites can have large horizontal displacement from their parent lightning strokes. *Wescott et al.* [2001] reported a mean horizontal offset of 25.2 ± 18.8 km and *Lu et al.* [2013] found that the mean horizontal offset was 17 km for prompt sprites (<20 ms after the parent stroke) and 45 km for delayed sprites (>20 ms after the parent stroke). However, *São Sabbas et al.* [2003] found no difference in sprite-lightning horizontal offset between prompt and delayed sprites.

The probability of occurrence of a sprite related to a given stroke can be determined from the time scale (TS) and the charge moment change (CMC) of the stroke. The TS of a lightning discharge is the whole recognizable duration of a lightning stroke (return stroke + continuing current, if present).

The CMC is defined as time integral of a current moment along a vertical lightning channel $M_I(t)$. If the time interval for integration is the TS, then the CMC is called total charge moment change [*Huang et al.*, 1999]. If the time interval for integration are the first few ms after the return stroke, then the CMC is called impulsive charge moment change [*Lu et al.*, 2013, *Hu et al.*, 2002]. More details about CMC and TS and their relation to sprite-halo generation can be found, e. g., in [*Špačková et al.*, 2017]. Besides the CMC and TS of a stroke, the peak current or energy of a discharge can be estimated. *São Sabbas et al.* [2003] showed that the peak current distribution of sprite-generating discharges is more flat and spans to higher peak currents than that of non-sprite-generating discharges. *Qin et al.* [2013] showed that the peak current determines the halo luminosity.

Instrumentation and Data Analysis Methods

Optical images were recorded in Nýdek, Czechia (49.668N 18.769E) and in Sopron, Hungary (47.6837N, 16.5830E). The distance between the two stations is 273 km. Both sites use cameras with an optical resolution of 720 x 576 pixels and 50 video frames per second (deinterlaced). TLEs are identified using the UFOCapture software (a similar technique was used by *Bór et al.*, 2009). Locations of sprites are determined using the UFOAnalyzerV2 software. In this software, an azimuth angle of a sprite can be identified by comparison of the star background with a star map at that time. Using the azimuth angle, the distance to a sprite (and then its location) and its altitude range are derived by the software based on the two assumptions: the sprite top should be in a range of 80-85 km and sprite top and bottom should be above the same point on the earth's surface. This mechanism introduces an inherent location uncertainty on the source-observer line due to the assumption of the top altitude. More accurate location can be derived by observing the same sprite from at least two stations and by triangulation [*Wescott et al.*, 2001]. It was necessary to know the occurrence times of the captured optical events accurately in order to identify the corresponding events in other datasets. In Nýdek, only approximate PC time was available while GPS time stamps with millisecond accuracy were used in Sopron. Accurate observation times of optical events recorded in Nýdek were found by analyzing 4 complex sprite events which were captured simultaneously from both sites. Difference between observation time of the same sprite recorded in Sopron and in Nýdek was 3.892 s for all simultaneously captured sprites in these 4 complex events. This time difference was then used to correct the recorded observation times in Nýdek.

The location and the energy E of the parent lightning strokes used in this study were provided by the World Wide Lightning Location Network (WWLLN). The network stations operate at frequencies of 6-18 kHz in the VLF range with a sampling frequency of 48 or 50 kHz. Besides the location and the energy, the network provides the time of occurrence in microseconds, an error in energy estimation for each detected lightning discharge and the number of stations used for the calculation of stroke location and for the estimation of the stroke energy. The network consisted of more than 70 stations in September 2013 [*Hutchins et al.*, 2014]. The network detects both cloud-to-ground (CG) and intracloud (IC) discharges; although, the detection efficiency is greater for CG than IC discharges [*Rodger et al.*, 2005, *Abarca et al.*, 2010]. This can be explained by the fact that WWLLN tends to detect discharges with higher peak currents [*Abarca et al.*, 2010]. To compare WWLLN-based data with other measurements, the peak current I_{peak} in kA can be converted to the energy E_{stroke} radiated by a stroke between the frequencies 6-18 kHz and estimated by WWLLN (in Jouls) by a relation [*Hutchins*, 2014]:

$$E_{\text{stroke}} = 2.23|I_{\text{peak}}|^{1.62}. \tag{1}$$

The measurement site of ELF waves generated by lightning, which belongs to the Geophysical Institute of the Czech Academy of Sciences, is located in a rural area in Nový Kostel (NK), Czechia (50.232N, 12.447E). One horizontal magnetic-field antenna, whose search coil axis is oriented approximately in the northeast-southwest direction, is sheltered inside a wooden cottage. Before sampling, a low-pass filter is applied. A low-pass filter with a cut-off frequency of about 8 Hz is used because the antenna was originally intended to measure possible electromagnetic precursors of seismic activity. After the filtering, the data are sampled with a frequency of 800 Hz and combined into groups of 16 samples. The GPS time is always assigned to a group which contains a whole minute GPS time stamp. Then a simple moving average is calculated over 32 samples while the averaging window moves forward by groups of 16 samples after each computation of the average. This mechanism results in the final 50 Hz sampling rate. Time is always attributed according to the stamp of the second group of 16 samples in each averaging window. As the minute stamp can occur at any time in the second half of the time stamped window, this mechanism introduces an inherent time uncertainty between -20 ms and 40 ms. A group delay of about 70 ms introduced by the low pass filter is accounted for in the calibration process. Return stroke pulses belonging to discharges included in this study were manually identified in the magnetic field waveforms. A full-width-at-half-maximum (FWHM) and a peak amplitude as a difference between the extreme value and the mean noise background were estimated for return stroke pulses, whenever it was possible.

The records from WWLLN, Nýdek and NK were examined for common events. A sprite recorded in Nýdek was matched with its parent lightning discharge in NK or WWLLN records if the time difference defined as time in NK or WWLLN subtracted from time in Nýdek was within a range of [-170 ms, 40 ms]. The positive limit of this interval was chosen as a sum of all possible differences (20 ms – a video field, 20 ms – a time resolution in NK); the negative limit (170 ms = 20 ms video + 20 ms time resolution + 130 ms) is larger because a sprite-parent discharge can precede its sprite by up to 130 ms [*Li et al.*, 2008, *Lyons et al.*, 2003]. A lightning discharge was considered as matched in the WWLLN and NK records if the return stroke pulse peak in NK occurred between the preceding and the following sample before/after the time of the stroke reported by WWLLN. This selection was based on the mechanism of the time stamping described above. Peaks in NK waveforms of 61% of all matched discharges occurred in the sample whose time immediately follows the time of the stroke reported by WWLLN.

From the known WWLLN location, the great-circle distance r and an azimuth angle ϕ_0 from a lightning stroke to the measurement site in NK were computed using a spherical model of the Earth's surface. To obtain the angle ϕ of arrival of magnetic field to our magnetic antenna, the angle of the search coil axis with respect to the geographic North was roughly estimated and added to the azimuth angle ϕ_0. To remove the effect of the arrival angle ϕ, a corrected magnetic field $y \equiv \frac{B_{exp}}{\cos\phi}$ is defined. It should be also noted that an azimuthal offset of $-10°$ was used to compute the corrected magnetic field. This correction is based on our previous findings [*Špačková et al.*, 2017] and can be explained by the inaccurate estimation of the azimuth of the antenna. Another possible explanation is based on the observations of a systematic azimuthal shift of ELF measurements of lightning waveforms reported by *Greenberg et al.* [2007] and *Bór et al.* [2016].

Observations

Locations of 72 sprites, one sprite-halo and one halo event registered between 19:37 and 00:49 UTC from Nýdek, Czechia, are shown on the map (Fig. 1). The area and time duration used for examination of NK or WWLLN records was chosen to be slightly larger than the area and time duration of optical observations from Nýdek. Therefore, the storm is considered to last between 19:35 and 00:51 UTC and the considered area of the storm extends between 47.7° and 50.4° N and 10.9° and 15.3° E. Tab. 1 shows the number of events registered by different measuring sites and the number of events included in the statistics. The missing detections in NK can be explained by a strong artificial noise present in the time of a missing detection or by the fact that the respective lightning discharge occurred in a direction in which the antenna has a low sensitivity. All sprites and halos in this study were produced by positive discharges. This is in accordance with expectations as almost all sprites are produced by positive cloud to ground strokes [*Williams et al.*, 2007]. Lightning discharges which did not generate sprite were found to be also positive with an exception of only 4 cases. This is in contrast with expectations as a the fraction of positive CG discharges is usually about 10 percent [*Orville and Huffines*, 1999]. This discrepancy can be caused by the above-mentioned fact that the WWLLN tends to measure lightning discharges with higher peak current. We might also hypothesize that the observed sprite-producing thunderstorm had unusually large reservoir of positive charges which led to an abnormal fraction of positive lightning.

Figures 2a and 2b show the distributions of energies and peak currents, respectively, of discharges detected by WWLLN. The energy radiated by a stroke was converted to peak current values using the equation (1). From the four negative non-sprite-parent discharges, two had a reliable energy (see Tab. 1), namely of 8.9 kJ and 11.8 kJ. Mean and median energies and computed peak currents of sprite-parent discharges and non-sprite-parent ones detected during the storm are shown in Tab. 2 for the two discharge polarities, along with the number of events in the categories.

Table 1. Number of events registered by different measuring sites and number of events included in the statistics. Non-sprite-parent discharges are in black, sprite-parent discharges in red.

measuring site	found	in statistics	remaining events excluded because
WWLLN	180 + 17	91 + 11	experimental energy error >70% of energy & energy estimates based <3 stations (Rodger et al. [2017], 32 URSI Gen. Assem.)
Nový Kostel	80 + 61	64 + 61	FWHM could not be assigned
Nýdek	72 (including 1 halo and 1 sprite-halo events)		

Fig. 2c shows the distribution of corrected magnetic field peak amplitudes of the return stroke pulses belonging to lightning discharges recorded in NK. In this figure, 64 non-sprite-parent and 61 sprite-parent discharges are plotted. For the computation of the arrival angle of the magnetic field from a sprite-parent discharge to the antenna, a sprite location was chosen for the cases when a location from WWLLN was not available. *Wescott et al.* [2001] found an average 25 km offset between a sprite and its parent lightning stroke by a triangulation. Based on this offset, the azimuth angle to the parent discharge from NK can be displaced up to 7° for a distance of 200 km. This displacement translates to an error in a corrected peak amplitude of the return stroke pulse of the parent discharge up to 80% for discharges perpendicular to the search coil axis in NK and up to 0.8% for discharges parallel with the search coil axis in NK. The average peak amplitude of return stroke pulses of sprite-parent discharges is 65.5 ± 42.1 pT. The average peak amplitude of return stroke pulses of non-sprite-parent discharges is 14.0 ± 11.0 pT. The peak amplitude of return stroke pulse of a discharge parent to one halo event is 129.2 pT and the peak amplitude of return stroke pulse of a discharge parent to one sprite-halo event is 43 pT.

The distribution of full-width-at-half-maxima of return stroke pulses is shown in Fig. 2d. The average FWHM of pulses belonging to 61 sprite-parent discharges is 83 ± 40 ms. The average FWHM of pulses belonging to 64 non-sprite-parent discharges is 58 ± 17 ms. Values of 298 ms, in case of sprite-parent discharges, and 250 ms, in case of non-sprite-parent discharges, are significantly than other values; hence, they are considered as outliers. One possible explanation of such large FWHM can be two strokes so close in time that their peaks in magnetic field records merge into one. The FWHM of return stroke pulse of a discharge parent to one halo event is 48 ms. This short FWHM is in accordance with expectations as halos can occur only after impulsive discharges [*Adachi et al.*, 2008]. The FWHM of return stroke pulse of a discharge parent to one sprite-halo event is 67 ms.

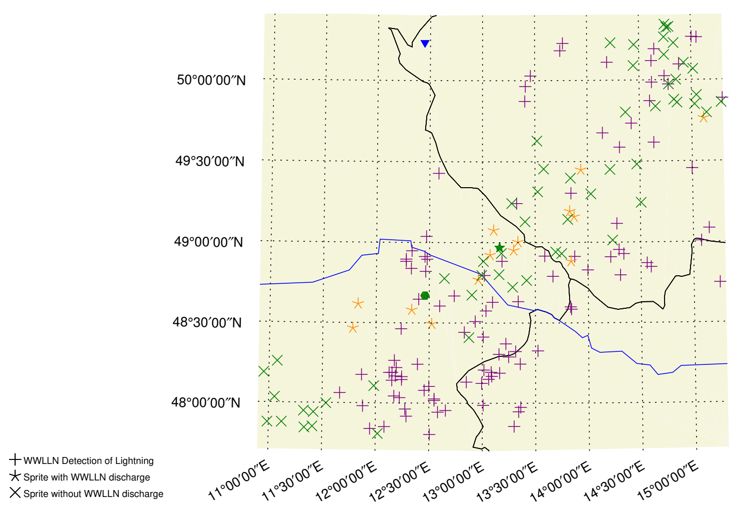

Figure 1. Storm on 6 August 2013 with locations of sprites (with WWLLN discharge – orange and without WWLLN discharge – green signs), a halo (green hexagon) and a sprite-halo (green star) recorded in Nýdek, lightning discharges (purple crosses) measured by WWLLN and measuring site in Nový Kostel (blue triangle). Locations of sprites can have a significant error as they are based on observations of only one site. This inaccuracy is not marked in the map.

Table 2. Mean and median energies (E) and peak currents (I_{peak}) of different groups of lightning.

category	number	mean E [kJ]	median E [kJ]	mean I_{peak} [kA]	median I_{peak} [kA]
with a TLE (all positive)	11	28.4 ± 13.4	25.4	334 ± 97	319
without a TLE	91	18.1 ± 18.6	11.4	233 ± 147	195
positive without a TLE	89	18.3 ± 18.8	11.4	234 ± 149	195
negative without a TLE	2	10.3 ± 2.0	–	183 ± 22	–

Discussion and Conclusions

We analyzed a storm of 06 August 2013. We captured 72 sprites in Nydek and found 197 lightning discharges in the records from the World Wide Lightning Location Network. The median energy 25.4 kJ for sprite parent discharges is larger than the median energy 14.1 kJ for non-sprite-parent ones. We can compare our results with *Chen et al.* [2014] who found that the median energy of sprite-parent discharges occurring between May 2009 and December 2012 was 7 kJ and the median energy of all lightning discharges detected globally in the same time interval was 0.9 kJ. The median energy of all lightning occurring globally during the storm on 6 August 2013 is 3.4 kJ. Hence, median energies found by *Chen et al.* [2014] are approximately 3.5 times smaller than median energies of discharges from the storm of 6 August 2013. Nevertheless, the ratio of mean energies of sprite parent discharges and all discharges occurring globally during the same time interval estimated for the storm on 6 August 2013 and the same ratio reported by *Chen et al.* [2014] are very similar (7.5 and 7.8).

We also analyzed return stroke pulses in the horizontal magnetic field waveforms recorded in Nový Kostel. The average peak amplitude of return stroke pulses belonging to 61 sprite-parent discharges (65.5 pT) is approximately four times larger than the average peak amplitude of return stroke pulses belonging to 64 non-sprite-parent discharges (14.0 pT). This means that lightning discharges with larger

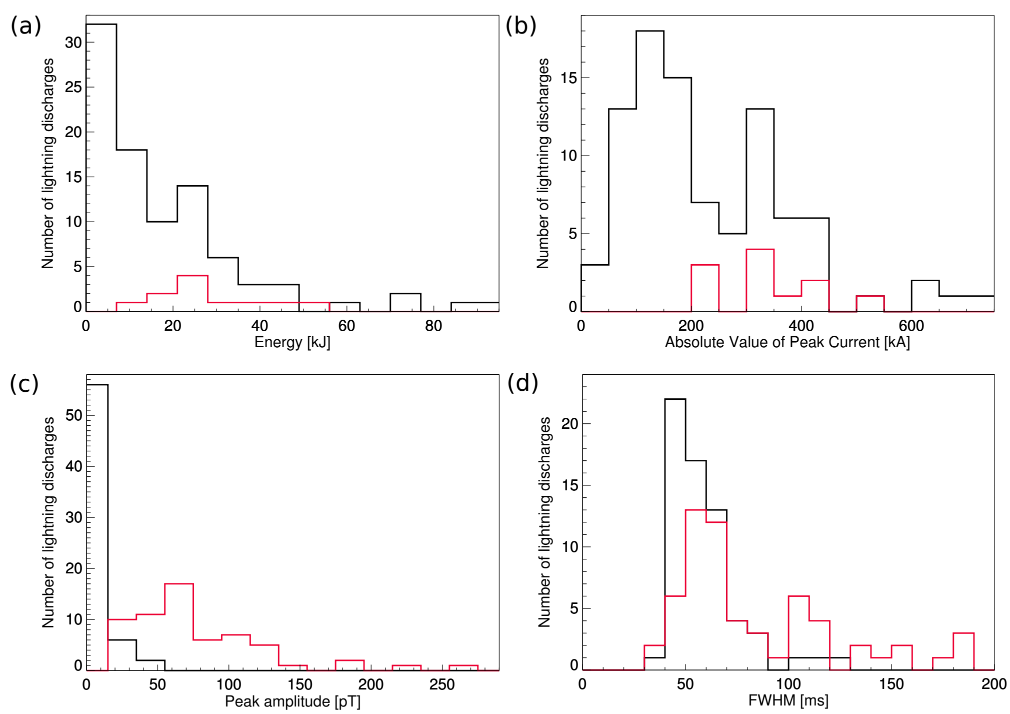

Figure 2. In all figures, black represents non-sprite-parent discharges, red represents sprite-parent ones. (a) Energy distribution. (b) Peak current distribution. (c) Distribution of magnetic field peak amplitudes of return stroke pulses. (d) Distribution of the full-width-half-maxima of return stroke pulses. Outlying values of 298 ms, in case of sprite-parent discharges, and 250 ms, in case of non-sprite-parent discharges, are not shown.

energies or return strokes pulse peak amplitudes show higher probabilities to generate sprites. Also, the mean full-width-half-maximum of return stroke pulses of sprite-parent lightning discharges (83 ms) is larger than these of non-sprite-generating discharges (58 ms). This indicates longer continuing currents occurring in sprite-generating discharges.

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