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TROPOSPHERIC LIGHTNING AS A SOURCE OF HIGH ALTITUDE LIGHTNING (HAL) DISCHARGES

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ABSTRACT

High altitude lightning (HAL) discharges are a family of short lived electrical-breakdown phenomena that occur at altitudes ranging from cloud tops to the ionosphere. HAL discharges include mainly blue starters, blue jets, red sprites and elves. In this paper, it is described that the tropospheric cloud-to-ground (CG) lightning discharges pave the way of HAL discharges. The electric field, generated due to CG lightning discharge in the upper atmosphere is calculated. This electric field deposits the heat energy in the ambient space which comes in the form of HAL discharges. An altitude profile of heat energy density, deposited in the body of HAL discharges is also calculated. The HAL generating electric field deposits huge amount of energy at lower altitudes as compared to the higher altitudes. The energy loss at an altitude of 20 km where blue starters/jets initiate comes out to be of the order of 10^{-4} Jm^{-3}. Similarly the energy loss at sprite initiating altitude (70 km) comes out to be of the order of 10^{-8} Jm^{-3}. This shows that the blue starters/jets are more luminous as compared to the red sprites, which is in conformity with the experimental observations.

Keywords: Lightning, Sprites, Blue jets, Blue starters, Elves, Ionosphere

INTRODUCTION

High altitude lightning (HAL) discharges are the optical emissions which occur from the top of the thunderclouds to the lower ionosphere. HAL discharges include mainly blue starters, blue jets, red sprites, and elves. Although Scottish physicist C. T. R. Wilson had predicted about them in 1920, the direct visual evidences were documented on July 6, 1989 by scientists from the University of Minnesota. These discharges are categorized according to their physical properties, altitudes of occurrence, duration, and the kind of emissions they produce.

Blue starters and blue jets are blue colored upward moving luminous phenomena which initiate directly from the top of the active thundercloud. Blue starters initiate from 17.7±0.9 km and propagate upwards up to 25.7 km with a velocity ranges from 27-153 km/s [1]. Blue jets appear to propagate in a conical shape at speeds of 100 km/s and reach the terminal altitudes of 40-50 km [2]. The duration of blue jets ranges from 200-300 ms [2]. It has been seen that sometime streamers initiate as a blue starters and get converted into blue jets at higher altitudes [2]. Blue starters appear to be brighter than blue jets.

Red sprites are the mesospheric phenomena which occur at altitudes ranging from 40 to 80 km [3]. These are the most frequent candidates among the HAL discharges. Sprites are classified into two types-“columniform” and “carrot” sprites [4]. Columniform sprites are smaller in size whereas carrot shaped sprites are very large, highly energetic, and always occur in clusters [5]. Sprites are primarily red in color and turn in blue kind of tendril structures at lower altitudes. These are associated with strong positive cloud-to-ground (CG) lightning discharges [6]. The duration of these discharges are short, ranging from one millisecond to tens of milliseconds [7]. They usually occur at the dying stage of the thunderstorm. Red sprites are the strong source of extremely low frequency (ELF) radiation [8,9]. Sprites consist of streamers [10]. Such streamers are initiated in the lower ionosphere by electron patches caused by the electromagnetic radiation from horizontal intracloud (IC) lightning and then develop downwards in the static electric field due to the thundercloud. Hu et al. [11] reported that the ambient electric field "E" for the initiation of sprite streamers can be well below the local air breakdown electric field "E_k". They observed the value of E about 0.2 E_k, 0.3-0.5 E_k and above 0.5 E_k to initiate dim, typical and bright sprites respectively. Sprite streamers can propagate upwards as well as downwards from their point of origination. Their speed of propagation ranges from (1-3) $\times 10^7$ ms^{-1}[12].

Elves are lower ionospheric discharges which occur at altitudes of 75-105 km. They have very short duration typically < 1 ms, and appear as a dim flattened and expanding glow of 100-300 km in diameter [13]. Their speed of propagation ranges from one-tenth to the one-third of the speed of light. Experimental observations have been shown that elves are associated with VLF radiation. They generally require large peak current (>70 kA) of CG lightning for initiation [13].

In this paper, a process has been described which can generate the HAL discharges. The HAL discharges generating electric field has been calculated. This electric field deposits the heat energy in the atmosphere which can excites the neutral atoms and molecules of the ambient atmosphere resulting in different kind of discharges.

HAL DISCHARGES GENERATING ELECTRIC FIELD:

Blue jets and blue starters are formed by an attachment-controlled ionizing wave which move upwards in the presence of downward directed quasi-electrostatic field, caused by the extraordinary large thundercloud charge (Q>100 C) transfer by the strong positive CG lightning discharges [14]. The thundercloud charge is carried out by the stepped leader, propagating from cloud to ground in discrete steps. As the stepped leader nears the ground, a highly luminous ground potential wave called "return-stroke" is generated. Return stroke contain the maximum amount of current. A typical CG lightning discharge is associated with both return stroke current and continuing current. Return stroke current is momentary (~100 μs) while continuing currents flows over a longer period of time (several tens of ms). Red sprites are produced due to the large continuing current moment (>11 kA.km) and charge moment change (>600 C.km) associated with parent CG lightning discharges [15]. There are evidences of continuing currents in sprite producing CG and horizontal IC lightning discharges [16, 17]. Experimental observations indicate that elves are also associated with large CG lightning discharges, but preceding the onset of sprites [13]. Since almost all the HAL are associated with the strong CG lightning discharges, so we consider only the positive CG lightning discharges for our calculation. The total current associated with a positive CG lightning discharge can be written by [18]

$$I(t) = \sum_{k=1}^{4} I_k e^{-\frac{t}{\tau_k}} \qquad t \geq 0 \tag{1}$$

where,

I_1=-60.45 kA; I_2=54.1 kA; I_3=5 kA; I_4=1 kA; τ_1=1.66 μs; τ_2=33.33 μs; τ_3=30 ms; τ_4=50 ms.

The equation (1) contains both the return stroke current and continuing current. The first two terms are associated with return-stroke current. The return stroke current is not long lasting. The time period for this is about 100 µs. On the other hand the duration of continuing current is from one millisecond to a few tens of milliseconds. So, the continuing current can carry large amount of charge roughly from several tens to hundreds of coulombs. Continuing currents carry the charge slowly and help to build up the electrostatic field in the upper atmosphere.

The positive CG lightning deposits a negative charge in the cloud and produces an external electric field at altitudes z>>h given by [10]

$$E_l = \frac{hQ(t)}{\pi\varepsilon_0 z^3}\left[1+\left(\frac{z}{2h_i - z}\right)^3\right] \quad (2)$$

where,

$$Q(t) = \int_{t=0}^{t} I(t)\, dt \quad (3)$$

h=10 km, the height of the charge removal; h_i=80 km, the height of the ionosphere; ε_0=dielectric constant of air.

The total charge removed by the positive CG lightning comes out to be 200 C. This can ranges from 20-1000 C [19]. The external electric field exerts a force on the atmosphere which responds with the electric field E. The evolution of E can be described by the linear differential equation given by [20]

$$\varepsilon_0 \frac{dE}{dt} = -\sigma E + J(t) \quad (4)$$

where, $J(t) = \varepsilon_0 \partial_t E_l$ and σ(z) is the ambient atmospheric conductivity.

The atmospheric conductivity is given by [21]

$$\sigma(z) = 5\times10^{-14} \exp(z/6\ \text{km}) \quad (5)$$

The solution of eq. (4) is

$$E(t,z) = K\left[\frac{I_1 e^{-\frac{t}{\tau_1}}}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_1}\right)} + \frac{I_2 e^{-\frac{t}{\tau_2}}}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_2}\right)} + \frac{I_3 e^{-\frac{t}{\tau_3}}}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_3}\right)} + \frac{I_4 e^{-\frac{t}{\tau_4}}}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_4}\right)}\right] + C\, e^{-\frac{\sigma}{\varepsilon_0}t} \quad (6)$$

where, "K" and "C" are constants of time. The value of "K" is given by

$$K = \frac{h}{\pi\varepsilon_0 z^3}\left[1+\left(\frac{z}{2h_i - z}\right)^3\right] \quad (7)$$

The constant "C" can be calculated using the boundary conditions. The calculated electric field at the beginning of the discharge process should be zero, i.e. E(t=0)=0. Using this boundary condition the value of constant "C" comes out to be

$$C = -K\left[\frac{I_1}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_1}\right)} + \frac{I_2}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_2}\right)} + \frac{I_3}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_3}\right)} + \frac{I_4}{\left(\frac{\sigma}{\varepsilon_0}-\frac{1}{\tau_4}\right)}\right] \quad (8)$$

Eq. (6) represents the HAL discharges generating electric field. This shows that higher the ambient conductivity lower will be the E(t,z) to produce discharges. The electric field E(t,z) decays at higher altitudes quickly, but sometime if the charge transfer by CG lightning is very high then it can penetrates up to the ionospheric region where the breakdown electric field is very low to produce red sprites.

Heating of the upper atmosphere

The HAL discharges generating electric field E(t,z) deposits the electrical energy in the upper atmosphere. The heat energy density deposited in the atmosphere can be written by

$$\varepsilon_d = \int_{t=0}^{\infty} \sigma(z)E^2(z,t)\,dt \qquad (9)$$

The altitude profile of "ε_d" has been shown in Fig. 1. The calculated energy density has been compared with the previous reported value (equation no. 12) using point charge (Q=200 C) model [19]. The calculated energy density is overestimated at the altitudes below 40 km and at the same time it is also underestimated at altitudes of above 70 km as compared to the previous results [19]. It is revealed that the HAL discharges generating electric field deposits the maximum energy at the lower altitudes. So, the discharges like blue starters and blue jets are more favorable in our case. At the same time this electric field deposits the energy at upper altitudes also, so it may also be responsible for red sprites type of discharges. Further, it has been seen that the lower altitude discharges are brighter than higher altitude lightning discharges, so our altitude distribution of energy density is well in conformity with the same.

The calculated electric field "E(t,z)" endures for several milliseconds, so the ionospheric lightning discharges known as elves having very short time duration of around 0.1 ms may or may not be associated with this electric field. However, it is believed that the powerful return stroke having very short duration of around several hundreds of microseconds can generate strong electromagnetic pulses which ionize the lower ionosphere and result in elves.

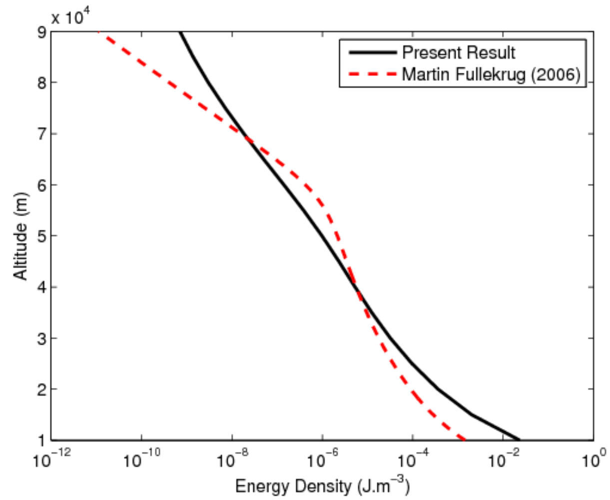

Fig. 1 The altitude profile of energy density in the upper atmosphere

RESULTS AND DISCUSSION

The electric field E(t,z) developed in the upper atmosphere for the generation of HAL discharges especially blue starters, blue jets and red sprites is calculated. At a particular time, the calculated electric field decreases with height. This electric field deposits heat energy in the ambient space to form HAL discharges. The maximum heat energy is deposited in the stratospheric region where blue starters and blue jets are initiated. An altitude profile of dissipated energy density is shown in Fig. 1. The energy density deposited at 20 km altitude comes out to be around 3.63×10^{-4} Jm^{-3}. Similarly, the energy deposited at the higher altitudes is responsible for the occurrence of red sprites. The energy density at 70 km altitude where most of the red sprites initiate comes out to be around 1.82×10^{-8} Jm^{-3}. It is found that the energy density deposited at the higher altitudes is very low as compared to the lower altitudes. It is obvious, because the electric field also decreases with height. Experimental studies have shown that the electric discharges are more favorable at low pressures. Since atmospheric pressure decreases exponentially with height, so it is assumed that this much energy may produce sufficient heating and ionization at mesospheric region to produce red sprites. Present results have been compared with the previous results and it is found well in conformity with them. One can compare the total heat energy loss in HAL with the tropospheric cloud-to-ground lightning discharges [22]. Several authors have observed the current in the body of HAL discharges especially in red sprites and blue jets [23, 24]. The vertical current moment produces the electromagnetic radiation in ELF/VLF region which can affect the ionospheric parameters like electron density, electron temperature, ion temperature and ion composition etc. HAL discharges may play the important role for the enhancement of ionospheric temperature reported by some researchers [25]. Since sprites and jets contain significant amount of current within their body so it is suspected that the HAL discharges may modify the global atmospheric electric circuit. Recently, Peterson et al. [26] reported the NO_x (NO and NO_2) production from sprites and jets in the middle atmosphere. They used a pressure-controlled chamber and high-voltage power supply to simulate the HAL discharges. Production of NO_x may enhance the level of ozone in the tropospheric and stratospheric regions which points the critical issue of “Global Warming”.

CONCLUSION

The principal objective of the above study was to investigate the association of tropospheric lightning with HAL discharges. The electric field generated due to strong positive CG lightning discharges in the upper atmosphere has been calculated. Further, the heat energy density deposited due to the electric field at different altitudes has also been calculated. The deposited heat energy decreases with altitude, which describes that the lower altitude discharges like blue starters/jets are more luminous than the higher altitude discharges like red sprites. We hope this study will be useful to solve the future aeronautics and space related problems.

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