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Electrical parameters of red sprites

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RESUMEN

Los duendes rojos son una clase exótica de rayos que surgen por arriba de las tormentas eléctricas. Se han obtenido expresiones de la velocidad y la corriente de estos fenómenos. La primera expresión es gaussiana. La corriente que fluye en el cuerpo del duende rojo se comporta de manera similar a una corriente de retorno típica. Las variaciones en el tiempo del momento de corriente y del cambio en el momento de carga se han calculado con ayuda de las expresiones de velocidad y corriente. También se ha obtenido el campo de radiación eléctrica generado por el momento de corriente del duende. Este campo alcanza su máximo alrededor de los 40 Hz con una amplitud del orden de 10^{-5} V/m a 200 km del canal del duende. La energía total disipada en el cuerpo de los duendes rojos es del orden de 10^9 J.

ABSTRACT

Red sprites are the exotic kind of lightning above thunderstorms. Expressions for the velocity and current of sprites have been obtained. The velocity expression comes out to be Gaussian. The calculated current flowing in the sprite body behaves just like a typical lightning return stroke current. The variations of current moment and charge moment change with time have been calculated with the help of velocity and current expressions. The approximate radiation electric field generated from the current moment of sprite also has been obtained. The radiation electric field peaks at about 40 Hz with an amplitude of the order of 10^{-5} V/m at 200 km from the sprite channel. The total energy dissipated in the body of red sprites is of the order of 10^9 J.

Keywords: Sprites, extremely low frequency (ELF), current moment, charge moment change.

1. Introduction

Sprites are upper atmospheric lightning that occur above thunderstorms at altitudes ranging from clouds top to as high as 90 km. Probably Franz *et al.* (1990) were the first authors to detect sprites from ground based imaging systems. Sentman *et al.* (1995) gave the strong evidence of occurrence of sprites through an aircraft campaign. Sprites are initiated by the strong positive cloud-to-ground (CG) discharges (Boccippio *et al.,* 1995; Reising *et al.,* 1996; Huang *et al.,* 1999; Price *et al.,* 2002; Williams *et al.,* 2007). The proposed generation mechanisms include ambient electron heating by quasi-electrostatic thundercloud fields, resulting in ionization and excitation of optical emissions (Pasko *et al.,* 1997), and the secondary cosmic ray electrons of energy ~1 MeV that become runaway electrons (Bell *et al*., 1995; Roussel-Dupré and Gurevich, 1996) in the presence of large quasi-electrostatic fields which collide inelastically with the neutral O_2

and N_2 molecules, resulting in loss of energy and therefore in atomic and molecular excitations and subsequent optical emissions. Sprites can be generated by acoustic waves originated in the lower atmosphere due to natural cataclysms like hurricanes, thunderstorm lightning and tornados (Aramyan and Galechyan, 2009), and propagate upwards as well as downwards from their points of origin (Sentman *et al.,* 1995). They endure for several milliseconds, and are typically delayed in time ranging from ~3 ms (Winckler, 1995) to several tens of ms (Fukunishi *et al*., 1995) with respect to the onset of the causative CG lightning. Generally, sprites occur during the dying stage of thunderstorms, and may appear singly as well as in clusters of two or more. The brightest red region of a unit sprite lies between altitudes of 66 and 75 km, below which faint tendrils extend downward up to 40-50 km (Pasko *et al.,* 1997). The lateral extent of unit sprites is typically 5-10 km and sprite clusters may occupy a large volume greater than 10^4 km^3 (Sentman *et al.,* 1995). The energy dissipated in the sprite channels is of the order of 10^{10} J (Dowden *et al.,* 1996). This energy excitates the various chemical constituents and scales the luminosity of sprites, which can have different shapes and sizes, depending upon the causative CG lightning. The most common types are columnar, carrot, angels, jellyfish, and A-bomb sprites (Williams, 2001). The main reason for the development of lightning discharges between a thundercloud and the ionosphere is the exponential reduction of pressure with height (Petrov and Petrova, 1999).

The purpose of this paper is to calculate the electrical parameters of red sprites like current moment, charge moment change, radiated electric field from sprites and total energy dissipated in their body.

1.1 Physical mechanism of red sprites

The breakdown ionization of upper atmosphere by thundercloud electric fields was first mentioned by Wilson (1925). He calculated that the thunder cloud electric field decreases with altitude h as $\sim h^{-3}$ and the critical breakdown electric field E_k decreases exponentially, *i.e.* much faster than the thundercloud electric field, so that there would be a height where the thundercloud electric field exceeds E_k and the discharge takes place. The fundamental reasons behind the electro-dynamical coupling between the cloud tops and the ionosphere are the heating of the ambient electrons by large quasi-electrostatic fields $E_{Q\text{-}E}$ generated by the strong CG lightning (Pasko *et al*., 1995) and the runaway electron (Bell *et al.,* 1995; Roussel-Dupré and Gurevich, 1996; Taranenko and Roussel-Dupré, 1996). Raizer *et al*. (1998) calculated $E_{Q\text{-}E}$ using a simple dipole model with cloud charge Q left at altitude z above the earth. They assumed the earth and ionosphere as perfect conducting boundaries. The $E_{Q\text{-}E}$ generated in the upper atmosphere ($h >> z$) is given by

$$E_{Q-E} = \frac{zQ}{\pi\varepsilon_0 h^3}\left[1+\left(\frac{h}{2h_i - h}\right)^3\right] \quad (1)$$

where h_i ~90 km is the height of ionosphere. It can be shown with the help of Eq. (1) that only the large charge moment change from conventional lightning discharge can generate the sufficient amount of electric field to produce a breakdown in the atmosphere (60-90 km). However, it has been found experimentally that sprites can propagate up to the thundercloud tops (40 km), so another mechanism, the "runaway breakdown", is very effective to explain the breakdown of lower atmosphere (40-50 km). Runaway breakdown involves the cosmic ray seed electrons with energy $\varepsilon_c \sim$ 0.1-1 MeV, which accelerate in the presence of large $E_{Q\text{-}E}$ and bombard the atmosphere (Bell *et al.,* 1995). The electric field E_{RB} required to accelerate the cosmic seed electrons is one-tenth of the conventional critical breakdown electric field E_k. The calculated value of E_{RB} (Gurevich and Zybin, 2001) is given by

$$E_{RB} = 2.16\times10^5 e^{-\frac{h}{H}} \tag{2}$$

where H = 7.2 km, the scale height of the atmosphere. Figure 1 shows the heating of the upper atmosphere and the runaway mechanism by the $E_{Q\text{-}E}$ generated in the upper atmosphere as an effect of the strong +ve CG lightning discharge, resulting in red sprites.

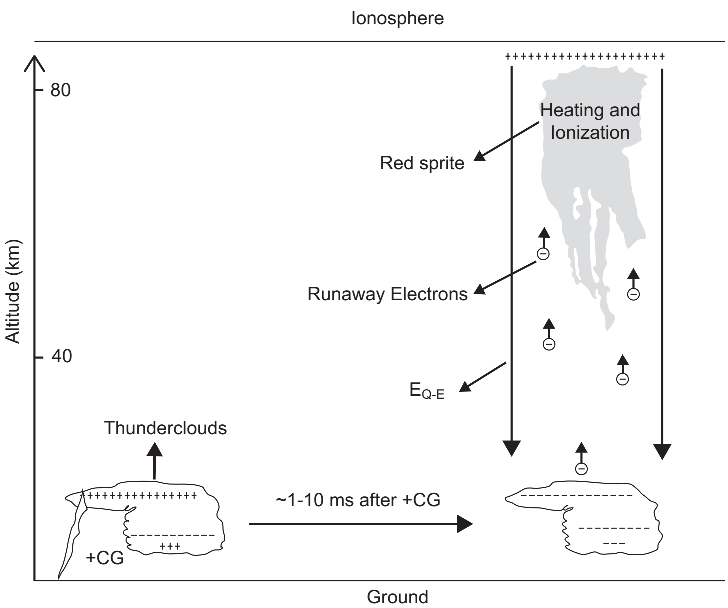

Fig. 1. The schematic diagram shows that as soon as the +CG lightning occurs the $E_{Q\text{-}E}$ is generated in the upper atmosphere, resulting in red sprites.

2. Velocity of red sprites

Stanley *et al.* (1999) adopted a high speed imaging technique and measured initial sprite velocities in excess of 10^7 m/s. McHarg *et al*. (2002) reported the velocity of propagation of downward and upward luminosity of the order of 10^7-10^8 m/s. Moudry *et al.* (2002) reported the fast and slow expansion of sprites with an average velocity of 10^7 m/s in the bright region and 10^6 m/s in the bottom part of the dim sprite. Li and Cummer (2009) measured the downward sprite peak velocities in the range of 3-10% of the speed of light. The sprites consist of streamers which propagate in the $E_{Q\text{-}E}$ produced by the strong causative positive CG lightning. Raizer *et al.* (1998) described the propagation of red sprites as the cluster of streamers originated from the plasma patches. Their calculations can be fitted by a Gaussian distribution of the form

$$V(t) = V_0 e^{-b\,(t-a)^2} \tag{3}$$

where V_0, a, and b are constants. From the knowledge of various measurements we estimated the values of these constants. We found that V_0 is equal to 1.16×10^7 m/s to account for the peak value of sprite velocity. The other constants are a and b, whose values are 3.83×10^{-3} s and 4.13×10^5 s^{-2} respectively. Constant a determines the time at which the sprite velocity reaches its peak value and b is responsible for the total time period of occurrence of sprites. The simulated result of Raizer *et al.* (1998) and the plot of Eq. (3) are shown in Figure 2. The sprites first accelerate and then decelerate at an almost constant rate close to 0.6×10^{10} m/s. Deceleration rate of sprites from Eq. (3) is very close to the measured typical value of 1×10^{10} m/s (Li and Cummer, 2009).

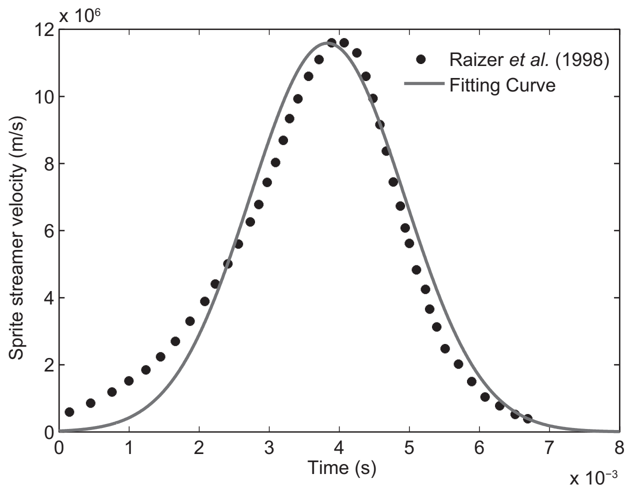

Fig. 2. Time variation of the velocity of red sprites.

3. Current moment and charge moment change of red sprites

Earlier studies of extremely low frequency (ELF) electric and magnetic field signals have shown some unusual pulses during sprite events (Cummer, 2003). It has been observed that these signals do not contain energy at frequencies higher than 1 kHz. Cummer (2003) suggested that these pulses were associated with high altitude electric current in the sprite itself and not with a lightning process. The first experimental evidence that electrical currents may be flowing in the body of sprites was given by Cummer *et al*. (1998). This current generates ELF electromagnetic energy at levels comparable to that produced by the parent CG lightning. Cummer *et al.* (1998) described that this vertical current flowing in a narrow region (about 10%) of the sprites is the main source of ELF radiation. Cummer *et al.* (2006) found that the sprite current pulses begin 2.5 ms after the onset of the return stroke. The peak vertical sprite current ranges from 1.6 to 3.3 kA (Cummer *et al*., 1998), and 5-10 kA (Rycroft and Odzimek, 2010). It can be as high as 25 kA (Cummer, 2003) for typical sprites. According to Cummer *et al.* (1998), the measured values of the current moment during a sprite have a very large initial peak, which may be due to the continuing current from the causative CG positive discharge. The second peak is due to the sprite current. The current flowing through the body of the sprite at the beginning must be zero and it must have a later peak to account for the peak in current moment. The current flowing through the sprite channel is shown in Figure 3. The sprite current *i(t)* can be given by

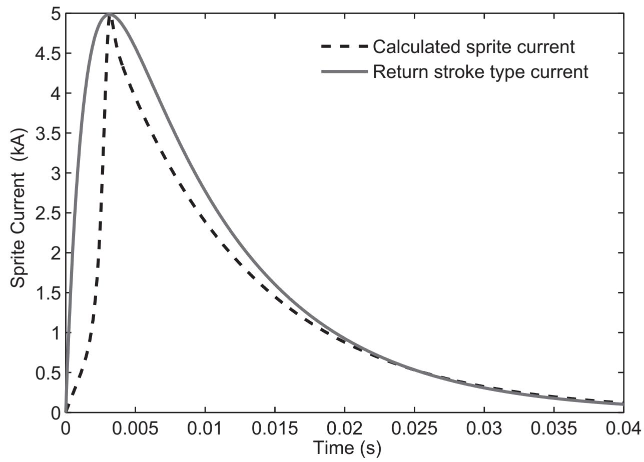

Fig.3. Time variation of the sprite current.

$$i(t) = A\sigma(t)E(t) \quad (4)$$

where $A \approx 400\ \text{km}^2$ is the average cross section area of the sprite in which current flows and it is assumed to be constant with time; $\sigma(t)$, the ambient conductivity ahead of the propagating front of the sprite channel; and $E(t)$ the electric field at the tip of the channel. Using the simple point charge model (Fullekrug, 2006), the sprite that generates the electric field $E(t)$ is given by

$$E(t) = E_0 \frac{e^{-t/\tau_q} - e^{-t/\tau_r}}{\tau_q/\tau_r - 1} \quad (5)$$

where $E_0 = \frac{-1}{4\pi\varepsilon_0}\frac{Q_0}{r^2}$, the static Coulomb field,

where $Q_0 = 200$ C, the charge removed by the +ve CG lightning; $r = 10$ km, the radial distance from the charge point; $\tau_q = 10$ ms, the duration of lightning current; and $\tau_r = \varepsilon_0/\sigma(z)$, the relaxation time of the electric field. The ambient conductivity ahead of the sprite front (Fullekrug, 2006) is given by

$$\sigma(\text{z}) = \sigma_0 e^{(z-z_0)/s} \quad (6)$$

where $\sigma_0 = 6.4 \times 10^{-10}$ S/m; $z_0 = 50$ km; and $s = 3.2$ km describe the conductivity gradient in the earth's atmosphere. The altitude z of the propagating front of the sprite channel can be written as

$$z = z_0 + \int_0^t V(t)\, dt \quad (7)$$

where z_0 is the altitude of sprite initiation. The approximate sprite current has been calculated from Eqs. (4), (5), (6), and (7). The calculated value of the current has been shown in Figure 3, where a double exponential current expression similar to the return stroke has also been plotted. As the difference between them is very small, we take the sprite current to be

$$i(t) = i_0[\exp(-\gamma t) - \exp(-\delta t)] \tag{8}$$

where i_0, γ and δ are constants. The estimated values of γ and δ are 1.10×10^2 s^{-1} and 7×10^2 s^{-1} respectively, and i_0 is the constant which can be taken into account for the peak value of the sprite current. The value of i_0 is taken to be 8.35×10^3 A for the peak current of 5 kA.

The current moment M_c is the multiplication of current and the channel length through which it has propagated. The mathematical expression is given by

$$M_c(t) = 2i(t)\int_0^t V(t)dt \tag{9}$$

It has been assumed here that the sprite channel is perfectly conducting and the current generated on its tip is immediately connected to all parts of the channel. The calculated peak value of M_c from Eq. (9) is around 260 kA/km (Fig. 4). Cummer *et al.* (1998) measured the M_c of a few sprites and obtained values ranging from 150 to 240 kA/km. The charge moment change M_q defined by $M_q = q(t)\int_0^t V(t)\,dt$ has also been calculated. The maximum value is around 2050 C/km and it is shown in Figure 4.

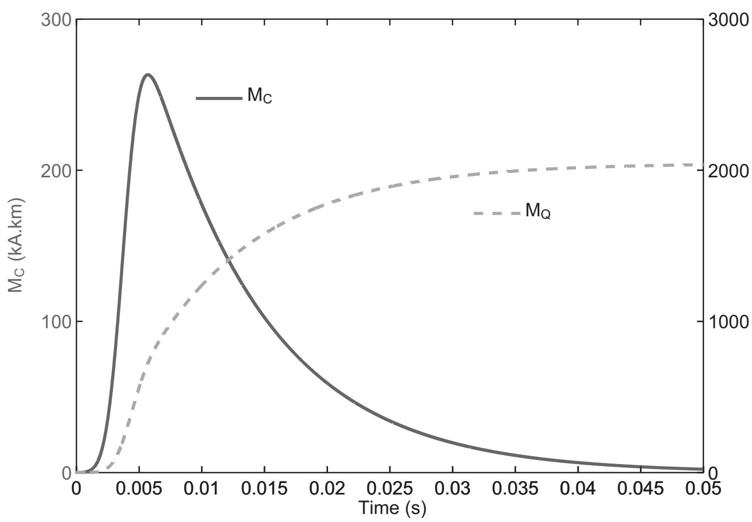

Fig. 4. Sprite current moment Mc and charge moment Mq vs. time.

4. ELF emissions from red sprites

Cummer *et al.* (1998) observed that the lightning sprites produced ELF signals and very low frequency (VLF) signals were absent. Cummer (2003) observed that the lightning sprites radiate ELF pulses. The source of these ELF pulses is the vertical current flowing through the body of sprites. A vertical electric field is developed due to the current moment of the sprites. The peak radiation frequency of the vertical electric field can be obtained with the help of velocity and current expressions. Leise and Taylor (1977) and Rai (1978) showed that the Fourier component of the radiation field $E_r(\omega)$ is related to the Fourier component of current $i(\omega)$ and velocity $V(\omega)$ by

$$E_r(\omega) = \iota\omega\kappa i(\omega)V(\omega) \tag{10}$$

where $\kappa = \dfrac{1}{2\pi\varepsilon_0 c^2 R}$, ω is the angular frequency of radiation, and R is the distance of observation from the source.

The Fourier component $E_r(\omega)$ of the vertical electric field must have a peak. Figure 5 shows the calculated electric field, which lies mainly in the ELF region (0-300 Hz). Radiated electric field peaks at around 40 Hz with an amplitude of the order of 10^{-5} V/m at a distance of about 200 km from the sprite channel.

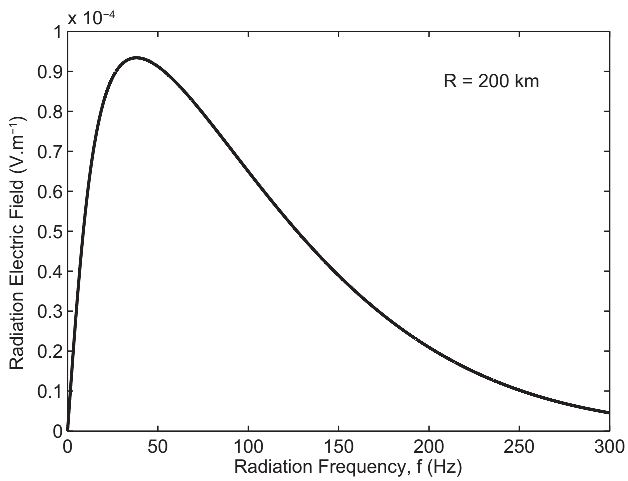

Fig. 5. Variation of the vertical electric field with frequency.

5. Energy dissipated in the red sprites

As we know, the energy loss in the upper atmosphere due to the quasi-electrostatic heating and inelastic collisions between runaway electrons and neutral N_2 and O_2 molecules comes in the form of sprites. The released energy dissociates into ionization, excitation, expansion, radiation and kinetic motion of the particles in the body of sprites. The total energy loss in sprites is given below:

$$W = \int_{t=0}^{\infty} U_k \; i(t) \; dt \tag{11}$$

where U_k is the potential difference between 40 km and 90 km altitudes.

The value of U_k can be calculated with the help of conventional breakdown electric field E_k.

$$U_k = -2160\times10^3 \int_{h=40\ km}^{90\ km} e^{\frac{-h}{H}}\ dh \tag{12}$$

The calculated value of potential difference U_k for the propagation of sprites between 40 km and 90 km is around 60 MV. With the help of Eqs. (11) and (12), the value of total energy loss in the body of sprites comes out to be of the order of 10^9 J, which is one order of magnitude less than the previous estimated value of 10^{10} J (Dowden *et al.,* 1996).

6. Results and discussions

The sprite electrical parameters, namely current moment, charge moment change and radiation electric field, have been calculated. The peak value of the current moment is 260 kA/km for a peak current of 5 kA. Cummer *et al*. (1998) measured the current moment of three sprites and reported values ranging from 150 to 240 kA/km. The total charge transferred from stratosphere to ionosphere by the sprites is around 63 C, corresponding to the peak current of 5 kA. Cummer *et al*. (1998) observed three sprites having peak currents ranging from 1.3 to 3.3 kA. If we take the peak current in the sprite channel to be 3.3 kA, the calculated value of total charge transfer comes to be around 41 C, which is consistent with the 42 C charge transfer for the largest of the three sprites reported by Cummer *et al*. (1998). The calculated maximum value obtained for the charge moment change is around 2050 C/km. The value of the radiated electric field in the frequency domain has also been calculated. The vertical electric field radiated by sprites lies within the ELF (0-300 Hz) range. The vertical electric field peaks at around 40 Hz with an amplitude of 9.3×10^{-5} V/m at 200 km from the sprite channel (Fig. 5), which is in conformity with the experimental values reported by different researchers (Cummer *et al.,* 1998; Cummer, 2003). These ELF waves generated from the sprite propagate in the earth-ionosphere waveguide and may contribute to the Schumann resonances. It is suspected that the sprites play a crucial role in enhancing the ionospheric temperature reported by Sharma *et al.* (2003). Finally, we calculated the energy dissipated in the sprite body due to the quasi-electrostatic heating and runaway mechanism, which was of the order of 10^9 J, one order of magnitude less than the previously reported value of 10^{10} J (Dowden *et al*., 1996).

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References

Aramyan A. R. and G. A. Galechyan, 2009. Formation of red sprites. *Laser Phys.* **19**, 1480-1482.

Bell T. F., V. P. Pasko and U. S. Inan, 1995. Runaway electrons as a source of red sprites in the mesosphere. *Geophys. Res. Lett.* **22**, 2127-2130.

Boccippio D. J., E. R. Williams, S. J. Heckman, W. A. Lyons, I. Baker and R. Boldi, 1995. Sprites, ELF transients and positive ground strokes. *Science* **269**, 1088-1091.

Cummer S. A., U. S. Inan, T. F. Bell and C.P. Barrington-Leigh, 1998. ELF radiation produced by electrical currents in sprites. *Geophys. Res. Lett.* **25***,* 1281-1284.

Cummer S. A., 2003. Current moment in sprite-producing lightning. *J. Atmos. Sol-Terr. Phys*. **65**, 499-508.

Cummer S. A., H. U. Frey, S. B. Mende; R. R. Hsu, H. T. Su, A. B. Chen, H. Fukunishi and Y. Takahashi, 2006. Simultaneous radio and satellite optical measurements of high-altitude sprite current and lightning continuing current. *J. Geophy. Res.* **111***,* A10315. DOI:10.1029/2006JA011809.

Dowden R., J. Brundell, C. Rodger, O. Mochanov, W. Lyons and T. Nelson, 1996. The structure of red sprites determined by VLF scattering. *IEEE Antenn. Propag. M.* **38**, 7-15.

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

Fukunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U. S. Inan and W. A. Lyons, 1995. Lower ionospheric flashes induced by lightning discharges. *EOS Suplemment* **46***,* F114, A41D-7.

Fullekrug M., 2006. Elementary model of sprite igniting electric fields. *Am. J. Phys.* **74**, 804-805.

Gurevich A.V. and K. P. Zybin, 2001. Runaway breakdown and electric discharges in thunderstorms. *Phys-Usp*. **44***,* 1119-1140.

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

Leise J. A. and W. L. Taylor, 1977. A transmission line model with general velocities for lightning. *J. Geophys. Res.* **82***,* 391-396.

Li J. and S. A. Cummer, 2009. Measurement of sprite streamer acceleration and deceleration. *Geophys. Res. Lett.* **36**, L10812. DOI:10.1029/2009GL037581.

McHarg M. G., R. K. Halland, D. Moudry and H. C. Stenbaek-Nielsen, 2002. Altitude-time development of sprites. *J.Geophys. Res.* **107**(A11), 1364. DOI: 10.1029/2001JA000283.

Moudry, D. R., H. C. Stenbaek-Nielsen, D. D. Sentman and E. M. Wescott, 2002. Velocities of sprite tendrils. *Geophys. Res. Lett.* **29**, 1992. DOI: 10.1029/2002GL015682.

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

Pasko V. P., U. S. Inan, Y. N. Taranenko and T. F. Bell, 1997. Sprites produced by quasi-electrostatic heating and ionization in the lower ionosphere. *J. Geophys. Res.* **102,** 4529-4561.

Petrov N. I. and G. N. Petrova, 1999. Physical mechanisms for the development of lightning discharges between a thundercloud and the ionosphere. *Tech. Phys.* **44**, 472-475.

Price C., M. Asfur, W. A. Lyons and T. Nelson, 2002. An improved ELF/VLF method for globally geolocating sprite-producing lightning. *Geophys. Res. Lett.* **29**, 11-14.

Rai J., 1978. Current and velocity of the return stroke lightning. *J. Atmos. Terr. Phys.* **40**, 1275-1280.

Raizer Yu. P., G. M. Milikh, M. N. Shneider and S. V. Novakovski, 1998. Long streamers in the upper atmosphere above thundercloud. *J. Phys. D: Appl. Phys.* **31**, 3255-3264.

Reising S. C., U. S. Inan, T. F. Bell and W. A. Lyons, 1996. Evidence for continuing current in sprite-producing cloud-to-ground-lightning. *Geophys. Res. Lett.* **23**, 3639-3642.

Roussel-Dupré R. A. and A.V. Gurevich, 1996. On runaway breakdown and upward propagating discharges. *J. Geophys. Res.* **101**, 2297-2311.

Rycroft M. J. and A. Odzimek, 2010. Effects of lightning and sprites on the ionospheric potential and threshold effects on sprite initiation, obtained using analog model of the global atmospheric electric circuit. *J. Geophys. Res.* **115** (A00E37). DOI:10.1029/2009JA014758.

Sentman D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton and M. J. Heavner, 1995. Preliminary results from the Sprites94 Aircraft Campaign: Red sprites. *Geophys. Res. Lett.* **22***,* 1205. DOI:10.1029/95GL00583.

Sharma D. K., J. Rai, M. Israil, P. Subrahmanyam, P. Chopra and S. C. Garg, 2003. Enhancement in ionospheric temperatures during thunderstorms. *J. Atmos. Solar-Terr. Phys.* **66**, 51-56.

Stanely M., P. Krehbeil, M. Brook, C. Moore, W. Rison and B. Abrahams, 1999. High speed video of initial sprite development. *Geophys. Res. Lett.* **26**, 3201-3204.

Taranenko Y. N. and R. A. Roussel-Dupré, 1996. High altitude discharges and gamma-ray flashes: a manifestation of runaway air breakdown. *Geophys. Res. Lett.* **23**, 571. DOI:10.1029/95GL03502.

Williams E. R., 2001. Sprites, elves, and glow discharge tubes. *Phys. Today* **54**, 41-47.

Williams E., E. Downes, R. Boldy, W. Lyons and S. Heckman, 2007. Polarity asymmetry of sprite-producing lightning: a paradox? *Radio Sci.* **42***,* 15 pp. DOI:10.1029/2006RS003488.

Wilson C. T. R., 1925. The electric field of a thundercloud and some of its effects. *P. Phys. Soc. Lond.* **37**, 32D. DOI:10.1088/1478-7814/37/1/314.

Winckler J. R., 1995. Further observations of cloud-ionosphere electrical discharges above thunderstorms. *J. Geophys. Res.* **100,** 14335-14345. DOI:10.1029/95JD00082.