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Theses of doctoral (PhD) dissertation

Studying lightning discharge related upper atmospheric transient luminous events and Schumann resonance transients

József Bór

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Supervisor:
Dr. Sátori Gabriella, candidate of Earth science

Introduction

Atmospheric electricity is one of the background constituents of our environment, the direct impact of which to our everyday life is occasional. Such events are mostly related to lightning discharges [Rakov and Uman, 2003]. Atmospheric electricity, however, provides a simple and economic way to explore and follow other processes in the nature which have well defined connection with it. Probably the most common example for this is the forecasting of severe weather by detecting electromagnetic radiation from lightning flashes.

Transient luminous events (TLEs) are various brief optical emissions between the top of the thunderclouds and the lower boundary of the ionosphere. These emissions are consequences of occasional, intensive flow of electromagnetic energy and charge in the upper atmosphere up to 90-100 km height [Füllekrug et al., 2006]. In this manner, they are similar to tropospheric lightning flashes as being indicators of the electric activity in the atmosphere. The properties of these events, as well as their interactions with other elements of the environment need to be found, so their role and importance in the global electric circuit can be fully mapped and the possibility of their utilization in exploring our atmosphere can be revealed. Some of the TLEs are initiated in a short lived quasi-static electric field that builds up between the thundercloud and the ionosphere following intense lightning discharges. The charge moment change (CMC) of the causative lightning flash is an important parameter that characterizes the strength of the evolving quasi-static field. The CMC in lightning flashes can be remotely and relatively easily estimated from the extremely low frequency (ELF, 3-3000 Hz) radiation of the discharge.

Schumann resonance transients (SRTs, or Q-bursts) are signals of relatively high energy wave packets in the lower ELF band. These wave packets originate from individual, intense lightning flashes and they can propagate global distances in the Earth-ionosphere waveguide. Far from the source, their energy is mostly concentrated near the lowest electromagnetic resonance (Schumann resonance-SR) frequencies of the spherical thin shell shaped waveguide [Nickolaenko et al., 2010]. Polarity, location, current moment and CMC of source discharge can be deduced from the recorded time series of the SRTs. Many TLEs has a parent lightning discharge that also produces a SRT [Boccippio et al., 1995], so using the SRTs to study the electric environment required for the initiation of TLEs is plausible.

While the global occurrence rate of lightning flashes is about 50 events on average, generally only 1-2 SRTs can be observed per minute. This usually makes it possible to process the observed SRTs individually, which not only does help in determining the parameters of the source discharge, but also enables the examination of the momentary state of the waveguide. Large amplitudes of the SRTs and their coherent appearance in the electric and magnetic field components separate them from the background ELF signal, which is always present due to the activity of many average lightning discharges. In this background ELF signal, the integrated and superimposed effects of the global distribution and activity of the sources as well as those of the geometric and electromagnetic properties of the waveguide are present simultaneously, so the investigation of the contribution of individual factors is more difficult [Nickolaenko and Hayakawa, 2002; Price et al., 2007].

Aims of the study

The aspirant has set himself to deduce the polarity and CMC of TLE producing lightning flashes in different areas of Europe as well as on the globe from time series of SRTs recorded in the István Széchenyi Geophysical Observatory of the Hungarian Academy of Sciences (NCK). He also wished to compare the deduced values with those from other similar investigations and observations by other research groups.

Another aim of the study was to examine whether any distortion of lightning parameters deduced from SRTs occurs if the ELF waves propagating between the source and observer pass through the day-night terminator line of the Earth-ionosphere waveguide as it has been suggested by the results of background SR observations [Sátori et al. 2007].

The aspirant has also initiated the observations of TLEs in Central Europe from Sopron, Hungary. His aim was to study the occurrence rate, optical properties, and initiation conditions of TLEs in the region and to compare the findings with results of other observations of such events around the world.

Performed work and applied methods

The aspirant looked through the established methods for processing SRT data and selected the one which fits the best to the parameters of the ELF recording station in the István Széchenyi Geophysical Observatory. He coded each segments of the processing, improved the performance of the original method at some steps and created a software package in Matlab 4.2c environment. He developed a Windows 32 bit application in C++ language for displaying the raw data recorded by the data acquisition system.

He examined the records of NCK station, as well as the records of the ELF observatory near Mitzpe Ramon, Israel to find SRTs which originate from the same lightning flashes. He located the sources, deduced the current moment spectra at both stations, and evaluated the ratio of the corresponding spectra for each source discharge. Then, the results were grouped according to the positions of the recording stations and the source relative to the day-night terminator line, and the ratios of the current moment spectra were compared among elements inside each group and among the different groups to find signatures of the effect of crossing of the day-night terminator line above the stations.

SRTs from parent lightning flashes of red sprite type TLEs detected above Western Europe in 2003 and 2005, above the Eastern Mediterranean region near Israel between 2005 and 2009, and above Middle-West Africa near Niger in 2006 were identified in the records of NCK station by the time of optical observation. The CMC of the sources was deduced and the distribution of the values was examined and compared to CMC statistics of sprite producing lightning flashes in North America and Japan.

Again, time points of optical observations were used to find SRTs which corresponded to satellite based sprite halo type TLE detections. Distribution of deduced source polarities and CMC values was compiled and compared to a distribution characteristic to red sprites. The relation of the source CMCs to the brightness of sprite halos was also examined.

Utilizing the experiences of previous observation campaigns, the aspirant set up an optical observation system in Sopron, Hungary. He used that system together with lightning location information from the LINET lightning detection network to record TLEs in Central Europe starting from 2007. He also developed a driver program in C++ language to remotely direct the camera towards the actual region of interest.

Using LINET as well as very high frequency SAFIR lightning data, as well as other optical images from a nearby Slovakian observation site, he analyzed some of the properties of the TLEs in Central Europe on the grounds of the observations in 2007: the distribution of offsets between the causative flash and the appearance of the emission in space and time, the size of the emissions, and in case of grouped events the configuration of the members of the group. These properties were analyzed separately for different TLE types and emission shapes when it was possible. The results were compared to findings made upon similar observations in other regions and continents. The aspirant investigated the possible relation of the type of the appearing TLE to the peak current of the parent lightning flash, and to the height of causative cloud discharges as well. These parameters of the TLE producing lightning flashes were also compared to those of non TLE producing ones.

New results and achievements

1. Current moment spectra of several lightning discharges were deduced at two well separated observatories from their SRTs in the horizontal magnetic components of the atmospheric electromagnetic field. Characteristic difference between the current moment spectra of the same source could be found only when the receiving stations were on different sides of the ionospheric day-night terminator line. In such configuration, if the source was on the day side, spectral amplitudes below 19-20 Hz appeared to be lower at the night side receiving station than those at the day side station by 20% on average. This finding supports the conclusions drawn from background SR observations, namely that passing the day-night terminator line does have a considerable effect on the amplitudes of ELF waves [Sátori et al. 2007]. When the source was on the night side, spectral amplitudes of the deduced current moment spectrum were found to be higher at the observatory on the day side, but only above 25 Hz (note that signals only in the 5-30 Hz band were examined). For events with such a scenario, however, the variance of the current moment ratios was higher, so the conclusion drawn for the latter case needs to be verified by additional studies.

2. The order of magnitude of the CMCs as well as the distribution of the values from Western European, Eastern Mediterranean, and Middle-West African red sprite producing lightning discharges do not differ significantly and better resemble the CMC statistics of sprite producing lightning flashes in North America, than those observed in Japan. This result is unexpected for the Eastern Mediterranean events, for which the TLEs has been produced in winter thunderstorms with similar characteristics to those in Japan but with different structure as the summer continental thunderstorms. This result suggests that the actual dynamics and local factors (e.g. aerosol concentration) can be more important in sprite initiation than the general/average structure of thunderstorms.

3. The majority of sprite halos are produced by negative polarity parent lightning flashes. Sprite halos can more frequently be observed over sea or over continental coastlines than over land. These results are generalizations of the analogous findings by Frey et al., who have made their conclusions upon the examination of such events above North America [Frey et al., 2007]. Positive polarity sprite halos, on the other hand, seem to be equally frequent above land and above sea and less frequent above coastlines.

   A weak positive correlation was found between the brightness of sprite halos and the CMC of their parent lightning flashes independently of their polarity. This result indicates that the final brightness of this type of TLE is driven by factors which are not exclusively linked to the CMC of the parent lightning discharge. Identifying the factors which modulate the total number of emitted photons requires further studies.

4. A new TLE observation station has been established in Sopron, Hungary which provides a high number of good quality records of upper atmospheric optical emissions above Central Europe and works reliably since its installation.

   According to the observations, time delays between the appearance of red sprites and their parent lightning flash form three groups: short delays below 30 ms, long delays above 100-110 ms and intermediate delays between these two values. Most frequently short time delays (around 10 ms) can be found in Central Europe, which seem to be a common experience in case of summer continental sprites as the

same has been observed in Western Europe and in North America. Winter sprites above Eastern Mediterranean thunderstorms and those near Japan have characteristically longer time delays.

The distributions of time delays for sole and multiple (grouped) red sprite emissions are mostly similar independently from the shape of the emission (carrot, 'V', or column). The only exceptions to this rule are the cases of grouped columniform sprites, where no time delays longer than 30 ms has been observed.

According to TLE observations in more regions of the globe it seems to be a common property of sprite halos to appear right after (+ ~1 ms) their parent lightning discharge. Another time delay related finding which seems to be generally valid is that long time delays (>100 ms) for red sprites may occur only together with relatively smaller peak current parent flashes (<50 kA), while for very high peak current parent flashes (>100 kA) the encountered time delays are at most intermediate (< ~60 ms). TLE observations in Central Europe from Sopron fully support this experience.

5. Red sprites in Central Europe are not different from other red sprites observed around the world in that the peak current of their parent lightning discharge is usually above the average value for general lightning flashes, but at the same time the peak current is not determinative regarding their appearance. On the other hand, Central European observations suggests that although high peak current values are not necessary conditions for the appearance of sprite halos, lightning discharges with peak currents above ~110 kA are almost certainly to produce such emissions.

6. Red sprites most frequently appear horizontally shifted from their parent lightning flash. In Central Europe, the most frequent offset was 10-15 km for columniform sprites, while for carrot sprites there were two maxima in the distribution: one at 5-10 km and another at 23-30 km. The distribution of offsets (especially that for column sprites) fits well to the distributions found in North American sprite observations.

   Heights of the few observed red sprite and sprite halo producing cloud discharges suggest that such lightning flashes probably don't occur in the lower section of the thundercloud.

7. All columniform sprites produced by a single lightning flash seem to occupy the same height region. The altitude and vertical extension of the height range occupied by columniform sprites and sprite clusters produced by different parent lightning flashes varies considerably inside the 65-86 km height region.

   The vertical extension of the brightest, central part of carrot sprites is less variable; it is mostly between 9 km and 16 km. This central part of carrot sprites usually appears lower than column sprites. This latter result supports those similar conclusions which were drawn from triangulation of high speed camera images of sprites in North America [Stenbaek-Nielsen et al., 2010]. The diffuse top of carrot sprites almost always reach up to 86-89 km, independently from the length of the central region.

8. Simultaneously appearing sprites with circular symmetry or even with a biased variant of it are less frequent than those emission clusters or groups in which the spatial distribution of the members is (at least seemingly) random.

   In some cases, the orientation of the discharge channel of the parent lightning flash is similar to the direction of vertical tilting of the sprites, or to the tilting of the vertical symmetry axis of sprite groups with a biased symmetry. This observation fully supports modeling results, which indicate that the geometry of the emissions and the

orientation of the discharge channel of the parent lightning discharge are in fact related [Asano et al., 2009].

Exploitation of results

On one hand, the results in this thesis help to understand the nature of the interactions between the non-uniformities (in this case the day-night asymmetry) of the Earth-ionosphere waveguide and the propagation of ELF electromagnetic waves. This information can be used to correctly interpret the various quantities deduced from these electromagnetic waves. On the other hand, the properties of various TLEs were examined in Central Europe, where such investigation has not been carried out before. The results of the TLE related investigations help to separate common, global characteristics of these upper atmospheric electro-optical emission from those which mirror local or regional effects. The optical observation system established by the aspirant has proved to be a useful tool and it continues to serve upper atmospheric research in Central Europe.

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