# SPRITES AND PARENT THUNDERSTORMS

*A. Savtchenko*[1], *R. Mitzeva*[2]

[1]Sofia University, Faculty of Physics, Department of Meteorology and Geophysics, 5 James Boucher Blvd., 1164 Sofia, Bulgaria, e-mail: asavtchenko@phys.uni-sofia.bg
[2]Sofia University, Faculty of Physics, Department of Meteorology and Geophysics, 5 James Boucher Blvd., 1164 Sofia, Bulgaria, e-mail: rumypm@phys.uni-sofia.bg

**Abstract.** Sprites are a very fascinating member of the huge and varied family of Transient Luminous Events (TLEs), sometimes called also “high-altitude lightning”. Topic of extensive scientific research in the past decade, they are thought to be an interesting addition to the tropospheric lightning activity and an important participant in affecting the global atmospheric electric circuit and atmospheric circulation. Several theories have tried to explain the strange nature of sprites though there are still many unanswered question waiting to be uncovered. The present paper summarizes the known facts related to sprites according to the existing literature in the field of sprite research. The physical and optical properties of sprites are revealed as well as the physical mechanisms for their generation. The methods of detection are briefly introduced and some concepts of the numerical modeling of sprites are given. An attention is paid also to the characteristics of sprite-parent lightning and thunderstorms.

**Key words**: Sprites, positive cloud-to-ground lightning, thunderstorms

## Introduction

Since more than a century, various stories and reports appeared periodically in the scientific editions and magazines referring to amazing lights and fireworks high above active thunderstorms (Lyons et al., 2000). Because of lack of existing so far terms for such features, the observers used appellations as varied as “upward lightning,” “rocket lightning,” “cloud-to-stratosphere lightning,” and even “cloud-to-space lightning”. Even thou one of the reports was coming from the Nobel Prize winner in physics C. T. R. Wilson (Wilson, 1925), the atmospheric electricity community disregarded the amateur findings as missing hard evidence. On the night of 6 July 1989, while testing a low-light television camera (LLTV) for an upcoming rocket launch, John R. Winckler of the University of Minnesota made a fascinating and breath-taking discovery. Two frames of the video tape revealed brilliant columns of light extending far into the stratosphere above distant thunderstorms (Franz et al., 1990). This single documented observation activated scientists from disciplines as diverse as space physics, radio science, atmospheric electricity, atmospheric acoustics, and chemistry as well as aerospace safety, to explore the linkages between tropospheric thunderstorms and lightning in the middle and upper atmosphere. Being apprehensive about the safety and possible impacts on aerospace vehicles, the National Aeronautics and Space Administration (NASA) immediately initiated a review of video tapes from the space shuttle payload bay LLTV employed to image mesoscale lightning events. The investigation revealed over a dozen events appearing to match Winckler's observation (Boeck et al., 1998). On 7 July 1993, the first night of observation at the Yucca Ridge Field Station near Fort Collins, Colorado, Lyons (1996) documented over 240 sprites. Evidently they were not a rare occurrence. On the very next night, LLTV cameras onboard the NASA DC-8 detected huge flashes above a large thunderstorm complex in Iowa (Sentman and Wescott, 1993).

With the rush of discoveries, confusion soon arose regarding scientific terminology. Winckler and his colleagues initially termed their discovery a "cloud-to-stratosphere (CS) flash." Press reports frequently referred to "upward lightning" or "cloud-to-space lightning." But little was known of the underlying physics of these transient illuminations. Was it "lightning?" In which direction did it really propagate? Did it connect the cloud top with "space"? To avoid assigning a name that might later need revision, Davis Sentman of the University of Alaska proposed calling them "sprites" (mysterious and fleeting characters populating Shakespeare's *The Tempest*). Sentman's team also provided the first color images showing sprites to be primarily red with blue highlights on their lower extremities (Sentman et al., 1995), so the term red sprites has become widely used.

## Sprite properties

Several types of transient luminous events (TLEs) are now known to occur in the middle atmosphere above thunderstorms, and those have been given names such as "blue jets", "blue starters", "giant jets", "sprite halos", "red sprites", "elves" and "trolls" (see Figure 1).

Sprites are the most frequently observed of the TLEs (Sentman et al., 1995; Lyons, 1996). They are luminous spots of red light appearing from about 1 ms up to 10 ms after the lightning discharge and can last from a few milliseconds to few hundred milliseconds. Usually, the initiation occurs at 70-75 km altitude, with tendrils propagating downwards to almost 40 km and upward expanding diffuse glow (Pasko et al., 2002). Many similar discharges can be generated simultaneously over a horizontal distance of over 30-40 km. The lower portion of the sprites sometimes has a distinct blue coloration. Different sprites exhibit different features, as carrot and column shapes and some even looking like an eagle. The carrot sprite resembles a carrot with groups of streamers propagating downwards and flaring elements above, while the column sprites are very narrow, quasi-continuous and appear in clusters.

The planetary rate of sprite events is ~ 2.8 per minute (Ignaccolo et al., 2006) or ~ 7200 events per day (Füllekrug and Constable, 2000).

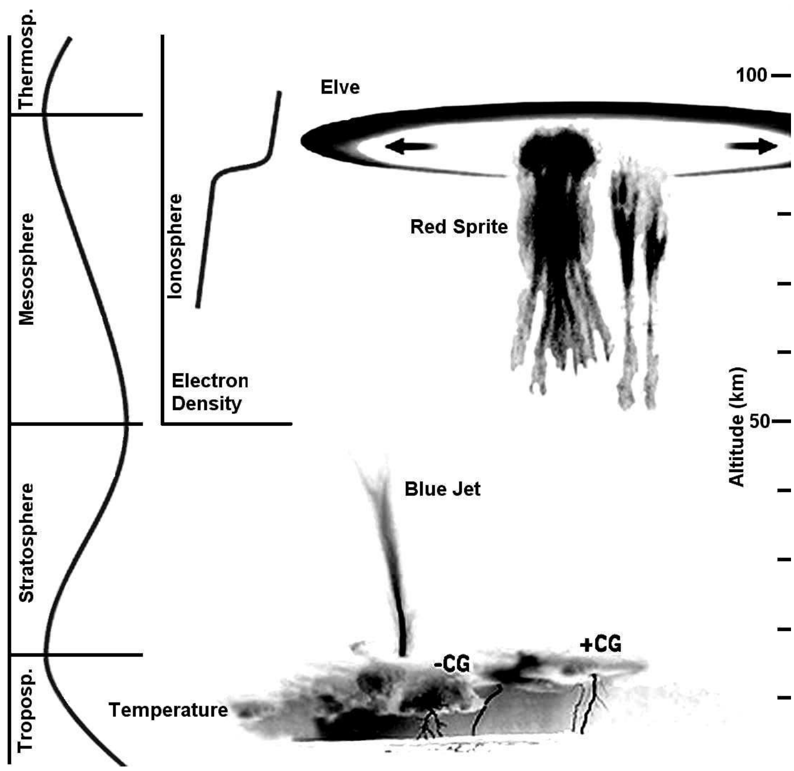


**Fig.1.** Pictorial view of elves, sprites and blue jets. (Adapted from Neubert, 2003).

## Sprite Color

In the TLEs, accelerated electrons hit the atoms and molecules of the atmosphere, much as in the aurorae (Northern and Southern lights). This can cause:

- Ionisation of the atoms or molecules, i.e. one or more electrons is removed completely. The remaining ion is often in an excited state.

- Electronic excitation of the atoms or molecules (Their outer electrons are transferred to a state of higher energy).

- Vibrational and rotational excitation of molecules, i.e. the atoms of a molecule start to oscillate with respect to each other, or rotate around their center of mass.

Thus TLEs excite atmospheric atoms and molecules and that these excited particles can emit light of specific wavelengths only. The red color of sprites comes from the fact that the difference in energies between the first and second excited states of a nitrogen atom happens to correspond to a wavelength our eye perceives as "red". But in reality, these emissions are not single-wavelength emissions but emission bands. This is because both the upper and lower electronic state may be in a different vibrational state with slightly different energies.

## Imaging Systems in Sprite Research

The sprite properties are known from video images (mostly taken at a repetition period of 33 ms) or from photometer traces (with 1 ms resolution or better). Studies have been made also using various instrumental techniques from aircraft, from balloons and from space (International Space Station) (Blanc et al., 2004) and from the Columbia Space Shuttle mission (Price et al., 2004). Sprites have been observed so far in Europe (Neubert et al., 2005), in USA (Lyons et al., 2003b; Pinto Jr. et al., 2004), in the Carribean region (Pasko et al., 2002), in Australia (Hardman et al., 2000), over winter storms in Japan (Hobara et al., 2001; Hayakawa et al., 2004), on the Asian continent and over the oceans surround Taiwan (Su et al., 2002, 2003; Hsu et al., 2003). However, because of the much higher lightning activity over Africa, Indonesia and South America, it is expected that sprites will be observed in these regions when scientists will be able to mount sprite-watch systems there.

## Ground Based Imaging

The ground based sprite-watch systems are usually mounted on the top of a mountain as sprites appear high above large and powerful thunderstorms. The system has to be far away from the thunderstorm which produces sprites so that the camera can have a clear view above them. The equipment consists of a security low-light level camera connected to a computer with GPS timing.

Several years ago, a team from the University of Alaska began to uncover the peculiar, often multibranching nature of sprites by recording them with high-speed cameras at rates up to 1000 frames per second. Steven Cummer and his coworkers reported video observations of sprites made in the foothills of the Rocky Mountains at up to 7200 frames per second (Cummer et al., 2006). The scientists captured the images from the Yucca Ridge Field Station in Fort Collins, Colorado, using an electronic camera designed to study fast phenomena like explosions. The fastest frame rates produced slow-motion imagery equivalent to stretching one second of normal-speed video into about five minutes of super-slow motion. The time between each frame was less than a millisecond.

## Space Based Imaging

Satellite based studies of upper atmospheric TLE events have several advantages. The most notable one is that global longitude latitude surveys of TLEs can be conducted from satellite orbit. The lack of atmospheric attenuation also provides many advantages such as UV viewing and quantitative interpretation of the measurements regardless of atmospheric conditions or viewing angles. Since TLEs are thunderstorm related phenomena they tend to occur when ground based viewing conditions are relatively unstable. Few experiments are now designed for sprite observations from space at the horizon: MEIDEX onboard of the Space Shuttle (Yair et al., 2004) and the first sprite experiment onboard a satellite – ISUAL.

The new instrument the Imager of Sprites/Upper Atmospheric Lightning (ISUAL) has been in orbit since May 20, 2004 making new observations of TLEs from space. The ISUAL payload includes a visible wavelength intensified CCD imager, a six wavelength channel spectrophotometer, and two channel Array Photometer (AP).

The LSO (Lightning and Sprite Observations) experiment on board of the International Space Station (ISS) has been designed to perform sprite observations at the nadir using an original method of spectral differentiation between sprites and lightning by an adapted filter (Blanc et al., 2004). The luminous emissions of sprites and lightning can be superimposed when they are observed from space at the nadir. Such observations are however needed for measuring simultaneously all possible emissions (radio, X, γ, high energy electrons) associated with sprites for a better understanding of the implied mechanisms. They are possible in specific spectral lines where sprites are differentiated from lightning. Absorption bands of the atmosphere are well adapted for this differentiation because the light emissions from sprites occurring in the middle and upper atmosphere are less absorbed in these bands than lightning emissions occurring more deeply in the atmosphere. The experiment is composed of two micro-cameras, one in the visible and near infrared, the other equipped with an adapted filter. Sprites, halos and super-bolts are identified by the ratio of the intensities received through the filter and in the whole spectrum.

## Non-optical Registration of Sprites

"Sprite signatures" are all non-optical events which indicate sprite occurrences. Up to date, four different sprite signatures have been reported in the literature: (1) Schumann resonance (Füllekrug and Reising, 1998); (2) Extremely Low Frequency (ELF) transients (Reising et al., 1999); (3) Very Low Frequency (VLF) perturbations (Haldoupis et al., 2004) and (4) Infrasound chirps (Farges et al., 2005).

## Schumann resonance

Schumann resonance is due to the thin layer of insulating air between the surface of the Earth and the conductive ionosphere acting as a waveguide. The limited dimensions of the Earth cause this waveguide to act as a resonant cavity for electromagnetic waves in the ELF band (the band of radio frequencies from 3 to 30 Hz, see Fig. 2). The cavity is naturally excited by energy from lightning strikes. The lowest-frequency (and highest-intensity) mode of the Schumann resonance is at a frequency of approximately 7.83 Hz. The fundamental mode of the Schumann Resonance is a standing wave in the earth-ionosphere cavity with a wavelength equal to the circumference of the Earth. Additional resonant peaks are found at 14, 20, 26, 33, 39 and 45 Hz.

The large and energetic lightning events that stand above the background resonance levels can be located globally on the basis of the electromagnetic measurements in Rhode Island (Huang et al, 1999), as with other workers at other locations (Hobara et al, 2001; Sato and Fukunishi, 2003). The two magnetometer signals are compared to determine the great circle path between lightning source and receiver. The calculation of the wave impedance, the ratio of vertical electric and horizontal magnetic field, is used to determine the distance along the great circle path. On this basis, the large and energetic positive flashes can be monitored on a continuous basis in both the African and the South America continents.

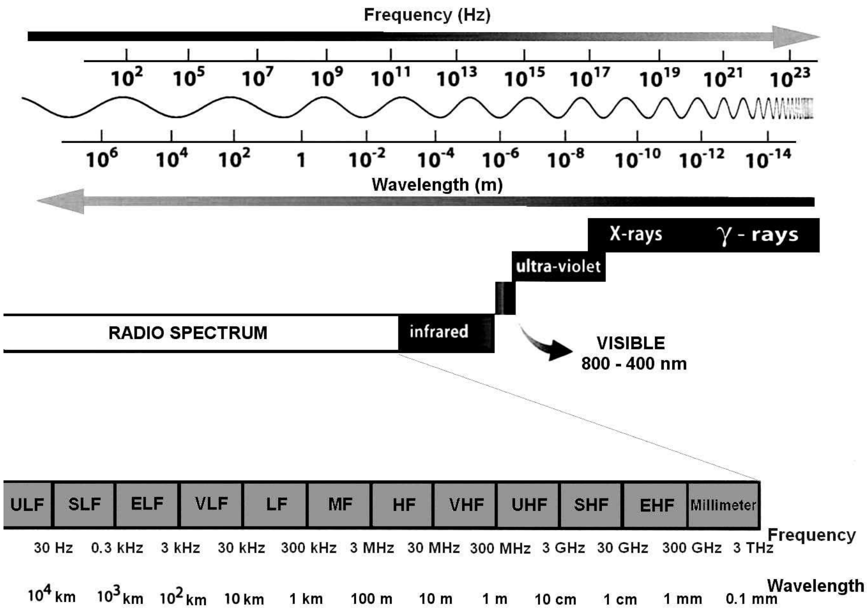


**Fig. 2.** The electromagnetic spectrum (according to the International Union of Radio Science) is divided into designated ranges: Ultra Low Frequency (ULF), Super Low Frequency (SLF), Extremely Low Frequency (ELF), Very Low Frequency (VLF), Low Frequency (LF), (MF) Medium Frequency (LF), High Frequency (HF), Very High Frequency (VHF), Ultra High Frequency (UHF), Super High Frequency (SHF), Extremely High Frequency (EHF).

## Extremely Low Frequency transients

Extremely low frequency electromagnetic waves (from 3 to 30 Hz) are used to explore the atmospheric electromagnetic environment of the Earth. Three networks of magnetometers record the properties of natural electromagnetic fields on the global, on the regional, and on the local scale.

The global magnetometer network detects locations of lightning discharges around the globe and monitors the temporal and spatial evolution of particularly intense thunderstorms. Satellite based cloud cover recordings help to determine the effective charge density of thunderclouds and reveal the electrical nature of severe weather.

The regional magnetometer network detects mesospheric electrical breakdown between the troposphere and the ionosphere, optically imaged with an intensified video camera as a transient optical emission, denoted sprite. About 20 % of the sprites produce electromagnetic signals which are similar to intense lightning discharges and the global detection efficiency of those signals is on the order of 80 % with a false alarm rate of 20 %.

The local magnetometer network is operated as an interferometer to measure the electromagnetic wave propagation speed, which is determined by the mesospheric conductivity. This variable conductivity is controlled by solar short wave radiation and energetic particle precipitation into the atmosphere, and can be monitored from the diurnal to the decadal time scale and this variability is likely to modulate the remote sensing of intense lightning discharges sprites.

## Very Low Frequency perturbations

The part of the electromagnetic spectrum described as VLF (Very Low Frequency) generally spans from 3 to 30 kHz. At those bands, the strong impulsive signals radiated by lightning discharges are termed “atmospherics", or simply “sferics". The explanation of early VLF events relies on two different, but not necessarily independent, processes: (1) heating of the lower ionosphere by strong quasi-electrostatic fields generated by lightning (Inan et al., 1996a; Pasko et al., 1995), and (2) ionization production during transient luminous events (TLEs), such as sprites, sprite halos and elves (Rodger, 2003; Mika et al., 2005).

## Infrasound chirps

Infrasound is sound with a frequency too low to be detected by the human ear. The study of such sound waves is sometimes referred to as infrasonics, covering sounds from the lower limit of human hearing (about 16 or 17 Hz) down to 0.001 Hz. This frequency range is the same one that seismographs use for monitoring earthquakes.

Chirps in infrasound recording are signals in which the frequency increases or decreases with time. They can be produced by a variety of sources: from lightning generated whistlers (Helliwell, 1965) to the acoustic emissions of bats (Carmona et al., 1997) and whales (Ford, 1991). Recently they have been associated with the occurrence of sprites over thunderstorm clouds (Farges et al., 2005).

The sprite signatures are located in the 1-10 Hz frequency range and in many cases a linear chirp of increasing frequency with time is observed. This signature is caused by the spatial extend of the sprite (from 20 to 50 km) (Farges et al., 2005), its orientation with respect to the infrasound station, and the reflectivity properties of the thermosphere. Pressure waves generated from different regions of the sprite will be reflected at different altitudes in the thermosphere with different absorption and dispersion properties before reaching the infrasound station. The net result is that pressure waves coming from the nearest end of the sprite will arrive first at the station with a low frequency content. Pressure waves coming from the farthest end of the sprite will arrive later at the station with a high frequency content. Sprite signatures which show an impulsive feature instead of a chirp are the result of a small spatial extension or of the alignment with the infrasound station (regardless of the spatial extent). The duration of the infrasound is directly linked to the horizontal size of the sprite.

## Characteristics of Sprite-Parent Thunderstorms and Lightning

Much of our understanding of the meteorology of sprite-producing lightning has been gained during field programs in the central U.S., though more recent programs in Europe, East Asia, the Middle East, Japan and Australia have greatly expanded the geographic domain of our understanding.

After the discovery of sprites, extensive field observations started and soon it became clear that the phenomenon was linked to lightning and was probably driven from below by individual lightning strokes (Winckler et al., 1996). The experiments showed (Boccipio et al., 1995; Reising et al., 1999) that sprite-producing lightning strokes are very strong radiators at the lowest frequencies detected by each system (< 100 Hz). Thus, the effective source of distant, low frequency radiation is not lightning current but rather current moment (the product of current and the length of the current channel) and total charge moment change (the time integral of current moment). So the primary difference between sprite-producing (SP) and non-sprite-producing lightning is that SP lightning strokes contain larger charge moment changes and thus transfer more charge from the cloud to the ground. During the STEPS program (Lang et al., 2004; Lyons et al., 2003b), detailed analyses of charge moment change suggested that at 600 C.km, there was a 10% of sprite initiation, reaching to 90% by 1000 C.km (Hu et al., 2002).

The conventional thundercloud is generally characterized by a positive dipole. Negative charges are distributed mainly in the mid-region of the cloud and the positive charges are at higher altitude. Such clouds are typically about as wide as they are tall. In contrast, a Mesoscale Convective System (MCS) has a horizontal extent more than 10 times its depth. This system has a significant lateral extent with a large, positive charge layer near cloud base, which in these systems is often close to the $0^{o}$C isotherm. One of the important characteristics in MCSs is its inverted dipole structure in comparison with the conventional isolated thundercloud (Williams, 1998; Lyons et al., 2003b).

A lightning flash that lowers positive (negative) charge to the ground is so-called positive (negative) cloud-to-ground (CG) lightning. The vast majority of lightning ground flashes worldwide are negative, although some exceptional cases such as lightning activity in wintertime over the Sea of Japan (Saito et al., 2003; Hayakawa et al., 2004) show a predominance of positive polarity.

Two different types of positive ground flashes are well known. Such discharges may be initiated from the upper region of the cloud, which leads to a long vertical extent to the ground in the case of the conventional thundercloud (Rust et al., 1981). The large positive charge reservoir near the base of the MCS stratiform anvil can also contribute a substantial amount of positive charge to the ground (Lyons et al., 2003b).

All field observations of sprites are concentrated on mid-latitude nocturnal mesoscale convective systems and complexes (MCSs and MCCs). According to several papers (Lyons, 1996; Lyons et al., 2003b) sprite-producing positive CGs tend not to occur until the storm has approached its mature stage and developed a considerable stratiform precipitation region. The sprite-producing positive CGs tend to cluster in a portion of the stratiform region, sometimes toward the trailing edge where cloud electrification processes are very different from those experienced in the high reflectivity convective cores. The MCS stratiform area usually reaches a minimum of 10-20x$10^{3}$ $km^{2}$ before significant sprite activity can be expected. Detailed analyses of lightning patterns from STEPS storms (Lyons et al., 2003b; Lyons and Cummer, 2004) have revealed several possible signatures. The main centers of VHF emissions, representing intra-cloud discharges, remained high in the cloud (8-12 km) during its active growth stage. But as the stratiform precipitation region expanded, a low-level secondary center of VHF activity developed and the +CGs began initiating sprites. As suggested by Williams (1998), this low level positive charge pool is located around 4 km AGL, near the melting layer

## Physical Mechanism and Numerical Models of Sprites

More than 80 years ago the Nobel Prize winner C.T. R. Wilson predicted (Wilson, 1925) the possibility of large scale gas discharge events above active thunderstorms. “While the electric force due to the thundercloud falls off rapidly as *r* increase, the electric force required to causing sparkling (which for a given composition of the air is proportional to its density) falls off still more rapidly. Thus, if the electric moment of a cloud is not too small, there will be a height above which the electric force due to the cloud exceeds the sparkling limit” (Wilson, 1925). His idea is illustrated on Figure 3. The electric field E due to thunderstorm electricity (shown with bold line) decreases with altitude proportional to $r^{-3}$. The conventional breakdown threshold field $E_k$ defined by the equality of the ionization and dissociative attachment coefficient (Raizer, 1991) decreases more rapidly with height. According to Wilson (1925) at height where $E > E_k$ the discharge spontaneously occurs.

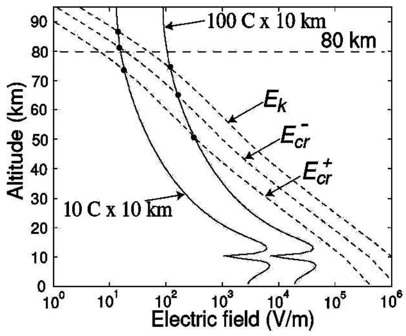


**Fig. 3**. The development of the electric field with height above an active thunderstorm.

The other two reference fields shown in Figure 3 – $E_{cr}^+$ and $E_{cr}^-$ are the minimum field required for the propagation of positive and negative streamer respectively (Raizer, 1991). It is worth to mention here that in addition to $E_k$, $E_{cr}^+$ and $E_{cr}^-$ there are several other important reference field, which were described using the so-called dynamic friction force of electrons in air *F* (Gurevich et al., 1992, Babich, 2003). There is a maximum in *F* at ~150 eV, which is called the thermal runway threshold ($E_c \approx 260$ kV/cm) and a minimum around ~1 MeV, called the relativistic runway threshold ($E_t \approx 2$ kV/cm). The maximum is created by a combined action of the ionization and excitation of different electronic states of $N_2$ and $O_2$ molecules. At higher energies >150 eV the friction force *F* decreases with increasing electron energy.

After the first registration of sprites, theoretical models, both electrostatic and electromagnetic, have been developed by a number of groups (Pasko et al., 1995, 2002; Bell et al, 1995; Inan et al., 1996; Huang et al, 1999 and others) to model the response of the upper atmosphere to thunderstorm fields and to lightning discharge currents. Maxwell's equations are solved self consistently through the atmosphere which has a modeled conductivity profile. The aim of most of the studies is to answer the questions: 1) how does the CG lightning initiate sprites; 2) what are the critical parameters for sprite initialization; 3) what controls the height of sprite initialization; 4) how does the sprite propagate in the ionosphere.

Summarizing all available information from field observation and from numerical simulations it was concluded that the energy source for sprites is electric field energy associated with lightning. This can be in the form of the quasi-static field due to the distribution of charge in a thunderstorm, or the electromagnetic pulse from a lightning discharge (Rycroft, 2006). Two basic theories for sprite formation above thunderstorms exist - conventional (thermal) and runaway (relativistic) electron discharge physics.

According to the conventional theory, sprites are generated by the electric field pulse ($E > E_k$) that travels upward toward the ionosphere from a positive cloud-to-ground (+CG) stroke of lightning (Neubert, 2003). Positive CG discharges can involve transfer (to the ground) of up to 300 C in several ms (Brook et al., 1982), resulting in large (up to ~1000 V/m at 50 km altitude) quasi-electrostatic (QE) fields due to the uncompensated negative charge left in and above the cloud. The ambient electrons and ions at all altitudes above the cloud are heated by the large QE fields, leading to optical emissions. The observed several to tens of ms duration of red sprites is consistent with the characteristic relaxation time of QE fields due to finite conductivity of the medium (Baginski et al., 1988). High-speed optical imaging has indicated that the sprite discharge propagates downward from an initial altitude of ~75 km, and then shoots upward as a recoil (Stenbaek-Nielsen et al., 2000). It seems that, in contrast to the fully ionized channels of conventional lightning, sprites are weakly ionized. Both normal lightning return strokes and sprites have electron energies of a few electronvolts (eV) or 20,000 to 30,000 K (Morrill et al., 2002). Thus, sprites can be classified as a form of lightning and are sometimes referred to as "high-altitude lightning".

According to the runway breakdown mechanism, the discharge initiates when the applied electric field is greater than the runway threshold. The relativistic theory suggests that an electrical breakdown mechanism carried by relativistic electrons also operates in sprites ($E > E_t$) (Roussel-Dupré and Gurevich, 1996). The idea is that free relativistic seed electrons generated by cosmic rays start an upward ionization avalanche, creating additional high-energy electrons. The existence of this process is supported by observations of X- and γ-radiation from the atmosphere above thunderstorms (observed by the Compton Gamma Ray Observatory), which suggest emission of Bremsstrahlung by MeV-energy electron beams in the upper atmosphere (Fishman et al., 1994). The role of relativistic breakdown in sprites remains a topic of intense research.

In addition to the studies concerning the source of sprite initiation and propagation there are attempts to model the small scale sprite streamer processes and photoionization effects (Kulikovsky, 2000) as well as the optical emission associated with sprite streamers (Liu and Pasko, 2004).

## Summary

Sprites are being observed for more than a century, with their extensive research embedded in the past 15 years, and the registration is being conducted with almost global coverage, although most intensive studies are made in USA and, recently, in Europe. Various methods of registration and observation of sprites are competing for effectiveness, amongst which are space and ground based imaging instruments and event registration methods using disturbances in different bands of the electromagnetic spectrum.

The field measurements reveal the close connection between sprites and positive cloud-to-ground lightning generated in the stratiform regions of mesoscale convective systems and complexes. Subsequently, numerical models are developed to study the generation and evolution of sprites.

Despite the active research campaign in the field of troposphere-ionosphere coupling, many outstanding questions still remain unsolved. One of them is the observed initiation of sprites at altitudes 70-80 km by very weak lightning discharges with small charge moment changes. The almost-exclusive association of sprites with ground flashes of positive polarity is another one (Williams, 2007). Few theories have been advanced to explain these observations, although none of them does fully fit the required conditions. Probably, another 15 years would be needed to unveil some of the unclear problems.

## References

Babich, L.P., 2003. High-energy phenomena in electric discharges in dense gases: Theory, experiment and natural phenomena, volume 2 of *ISTC Science and Technology Series*, Futurepast, Arlington, Virginia.

Baginski, M.E., C.L.Hale, and J.J.Olivero, 1988. Lightning-related fields in the ionosphere, *Geophys. Res. Lett*., **15**(8), 764-767.

Bell, T.F., V.P.Pasko, U.S.Inan, 1995. Runaway electrons as a source of Red Sprites in the mesosphere, *Geophys. Res. Lett*., **22**(16), 2127-2130.

Blanc, E., T.Farges, R.Roche, D.Brebion, T.Hua, A.Labarthe, and V.Melnikov, 2004. Nadir observations from the International Space Station. *J. Geophys. Res*., **109**(A2), doi:10.1029/2003JA009972.

Boccippio, D., E.Williams, S.Heckman, W.Lyons, I.Baker, R.Boldi, 1995. Sprites, ELF transients, and positive ground strokes, *Science,* **269**, 1088.

Boeck, W.L., O.H.Vaughan Jr., R.Blakeslee, B.Vonnegut, and M.Brook, 1998. The role of the space shuttle video tapes in the discovery of sprites, jets and elves, *J. Atmos. Solar-Terr. Phys.,* **60,** 669–677.

Brook, M., M.Nakano, P.Krehbiel, and T.Takeuti, 1982. The electrical structure of the Hokuriku winter thunderstorms, *J. Geophys. Res*., **87**(NC2), 1207-1215.

Carmona, R.A., W.L.Hwang, and B.Torresani, 1997. Characterization of Signals by the Ridges of their Wavelet Transform, *IEEE Trans. Sig. Proc*., **45**(10), 2586-2590.

Cummer, S.A., N.Jaugey, J.Li, W.A.Lyons, T.E.Nelson, E.A.Gerken, 2006. Submillisecond imaging of sprite development and structure, *Geophys. Res. Lett*., **33**, L04104, doi:10.1029/2005GL024969.

Farges, T., E.Blanc, A. Le Pichon, T.Neubert, T.H.Allin, 2005. Identification of infrasound produced by sprites during the EuroSprite-2003 campaign, *Geophys. Res. Lett*., **32**, L01813, doi:10.1029/2004GL021212.

Fishman, G.J., J.J.Brainerd, and K.Hurley, 1994. Discovery of intense gamma-ray flashes of atmospheric origin, *Science*, **264**, 1313–1316.

Ford, J.K.B., 1991. Vocal traditions among resident killer whales (*Orcinus orca*) in coastal waters of British Columbia, *Canadian Journ, Zool*., **69**, 1454.

Franz, R. C., R. J. Nemzek, and J. R. Winckler, 1990. Television image of a large upward electrical discharge above a thundertorm system. *Science*, **249,** 48–51.

Füllekrug, M., S.C.Reising, 1998. Excitation of Earth-ionosphere cavity resonances by sprite-associated lightning flashes, *Geophys. Res. Lett*., **25**(22), 4145-4148.

Füllekrug, M., S.Constable, 2000. Global triangulation of intense lightning discharges, *Geophys. Res. Lett*., **27**(3), 333-336.

Gurevich, A.V., G.M.Milikh, and R.Roussel-Dupre, 1992: Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm, *Phys. Lett. A.*, **165**, 463-468.

Haldoupis, C., T.Neubert, U.S.Inan, A.Mika, T.H.Allin, R.A.Marshall, 2004: Subionospheric early VLF signal perturbations observed in one-to-one association with sprites, *J. Geophys. Res*., **109**, A10303, doi:10.1029/2004JA010651.

Hardman, S.F., R.L.Dowden, J.B.Brundell, J.L.Bahr, Z.Kawasaki, and C.J.Rodger, 2000. Sprite observations in the Northern Territory of Australia. *J. Geophys. Res.*, **105,** 4689–4697.

Hayakawa, M., T.Nakamura, Y.Hobara, and E.Williams, 2004b. Observation of sprites over the Sea of Japan and conditions for lightning induced sprites in winter, *J. Geophys. Res*., **109**(A0), doi:10.1029/2003JA009905.

Helliwell, R.A., 1965. Whistlers and related ionospheric phenomena, *Stanford University Press*, Stanford.

Hobara, Y., N.Iwasaki, T.Hayashida, M.Hayakawa, K.Ohta, H.Fukunishi, 2001. Interrelation between ELF transients and ionospheric disturbances in association with sprites and elves, *Geophys. Res. Lett*., **28**(5), 935-938.

Hsu, R.R., H.T.Su, A.B.Chen, L.C.Lee, M.Asfur, C.Price, and Y.Yair, 2003. Transient luminous events in the vicinity of Taiwan, *J. Atmos. Solar-Terr. Phys*., **65**(5), 561-566.

Hu, W., S.A.Cummer, W.A.Lyons, and T.E.Nelson, 2002. Lightning charge moment changes for the initiation of sprites, *Geophys. Res. Lett*., **29**(8), doi:10.1029/2001GL014593.

Huang, E., E.Williams, R.Boldi, S.Heckman, W.Lyons, M.Taylor, T.Nelson, C.Wong, 1999. Criteria for sprites and elves based on Schumann resonance observations, *J. Geophys. Res*., **104**(D14), 16943-16964.

Ignaccolo, M., T.Farges, A.Mika, T.H.Allin, O.Chanrion, E.Blanc, T.Neubert, A.C.Fraser-Smith, M.Füllekrug, 2006. The Planetary rate of sprite events, *Geophys. Res. Lett*., **33,** L11808, doi:10.1029/2005GL025502.

Inan, U.S., V.P.Pasko, T.F.Bell, 1996a. Sustained heating of the ionosphere above thunderstorms as evidenced in ‘‘early/fast’’ events, *Geophys. Res. Lett*., **23**, 1067–1070.

Kulikovsky, A.A., 2000. The role of photoionization in positive streamer dynamics, *J. Phys. D., Appl. Phys*., **33**, 1514-1524.

Lang, T.J., S.A.Rutledge, K.C.Wiens, 2004. Origins of positive cloud-to-ground lightning flashes in the stratiform region of a mesoscale convective system, *Geophys. Res. Lett*., **31**, L10105, doi:10.1029/2004GL019823.

Liu, N., V.P.Pasko, 2004. Effects of photoionization on propagation and branching of positive and negative streamers in sprites, *J. Geophys. Res*., **109**, A04301, doi:10.1029/2003JA010064.

Lyons, W.A., 1996. Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res*., **101**(D23), 29641-29652.

Lyons, W.A., T.E.Nelson, E.Williams, S.Cummer, and M.Stanley, 2003b. Characteristics of sprite-producing positive cloud-to-ground lightning during the 19 July 2000 STEPS mesoscale convective systems, *Mon. Wea. Rev*., **131**, 2417-2427.

Lyons, W.A. and S.A.Cummer, 2004. Lightning charge moment changes in U.S. High Plains thunderstorms, *Geophys. Res. Lett*., **31**, L05114, doi:10.1029/2003GL019043.

Mika, A., C.Haldoupis, R.A.Marshall, T.Neubert, and U.S.Inan, 2005. Subionospheric VLF signatures and their association with sprites observed during EuroSprite-2003, *J. Atmos. Solar.-Terrest. Phys*., **67**, 16.

Morrill, J., E.Bucsela, C.Sierfing, M.Heavner, S.Berg, D.Moudry, S.Slinker, R.Fernsler, E.Wescott, D.Sentman, and D.Osborne, 2002. Electron energy and electric field estimates in sprites derived from ionized and neutral $N_2$ emissions, *Geophys. Res. Lett*., **29** (10), doi:10.1029/2001GL014018.

Neubert, T., 2003. On sprites and their exotic kin, *Science,* **300** (2), 747.

Neubert, T., T.Allin, E.Blanc, T.Farges, C.Haldoupis, A.Mika, S.Soula, L.Knutsson, O.Velde, R.Marshall, U.Inan, G.Satori, J.Bor, A.Hughes, A.Collier, S.Laursen, L.Rasmussen, 2005. Co-ordinated observations of transient luminous events during the EuroSprite-2003 campaign, *J. Atmos. Solar-Terr. Phys*., **67**, 807-820.

Pasko, V.P., U.S.Inan, Y.N.Taranenko, T.F.Bell, 1995. Heating, ionization and upward discharges in the mesosphere due to intense quasi-electrostatic thundercloud fields, *Geophys. Res. Lett*., **22**, 365–368.

Pasko, V.P., M.A.Stanley, J.D.Mathews, U.S.Inan, and T.G.Woods, 2002. Electrical discharge from a thunderstorm top to the lower ionosphere. *Nature,* **416,** 152–154.

Pinto, O.Jr., M.M.F.Saba, I.R.C.A.Pinto, F.S.S.Tavares, K.P.Naccarato, N.N.Solorzano, M.J.Taylor, P.D.Pautet, R.H.Holzworth, 2004. Thunderstorm and lightning characteristics associated with sprites in Brazil, *Geophys. Res. Lett*., **31**, L13103, doi:10.1029/2004GL020264.

Price, C., et al., 2004. Ground-based detection of TLE-producing intense lightning during the MEIDEX mission on board the space shuttle Columbia, *Geophys. Res. Lett*., **31,** L20107, doi:10.1029/2004GL020711.

Raizer, Y.P., 1991. *Gas discharge physics*, Springer –Verlag, Berlin, Heidelberg.

Reising, S.C., U.S.Inan, T.F.Bell, 1999. ELF sferic energy as a proxy indicator for sprite occurrence, *Geophys. Res. Lett*., **26**(7), 987-990.

Rodger, C.J., 2003. Subionospheric VLF perturbations associated with lightning discharges, *J. Atm. Sol.-Terr. Phys*., **65**, 591–606.

Roussel-Dupré, R., A.V.Gurevich, 1996. On runaway breakdown and upward propagating discharges, *J. Geophys. Res*., **101**(A2), 2297-2312.

Rust, W.D., D.R.MacGorman, and R.T.Arnold, 1981. Positive cloud-to-ground lightning flashes in severe storms. *Geophys. Res. Lett*., **8,** 791-94.

Rycroft, M.J., 2006. Introduction to the physics of sprites, elves and intense lightning discharges, Proceedings of the NATO Advances Study Institute on “Sprites, Elves and Intense Lightning Discharges”, Corte, Corsica, France, 24-31 July 2004**,** p.1-13.

Saito, M., M.Ishii, J.Hojo, A.Sugita, T.Idogawa, and K.Kotani, 2003. Development of lightning discharge observed by VHF radiation, In *Joint Technical Meeting on Electrical Discharges, Switching and High Voltage*, Okinawa, IEE Japan, HV-03-90.

Sato, M., H.Fukunishi, 2003. Global sprite occurrence locations and rates derived from triangulation of transient Schumann resonance events, *Geophys. Res. Lett.*, **30** (16), 1859.

Sentman, D.D., E.M.Wescott, 1993. Observations of upper atmospheric optical flashes recorded from an aircraft, *Geophys. Res. Lett*., **20**(24), 2857-2860.

Sentman, D.D., E.M.Wescott, D.L.Osborne, D.L.Hampton, M.J.Heavner, 1995. Preliminary results from the Sprites94 aircraft campaign: 1. Red sprites, *Geophys. Res. Lett*., **22**(10), 1205-1208.

Stenbaek-Nielsen, H.C., D.R.Moudry, E.M.Wescott, D.D.Sentman, F.T.Sao Sabbas, 2000. Sprites and possible mesospheric effects, *Geophys. Res. Lett*., **27**(23), 3829-3832.

Su, H.T., R.R.Hsu, A.B.Chen, Y.C.Wang, W.S.Hsiao, W.C.Lai, L.C.Lee, M.Sato, and H.Fukunishi, 2003. Gigantic jets between a thundercloud and the ionosphere, *Nature*, **423**, 974-976.

Yair, Y., P.Israelevich, A.D.Devir, M.Moalem, C.Price, J.H.Joseph, Z.Levin, B.Ziv, A.Sternlieb, A.Teller, 2004. New observations of sprites from the space shuttle, *J. Geophys. Res*., **109**, D15201, doi:10.1029/2003JD004497.

Wilson, C.T.R., 1925. The electric field of a thundercloud and some of its effects, *Proc. Phys. Soc. London*, 37(32D-37D).

Williams, E.R., 1998. The positive charge reservoir for sprite-producing lightning, *J. Atmos. Sol.-Terr. Phys*., **60**, 689-692.

Williams, E.R., E.Downes, R.Boldi, W.Lyons, S.Heckman, 2007. The polarity asymmetry of sprite-producing lightning: A paradox?, *Radio Sci.*—in press, doi:10.1029/2006RS003488.

Winckler, J.R., W.A.Lyons, T.E.Nelson, R.J.Nemzek, 1996. New high-resolution ground-based studies of sprites, *J. Geophys. Res*., **101**, 6997-7004.

## Спрайтове и родителски гръмотевични бури

А. Савченко и Р. Мицева

**Резюме.** Спрайтовете са един много впечатляващ член от голямото и разнообразно семейство краткотрайни светлинни явления, наричано още „мълнии от високата атмосфера”. През последното десетилетие те са обект на задълбочени научни изследвания и се смятат за интересно допълнение към тропосферната гръмотевична активност, както и важен фактор, оказващ влияние върху глобалната атмосферна електрическа верига и атмосферната циркулация. Съществуват няколко теории, които се опитват да обяснят странната природа на спрайтовете, но въпреки това остават много неразкрити въпроси. Настоящата статия обобщава известните факти, свързани със спрайтовете, според съществуващата литература в областта на изследванията на това явление. Изложени са физическите и оптични характеристики на спрайтовете, както и физичните механизми, отговорни за генерирането им. На кратко са представени методите за регистриране и са дадени някои концепции за числено моделиране на спрайтове. Особено внимание е оказано също и на характеристиките на родителските мълнии и гръмотевични облаци.