Radiation Phenomenon Due to Streamers of Sprites

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Abstract

An upper atmospheric phenomenon *i.e.*, sprites can be thought to be mainly caused by the propagation of positive corona streamers. This research presents the formulation for the calculation of radiation power received from the propagating corona streamers responsible for the origination of the sprites. The produced magnetic field variation using the calculated electromagnetic radiation power is found to be similar with the previous observation-based research work.

Keywords

Sprites, Radiation, Electric Field, Magnetic Field, Power, TLEs (Transient Luminous Events)

1. Introduction

C.T.R. Wilson, in 1925, firstly produced the theory of existence of thundercloud flashes high above the clouds which Sprites [1]. These sprites are the transient luminous events (TLEs) (**Figure 1(a)**) which are developed by the electromagnetic coupling between positive CG (cloud to ground) lightning discharges and thunderstorm charges present at stratospheric/mesospheric level. Actually, the sprites phenomenon occurs due the streamers discharges present during the propagation of sprites. They are optical flashes out for few milliseconds only with the speed of 10^7 m/s. They may reach at the maximum altitude of 40 to 95 Km and horizontally extend up to ~30 - 40 km. According to Qin *et al.* [2], the variation in their optical shapes and sizes arises for different types of sprites e.g., jellyfish sprite, column sprite (C-sprite), carrot sprite. These are mostly associated with the positive cloud to ground lightning phenomenon [3].

During three decades after the discovery of sprites since 1989, different theories have been established to understand the mechanism of sprites phenomenon e.g., conventional breakdown of air, relativistic runaway theory, gravity waves, Schumann resonance phenomenon etc. [4]. A number of filamentary structured streamers are presented in the sprite events which are usually responsible for the radiation from these sprites (Figure 1(b)).

Many authors demonstrated that the electromagnetic radiation took place by the CG lightning discharges comes under the radio frequency range as explained by Singh *et al.* [5]. Also, Farges and Blanc [6] and some other authors and have confirmed about the electromagnetic field which are associated with the sprites is highly comes under the ELF (Extremely low frequency) range. Different models as of Qin *et al.* [7] illustrate the mechanism for the positive corona streamers and demonstrate that these are the true cause of initiation of the sprites. Paras *et al.* [8] had also estimated the electric and magnetic field conception of RS-LC (Return stroke-lateral corona streamers) system and well defined the red sprites in time and frequency domain. Cummer *et al.* [9] have proposed the first experimental confirmation of radiation generated by the electrical currents flowing in the streamers of sprites' body to be in ELF range. Recently it is also analysed that during the streamer propagation, UHF and VHF radiation or greater frequency radiation produced due to the collision of these streamers. It is well reported out by Shi *et al.* [10].

Here we have tried out a previously used model [11] for the radiation from lightning to find out the variation of electromagnetic radiation produced by the streamers of sprites. The outcomes will be useful for further study and understanding the hypotheses made about the sprites and lightning in past. It will also produce a great effect in the atmospheric electricity. We have introduced here the whole modelling and the calculations are carried out to plot the results which
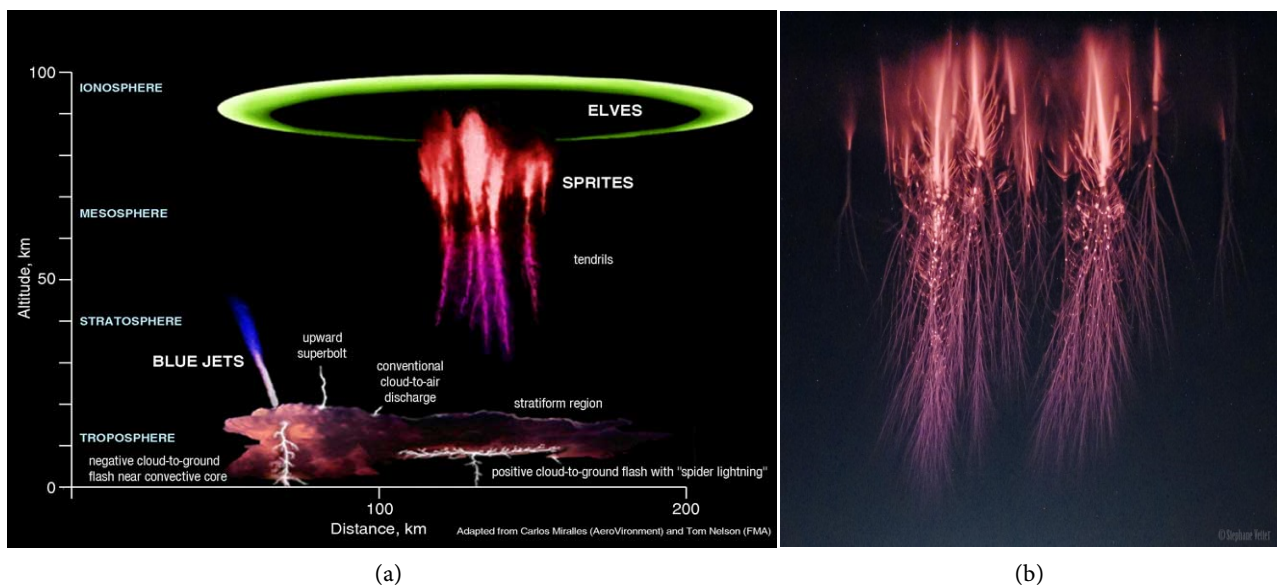
Figure 1. (a) Schematic illustration of Transient Luminous Events (TLEs); (b) Sprite lightning (HD view).

specify the mechanism of electromagnetic radiation due to streamers through sprites system.

2. Theoretical Model

As we know that electrical discharges present in stratospheric/mesospheric level produced by the streamers come out in the form of sprites. The optical movement of sprites can be seen up to the height of 40 to 90 km. Various electrical parameters for the radiation of streamers has been measured and defined by previous research workers [5].

2.1. Modelling Based Calaculations

The streamers propagate in form of a conical shape [11] onto their path by an exponential rise of charge on their tip [12]. The tip [taking width "a"] of this conical shape contains positive charge Q and rest part of this shape is uniformly distributed by negative charge –Q as defined by **Figure 2**. This model and formulation is formerly used by Pathak [11] for the higher frequency radiation from traditional lightning, *i.e.*, intracloud as well as CG lightning.

This whole system creates a variable dipole with dipole moment [11]

$$p(t) = \int r\rho(r,t)\mathrm{d}V \tag{1}$$

The integration gives

$$P(t) \approx (Q/4)z\hat{k} \tag{2}$$

where,

$$Q(t) = Q_0 \exp(t/\tau) \tag{3}$$

The calculation can be performed as the model used by Pathak [11]. The calculation steps are hereby shown above and below for clarity again.

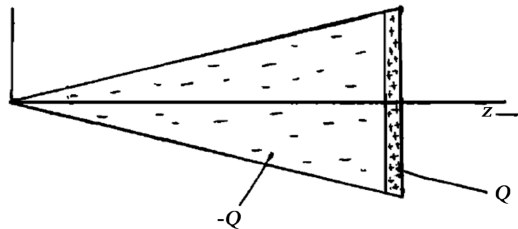Thus, the radiation power is formulated as,

$$P(t) = (1/4\pi\varepsilon_0)(2/3)\left(|p|^2\right)\big/c^3 = P_0(2+t/\tau)^2 \exp(2t/\tau) + P_1 t^2 \tag{4}$$

here, c and ε_0 are the speed of light in vacuum and permittivity of free space respectively. Then,

$$P_0 = \left(q_0 v^2/\tau^2\right)\big/96\pi\varepsilon_0 c^3 \text{ and } P_1 = 3Q_0 v^6\big/8\pi c^3 z_0^4 \tag{5}$$

By applying the Fourier transformation to transform the P_0 into the frequency domain, one gets

Figure 2. Assumed charge distribution in the streamer cone.

$$\left[P(\omega)\right]^2 = \left[\int_0^t P(t)\cos \omega t \mathrm{d}t\right]^2 + \left[\int_0^t P(t)\sin \omega t \mathrm{d}t\right]^2 \tag{6}$$

Now, assuming the case when $T\left(= 2\pi/\omega = 1/f\right) > t_0$; the above integration formulation can be separated into two parts. Thus, first part of Equation (4) is integrated between 0 and t_0 limits and the second part of it is integrated between t_0 and T limits. Further Equation (6) is divided in real and imaginary parts as shown below,

$$\left[P(\omega)\right]^2 = \underset{\text{real}}{\left[P(\omega)_R\right]^2} + \underset{\text{imaginary}}{\left[P(\omega)_I\right]^2} \tag{7}$$

Subsequently the formulation becomes as,

$$P(\omega)_R = 4P_0 I_{1t} + \left(4/\tau\right) I_{2t} + \left(1/\tau\right)^2 I_{3t} + P_1 I_{4t} \tag{8}$$

$$P(\omega)_I = 4P_0 I_{1t}' + \left(4/\tau\right) I_{2t}' + \left(1/\tau\right)^2 I_{3t}' + P_1 I_{4t}' \tag{9}$$

These above expressions are specified by Pathak [11].

By theoretical observations of sprites (Surkov *et al.* [13] and the references cited therein), the speed of streamers can be taken as

$$v \approx 10^6 \ \mathrm{m/s} \ .$$

An electrodynamics relation between radiated power and electric field is included in the thesis of Pathak [14] as the expression below:

$$P = E^2/120\pi$$

Whereas the electromagnetic theory says,

$$E = cB \tag{10}$$

Here, c is the speed of light *i.e.*, $c = 3 \times 10^8$ m/s

Then, the for the radiated power becomes

$$P = c^2 B^2/120\pi \tag{11}$$

Therefore,

$$B = \frac{\sqrt{120\pi P}}{c} \tag{12}$$

Pathak (1982) [14] included in his thesis that the effective power received at a distance "r" from the vertical propagation of sprites channel of radius "R" and length "L" is given by

$$P(\omega) = \frac{3}{4}\left(P_B(\omega)R^2\right)/r \cdot \tan^{-1}\left(\frac{L}{r}\right) \tag{13}$$

And $P_B(\omega)$ is the power radiated by one streamer only.

We have plotted radiated power with time in **Figure 3**.

2.2. Values Specification

Sprites can radially spread up to 10 km and here L can be taken as $\approx$60 km (*i.e.*, the altitude range of corona streamers of sprites) and if r is taken as 60 km. Then, Equation (12) resulted out for the magnetic field of sprites containing streamers and the produced magnetic field has been shown in **Figure 4**. The
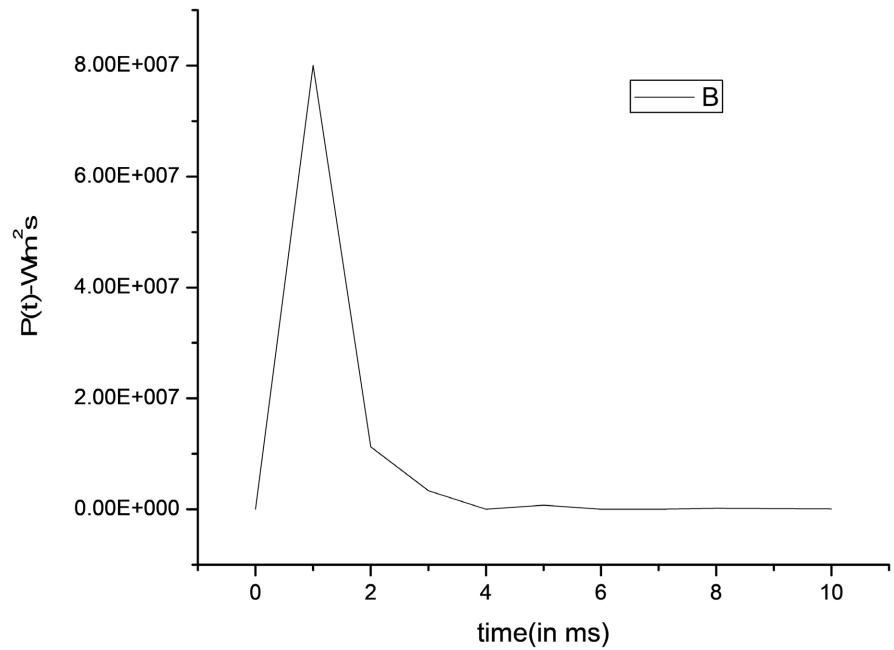
Figure 3. Calculated radiated power for the sprites plotted with the time.
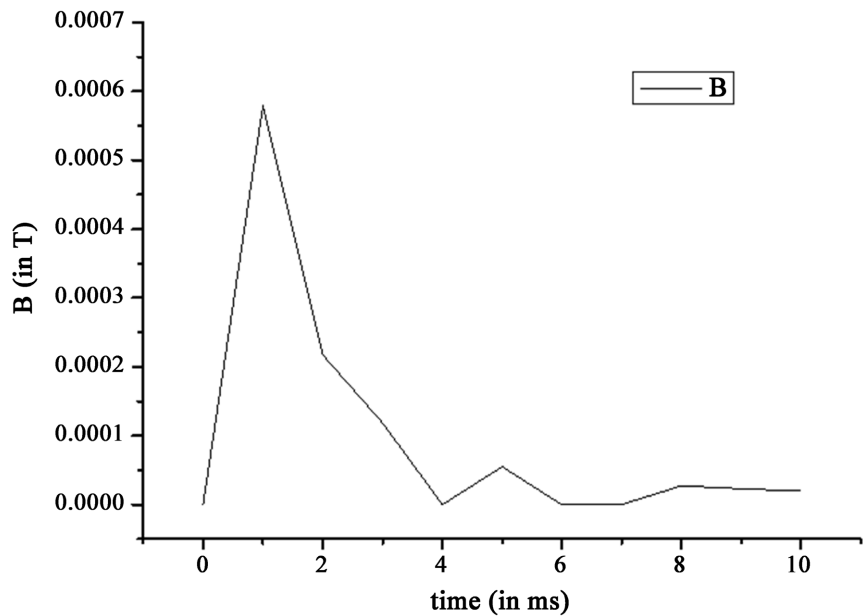
Figure 4. Calculated magnetic field sferic plotted with the time domain.

streamers propagation angle is taken as 15 degree as founded by Mcharg *et al.* [15].

Cummer *et al.* [9] found its instrumental observed sferic with the peak at 1 ms and 5 ms approximately equal to 0.000125 T and 0.00005 T respectively. If we compare our calculations, it brought the exact curve with the values 10^{-4} T and 5.4968×10^{-5} T at 1 ms and 5 ms respectively. Such that, we may say that the upper plotted sferic based on the Pathak [11] model is found to be true with the sferic which is actual practically observed by Cummer *et al.* [9].

3. Result and Discussions

In our paper, ELF (extremely low frequency) radiation through the propagation of streamers present in the sprites system has been estimated by adopting an earlier theoretical modelling, so that we may be able to bring the simulation result for the power radiated through the constituent streamers of sprites. Air density, thundercloud temperature, air pressure, the active atmospheric inhomogeneity, number of streamers etc. are assumed to be the important factors affecting the speed of and radiated power from sprites. It is also observed that the collision of streamers with each other during the time of occurrence the sprites is also favourable in emitting the strong or weak radiation. The length of streamers and the head on collision helps in producing the higher frequency electromagnetic radiation [10]. In our above numerical calculations, the radiated power variation with the time is established as shown in the **Figure 3**. The speed of constituent streamers of sprites grows with time, so the radiated power also increases with time. Eventually the peak $P(t) = 8.005320673 \times 10^7$ Wm^{2}s is observed at $t = 1$ ms with the values $\tau = 3.22246 \times 10^{-8}$ s & $Q_0 = 10^{-19}$C at the time of occurrence. And that symptomized to very low frequency electromagnetic radiation produced through the time taken and the growing speed of discharged streamers.

By above estimation of radiated power and further calculations, magnetic field variation has been plotted in the time frame. **Figure 4** described that the magnetic sferic due to streamers of sprites peaks at 1 ms and 5 ms. Afterwards the magnetic field due to radiation goes on decreasing. These peaks may be the result of different meteorological conditions occurring at that time of phenomenon such as perturbations of electrical discharges present on that place, variation in air density which is different for the different altitudes. It comes out that the magnetic field is of the order of approximately 10^{-9} T which is same as given by the experimentally observed sferic by Cummer [9]. The radiation produced through the streamers of sprites is under the radio frequency range or ELF range. The model used by Qin *et al.* [16] and our modelled results demonstrate the same conclusion about magnetic sferic of sprites. As such our sferic results are experimentally verified by the Cummer [9].

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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