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A study on heating of the lower ionosphere during lightning

S S De[1], S K Adhikari[1], M De[1] & B Bandyapadhyay[1]
and
A Guha[1], Suman Paul[1] & B K De[2]
[1]Centre of Advanced Study in Radiophysics & Electronics, University of Calcutta, Kolkata 700 009, India
[2]Department of Physics, Tripura University, Suriyamaninagar 799 130, West Tripura, India
E-mail: de_syam_sundar@yahoo.co.in

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Heating of the ionosphere due to incidence of electromagnetic pulses coming from lightning discharges has been theoretically investigated. The electromagnetic radiation from lightning discharges produces variation in ionizing frequency and effective collision frequency of electrons. The energy gained by the free electrons from the incident electric fields of wide-band electromagnetic pulses from lightning strikes is not instantaneously transferred to the heavy particles in the medium, due to which the electron temperature is raised. Variation of temperature increase has been estimated.

Keywords: Lightning discharge, Ionospheric heating

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1 Introduction

Various earlier models exist for the investigation of the primary and subsequent cloud-ground discharges including the effects of the leader and the return stroke current[1-3]. Above the thunderstorm cloud, the presence of luminous flashes at high altitudes is due to lightning. The peak luminosity is found[4,5] in the vicinity of 60 km. Various effects in the lower D-region of the ionosphere produced by electromagnetic radiations from lightning have been reported in terms of heating, attachment and ionization[6,7]. Wide-band electromagnetic pulses radiated from lightning strokes initiate the process of heating[8]. In this presentation, a model of electron heating at the lower edge of the ionosphere (D-region) due to incidence of electromagnetic pulses coming from lightning discharges has been investigated theoretically. A model for a vertical electric dipole is assumed to be present over the surface of the ground, capable of radiating mostly the horizontal component of electric field. There will be very weak and deficient radiations from the dipole in the upward direction. Hence, electron heating above this discharge is very poor. Thus, the influence of horizontal lightning strokes causing the variation of temperature increase will be discussed in this paper.

The electromagnetic radiation from lightning discharges produces variation in electron temperature, ionizing frequency and the effective collision frequency of electrons. The magnitude of temperature changes of electrons has been estimated through some model calculations.

2 Mathematical formulation

The physical situation may be represented in the more appropriate form by the following energy balance expression, the momentum transport equation and continuity equation[9] as:

$$\frac{3}{2}\frac{\partial}{\partial t}\left(NkT_e\right)+eN\nu(E+\nu\times H)+G_{eff}\left(T_e\right)\nu_e\left(T_e\right)$$
$$+\frac{3}{2}\delta\nu(T_e)Nk(T_e-T)-\nabla q-\chi\nabla^2 T+Q\frac{\partial N}{\partial T}=0 \quad \ldots (1)$$

$$\frac{\partial \nu}{\partial t}+(\nu.\nabla)\nu=-\frac{e}{m}E(t)-\upsilon_e(T_e)\nu$$
$$-\frac{e}{m}(\nu\times H)-\frac{\nabla p}{m}+\frac{\eta}{m}\nabla^2\nu \quad \ldots (2)$$

$$\frac{\partial N}{\partial t}=\left(\nu_i-\nu_\alpha\right)N-\alpha N^2 \quad \ldots (3)$$

where, $E(t)$ is the radiated horizontal electric field; H, the geomagnetic field; ν_i, the ionization frequency due to electron impact on neutrals; ν_e, the effective electron collision frequency; ν_α, the electron-neutral molecule attachment frequency; ν, the average electron velocity; Q_i, the ionization energy of the medium; N, the electron number density; $\delta = \frac{2m}{m'}$, m' is the mass of the heavy particle; T, the equilibrium temperature; T_e, the electron temperature; η, the coefficient of viscosity of the medium; χ, the thermal conductivity; G_{eff}, the effective fraction of energy transfer per collision; α, the electron–ion recombination coefficient and q is the heat flow vector given by

$$q = -\lambda(T_e)\nabla T_e$$

where, $\lambda(T_e)$ is the effective coefficient of electron energy conduction. Now

$$\lambda = k_T\left(1-\mu\tau'/\sigma_0 k_T\right)$$

where k_T is the coefficient of electron energy conduction at constant electron velocity; μ, the coefficient of electron energy conduction due to dc electric field; τ', the current flow coefficient due to thermal gradients at constant electron pressure, $p = NkT_e$; σ_0, the dc electrical conductivity and k is the Boltzmann constant. The other symbols have their usual significance.

Due to incidence of lightning pulses in the weakly ionized D-region of the ionosphere, the effective electron collision frequency (ν_e) and the ionizing frequency (ν_i) vary with electron temperature (T_e) because of their dependence on the average electron velocity. The ionization frequency ν_I represents the production and loss processes due to electron impact on neutrals. The asymptotic expression for ν_I when $kT_e << Q_i$ can be given by [10,11]

$$\nu_i(T_e) = n\left(\frac{8kT_e}{\pi m}\right)^{1/2}\left(\pi a_0^2\right)\exp\left(-\frac{Q_i}{kT_e}\right) \quad \ldots (4)$$

n is the neutral particle number density, a_0 the Bohr radius.

For wide energy range of electrons, the collision frequency would be averaged over the Maxwellian distribution of electron velocities, which is referred to as the effective collision frequency[12,13]. It has been taken as

$$\nu_e = n\nu S_m(\nu) \quad \ldots (5)$$

where, S_m is the velocity dependent momentum transport cross-section. Within the lower ionosphere, the collision between N_2, O_2 and Ar are important for the determination of effective collision frequency. Electron-neutral particle collisions are strongly dependent on T_e. The S_m values for O_2, N_2 and Ar are expressed as[14]

$$S_m = a + bT_e^{1/2} + cT_e + dT_e^{3/2} \quad \ldots (6)$$

where a, b, c, d are constants and dependent on the scattering length, polarisability of the target and different gas constants. The S_m values for O_2, N_2 and Ar are fitted to the power series in $T_e^{1/2}$ [Eq. (6)] by employing the experimental data of Englehardt *et al.*[15], Spencer and Phelps[16] and Milloy *et al.*[17], respectively. Values of the constants a, b, c and d are given in Table 1.

From Eq. (2), the expression of ν can be obtained as

$$\boldsymbol{\nu} = \exp(-A)\frac{e}{m}\int_0^t \boldsymbol{E}(t')\exp\{A + \int_t^{t'} Mdt''\}dt' \quad \ldots (7)$$

$$A = \int_0^t\left\{(\boldsymbol{\nu}.\nabla) + \nu_e(T_e) + \frac{\eta k^2}{m} + \frac{C}{m}\right\}dt' \quad \ldots (8)$$

$$M = \begin{pmatrix} 0 & H_z & -H_y \\ -H_z & 0 & H_x \\ H_y & -H_x & 0 \end{pmatrix}, \text{ and}$$

C is the Reynold's number. It determines the influence of pressure gradient within the plasma. Under different dynamical situations, a small value of C implies the dominance of fluid friction, and otherwise the effects of inertial force outweigh the effects of friction for a large value of C.

Substituting $\frac{\partial N}{\partial t}$ from Eq. (3) to Eq. (1) and making some algebraic simplifications, one can get the expression of normalized electron temperature as

Table 1—Values of *a, b, c, d* of Eq. (6)

Species	*a*	*b*	*c*	*d*
O_2	0.51468 (– 16)	0.14597 (– 16)	– 0.12554 (– 18)	0.35801 (– 21)
N_2	0.85924 (– 16)	0.12275 (– 16)	0.12679 (– 18)	– 0.16887 (– 20)
Ar	78638 (– 15)	– 0.39515 (– 16)	0.65673 (– 18)	– 0.35480 (– 20)

$$y=\frac{T_e-T}{T}=\frac{2}{3NkT\delta\nu_e(T_e)}[k_T(1-\frac{\mu\tau'}{\sigma_0 k_T})k^2T_e$$

$$-\chi k^2T-G_{eff}\nu_e(T_e)-Q_i\{(\nu_i-\nu_\alpha)N-\alpha N^2\}]-$$

$$-\frac{ie}{3\pi\varepsilon c^2[\exp\{\delta\nu_e(T_e)t\}-1]kT}$$

$$\int_0^t[-\exp(-A)\frac{e}{m}\int_0^{t'}E(t'')\exp\{A+\int_{t'}^{t''}Mdt'''\}dt']$$

$$\frac{\omega IdS(\omega)W(x)}{h}\times\exp\{-ikD+\delta\nu_e(T_e)t\}dt \qquad \ldots (9)$$

where $W(x)=\frac{x}{(x^2+1)^{3/2}}$, $\quad x=\frac{R}{h}$

Here h is the height of the lower edge of the ionosphere; $W(x)$, the space dependent part of the incident field; R, the horizontal distance from the source; ω, the angular wave frequency; IdS, the current moment of the source and D is the distance from the source to a point at the edge of the ionosphere.

3 Results

The heating effects have been considered by lightning strokes with specific temporal and spatial variations of temperature increases. The median peak current of 24 kA is assumed to reach after some microseconds (μs) later from the start[2,8]. The radiated spectra cover a wide frequency range from few Hz to several kHz. Numerical analysis reveals that in the time domain for horizontal discharges, the waves give a short intense positive pulse having a peak near around 4 μs [Fig. 1(a)], then shows an exponential decay, and are followed by a broad weak negative pulse with the maximum around tens of μs. The first positive pulse provides the heating of the lower ionospheric electrons. The nature of variation agrees with the previous work[8].

For the day-time model, the ionospheric plasma is taken to be sharply bounded at a height h = 50 km, where T = 272 K, the ambient temperature[18]. The peak velocity of the streamer is assumed as 9×10^7 ms^{-1}. The height of the lower edge of the ionosphere

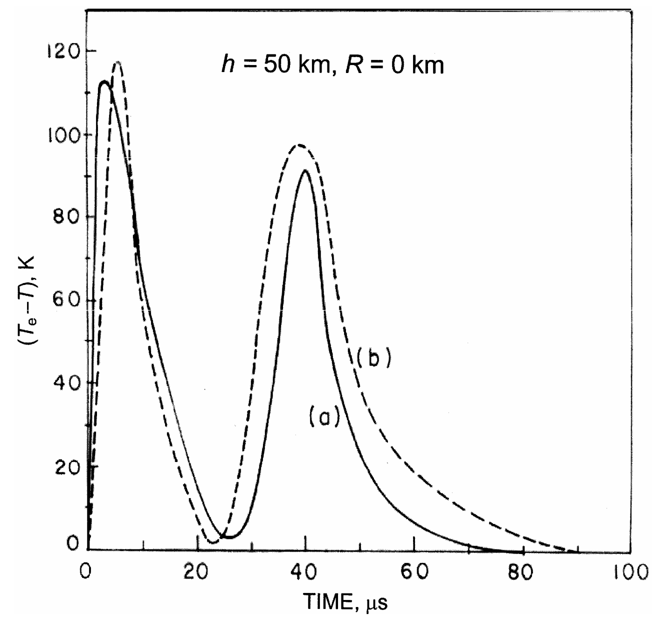

Fig. 1—Increase of electron temperature over the ambient value just after the horizontal discharge [The continuous line curve (a) represents the results of the present analysis. Here, the intense pulse gives the peak around 4.6 μs. At this instant after the start, the value of electron temperature may be even 115 K higher than its undisturbed value. Lightning discharge height = 4 km, h = 50 km. The dotted line curve (b) is due to an earlier work[2] analyzed under the identical physical situation.]

is chosen as 50 km, where the heating effects occur due to the incidence of electromagnetic pulses from lightning discharges. Here, the progression of a uniformly charged leader streamer has been considered from a spherical distribution of negative charge in the thundercloud towards the ground at a constant velocity. The frequencies used in the present calculations are 5.88×10^5 Hz, 3.03×10^4 Hz, 2.0×10^3 Hz and some other lower values. The calculation shows substantial heating from a single median stroke of cloud-to-ground discharge. The location of the lightning discharge is taken at a height of 4 km from the ground. The direct and ground reflected pulses have been considered. For horizontal discharges, the temporal variation of electron temperature above the stroke produced by the same source has been evaluated using Eq. (9). In the numerical analysis, data are taken from CIRA 72, IRI and different published papers. From the numerical analysis of Eq. (9), the plot of (T_e – T) versus time is drawn in Fig. 1(a). The continuous line curve of Fig. 1(a) represents the results of the present analysis, whereas the results of an earlier work [2] are shown by the dotted line curve [Fig. 1(b)]. It is seen from the

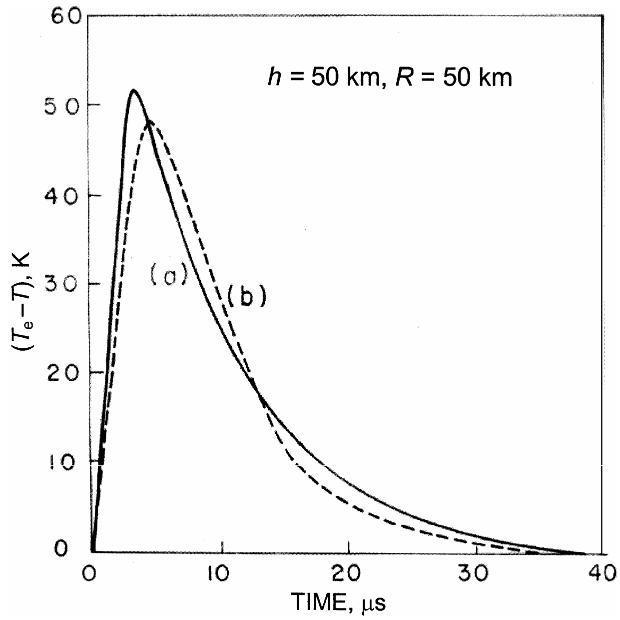

Fig. 2—Plots of variation of electron temperature over the surrounding value versus time for vertical discharge [The continuous line curve (a) shows the results of the present analysis whereas the dotted line curve (b) is due to an earlier work[2].]

present analysis that due to lightning discharges, the value of electron temperature at the lower ionosphere may be even 115 K higher than its undisturbed value. The outcome of this result is almost in agreement with earlier works with horizontal discharges[2, 8]. Moreover, the enhancement of temperature due to lightning discharge field maintains correspondence with the effective collision frequency growth[19].

The inclusion of the effects due to variation of effective collision frequency and ionizing frequency of electrons along with other parameters involved in the physical processes during lightning made the present formulation more consistent with the physical situation than the earlier works[2, 8]. Just after the weak vertical discharges, the variation of electron temperature over the surrounding value has been plotted in Fig. 2, where the curves (a) and (b) are drawn from the results of the present analysis and Jone's model, respectively. In Fig. 1, the occurrence of the second peak in heating at a delay of 40 μs is due to horizontal discharges, whereas it is absent in vertical discharges at R = 50 km (Fig. 2).

4 Discussion

When the incident electric field in the lower ionosphere is very high, the energy gained by the free electrons from such fields cannot be readily transferred to the heavy particles of the medium. Hence the average energy of the electrons or the electron temperature is raised by the incident field. Then the velocity distribution functions of the electrons will differ from Maxwellian function. The deviation of distribution function from Maxwellian form may be of importance in the interpretation of cross-modulation data. Similar situation prevails in the case of weakly ionized auroral ionosphere, which appears rapidly to reach non-Maxwellian stationary states under the effect of large convective electric fields[20]. For such interpretation, it has been generally assumed that the energy absorbed from the discharging field appears as a change in the temperature of the electrons and this change is simply given by 2/3 K times the absorbed energy. Actual conditions in the lower ionosphere, however, deserve a non-Maxwellian distribution.

In the lower D-region of the ionosphere, the ratio of the change in conductivity for the non-Maxwellian distribution and for the Maxwellian distribution would decrease in magnitude for non-elastic collisions within the medium. Hence, the error due to Maxwellian distribution will be reduced substantially for non-elastic or partly non-elastic collisions[21, 22]. Thus, for brevity, the Maxwellian distribution functions have been assumed considering the situation as the case of a weak heating, where the condition $(T_e - T)/T << 1$ is satisfied and the outer electric field is uniform[8].

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References

1 Galejs J, Amplitude statistics of lightning discharge currents and ELF and VLF radio noise, *J Geophys Res (USA)*, 72 (1967) 2943.

2 Jones D L, Electromagnetic radiation from multiple return strokes of lightning, *J Atmos Terr Phys (UK)*, 32 (1970) 1077.

3 Hill R D, Electromagnetic radiation from the return stroke of lightning discharge, *J Geophys Res (USA)*, 71 (1966) 1963.

4 Velinov I I Y & Tonev P T, Thundercloud electric field modeling for the ionosphere-Earth region. 1. Dependence on cloud charge distribution, *J Geophys Res (USA)*, 100 (1995) 1477.

5 Lyons W A, Characteristics of luminous structures in the stratosphere above thunderstorm as imaged by low-light video, *Geophys Res Lett (USA)*, 21 (1994) 875.

6 Taranenko Y N, Inan U S & Bell T F, Interaction with the lower ionosphere of electromagnetic pulses from lightning: heating, attachment and ionization, *Geophys Res Lett (USA)*, 20 (1993) 1539.

7 Milikh G M, Papadopoulos K & Chang C L, On the physics of high latitude lightning, *Geophys Res Lett (USA)*, 22 (1995) 85.

8 Nickolaenko A P & Hayakawa M, Heating of the lower ionosphere electrons by electromagnetic radiation of lightning discharges, *Geophys Res Lett (USA)*, 22 (1995) 3015.

9 El-Khami S E, Mcintosh R E & Tang T, Non-linear transient heating of a weakly ionized plasma by an rf field*, J Appl Phys (USA)*, 41 (1970) 424.

10 Lin S C, Limiting velocity for a rotating plasma, *Phys Fluids (USA)*, 4 (1961) 1277.

11 Papa R J, The nonlinear interaction of an electromagnetic wave with a time-dependent plasma medium, *Can J Phys (Canada)*, 43 (1965) 38.

12 Shkarofsky I P, Values of the transport coefficients in a plasma for any degree of ionization based on a Maxwellian distribution, *Can J Phys (Canada)*, 39 (1961) 1619.

13 Shkarofsky I P, Generalized Appleton-Hartree equation for any degree of ionization and application to the ionosphere, *Proc IRE (USA)*, 49 (1961) 1857.

14 Aggarwal K M & Setty C S G K, Collisions and transport of electrons in the ionosphere, *Indian J Radio Space Phys*, 9 (1980) 105.

15 Engelhardt A G, Phelps A V & Risk C G, Determination of momentum transfer and inelastic collision cross-sections for electrons in nitrogen using transport coefficients, *Phys Rev (USA),* 135 (1964) A1566.

16 Spencer F E & Phelps A V, Momentum transfer cross-section and conductivity integrals for gases of MHD interest, *Proceedings of the fifteenth symposium on the engineering aspects of magneto hydrodynamics, Philadelphia (USA)*, 1976.

17 Milloy H B, Crompton R W , Rees J A & Robertson A G, The momentum transfer cross-section for electrons in Argon in the energy range 0-4 eV, *Aust J Phys (Australia)*, 30 (1977) 61.

18 *Cospar International Reference Atmosphere (CIRA)*, Edited by A C Stickland (Akademi-Verlag, Berlin), 1972.

19 Inan U S, VLF heating of the lower ionosphere, *Geophys Res Lett (USA)*, 17 (1990) 729.

20 Hubert D J, Non-Maxwellian velocity distribution functions and incoherent scattering of radar waves in the auroral ionosphere, *J Atmos Terr Phys (UK)*, 46 (1984) 601.

21 Huxley L G H, A discussion of the motion in nitrogen of free electrons with small energies with reference to the ionosphere, *J Atmos Terr Phys (UK)*, 16 (1959) 46.

22 Frost L S & Phelps A V, Rotational excitation and momentum transfer cross sections for electrons in H_2 and N_2 from transport coefficients, *Phys Rev (USA)*, 127 (1962) 1621.