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Luminosity of the return stroke lightning

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ABSTRACT. This paper reveals the luminosity variation of the return stroke with time and the diameter of the channel. It has been found that the luminosity at first increases, attaining the maximum at about 4μ sec and then decreases continuously with time of its cloudward progress. Further, the luminosity decays after the return stroke phase is over. The luminosity for larger channel radii remains for longer time and also the subsequent return strokes are more luminous than the primary stroke. Our theoretical analysis is in good agreement with the experimental observations by various workers.

1. Introduction

Ever since the epoch making experiment by Benzamin Franklin, man has known little about the physical properties of lightning discharges until recently. Spectroscopy has provided some of the solutions to this complex phenomenon. Perhaps, Meyer (1894) was the first to obtain lightning spectra recorded on a photographic plate. Since then various authors (Schonland *et al.* 1935; Schonland 1937; Orville 1968; Uman 1969) have studied parameters like velocity, diameter, number of strokes per flash, electron density and temperature by spectroscopic observations. The common technique for such observations is to expose a little part of the channel to the slit or slitless spectrograph. However, nothing is known about the luminosity of the channel throughout its process.

In the present paper the luminosity of the return stroke at various times of its progress and the decay of luminosity of the channel after the return stroke phase has been investigated. Our theoretical results are in fairly good agreement with the experimental observations of various workers.

2. Theory

A cloud to ground lightning flash consists of one or more negatively charged partial discharges towards ground. The first partial discharge is known as stepped leader because its luminosity moves downwards in steps of 50 m with about 50μ sec time pause between the steps (Schonland 1956). The stepped leader forges its way downward through the virgin air with an average speed of about (10^5m/sec. When the stepped leader approaches ground at an altitude of 20 to 70 m, it is met by a positively charged streamer from the ground known as return stroke, which sweep up with an average speed of about 10^8 m/sec producing the electron concentration of the order of 10^{25}/m^3 (Uman 1969), to the extent of full ionization. The subsequent negatively charged partial discharges due to same cloud charge at irregular intervals moving downwards in the preionized channels are known as dart leaders. Further, in turn, dart leaders initiate the subsequent return strokes.

When the return stroke discharge is over, the fully ionized channel cools down due to its thermal expansion and the luminosity decreases slowly to zero. Luminosity, the luminous flux emitted by a source per second per unit solid angle is proportional to the intensity of the flux from the same. Therefore, in the present work we have computed intensity of various lines of emission from the lightning, summation of which over the total visible frequency range will give the knowledge of the total luminosity.

To investigate luminosity of the return stroke, a number of assumptions are made, *i.e.*, (1) the lightning stroke is optically thin, (2) thermodynamic equilibrium is attained within the stroke in a short time compared to the time in which the transport properties of the channel change, (3) the temperature and particle density in the stroke at the given time are approximately constant across the cross-section of the stroke. If the above assumptions are not made, one is subjected to go through the detailed calculations of excitation and ionization cross-sections, recombination rates, transition probabilities etc., many of which are not known. A complete discussion of the above assumption is made in Uman (1969) and they are found to exist in lightning.

The intensity of an emission line due to transition between two atomic energy levels can be written

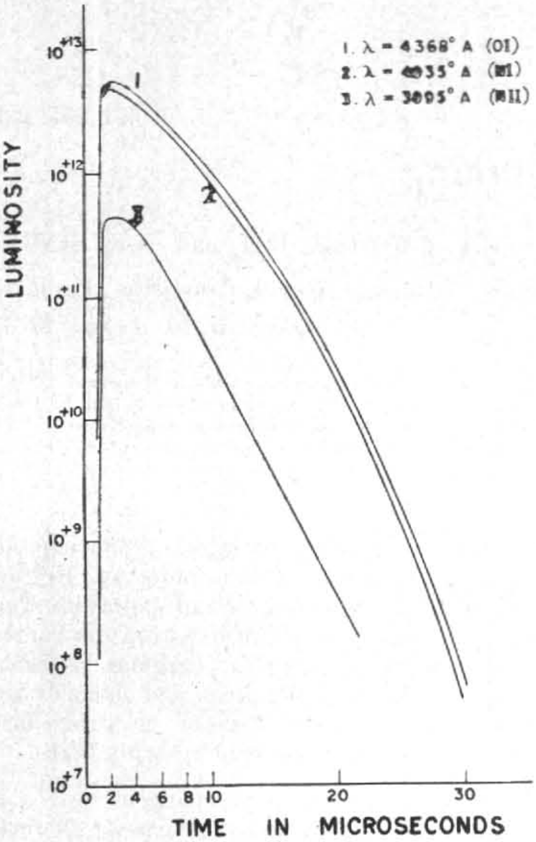

Fig. 1

Variation of luminosity (in arbitrary unit) with time of the return stroke progress

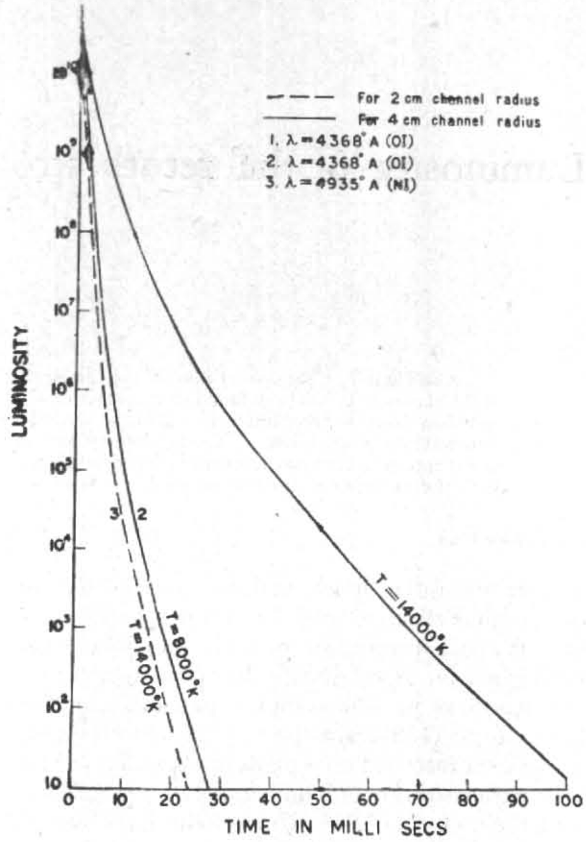

Fig. 2

Variation of luminosity (in arbitrary unit) of the expanding channel with time after the return stroke phase is over

as (Uman 1969),

$$I = G\, N_{it}\, Ah\nu \tag{1}$$

where A, is the Einstein emission coefficient for the transition, G is a geometrical factor, h is Planck's constant, ν is the frequency of emission line and N_{it} the number of atoms in the upper energy levels, at a time t given by

$$N_{it} = \frac{N g_i}{B} \operatorname{Exp} - \left(\frac{E_i}{KT_t}\right) \tag{2}$$

where, N is the total number of atoms of the species emitting a line frequency ν, K is Boltzman constant, g_i is the statistical weight of the i^{th} level.

In the above expression, though Exp.$[-(E_i/KT_t)$ is very small, N is of the order of $3 \times 10^{24}/\text{m}^3$ and g_i and B are generally of the order of magnitude unity, the expression becomes more than unity. Since the magnitude of G and A are not known in the present work to represent the variation of luminosity, ν Exp. $[-(E_i/KT_t)]$ is plotted against the time, the radius and the temperature of the channel.

The temperature *versus* time relation for the return stroke is given by Uman (1964) and is expressed as

$$T_t = \gamma\,(e^{-\beta t} - e^{-\alpha t}) + \delta \tag{3}$$

where, $\beta = 0.051$, $\alpha = 0.51$ $\gamma = 34000°\text{K}$ and $\delta = 1160°\text{K}$ are constants and t is in microseconds. Expressions (1), (2) and (3) give the variation of the luminosity of return stroke with time throughout its process.

When the return stroke phase has passed away the channel decays in intensity due to its thermal cooling. The decay of temperature depends upon the diameter of the channel and its central temperature. The decay of return stroke temperature

TABLE 1

Line	E_i (cm^{-1})
4935°A (NI)	106, 478·6
4368°A (OI)	99, 680·4
3995°A (NII)	147, 212·9
4447°A (NII)	187, 092·2

with time and radius for various central temperatures and channel radii is given by Uman and Voshall (1968) from which the luminosity decay with time of the return, when its phase has passed away, have been calculated for 14000°K and 8000° K central temperatures, and 2 cm and 4 cm channel radii.

In all above calculations the data for the excitation potential E_i has been taken from Moore (1949) which is given in Table 1.

In Table 1 (NI) represent the unionized and (NII) the singly ionized nitrogen atoms. Similarly (OI) is for the unionized oxygen atoms.

3. Results and Discussions

The intensity of the return stroke phase (Fig. 1) for various lines of emissions at first increases, becomes maximum at about 4μsec and then decreases continuously, the nature being approximately the same as for electric field, the velocity and the current.

When the return stroke phase is over, the luminosity starts decreasing and after some time it disappears. The decrease is due to the expansion and thermal cooling of the channel. If a streak camera is used to record the luminosity of the return stroke channel as a function of time and if the camera is set so that the peak luminosity does not overexpose the film, one reasonably expect to fail to record photographically the lightning channel after it has fallen much below a temperature of about 10,000°K. Certain positions on the channel, often apparent bends, are observed to retain their luminosity for relatively longer times. It is suggested that these positions of long lasting luminosity are sections of the lightning channel of enlarged radius. Therefore, the luminosity for a channel radius of 4 cm is expected to remain for longer times than for a channel of radius 2 cm and is evident from Fig. 2.

Fig. 3 shows the variation of luminosity with radius of the return stroke. The radius of the multiple return strokes varies approximately from 2 cm

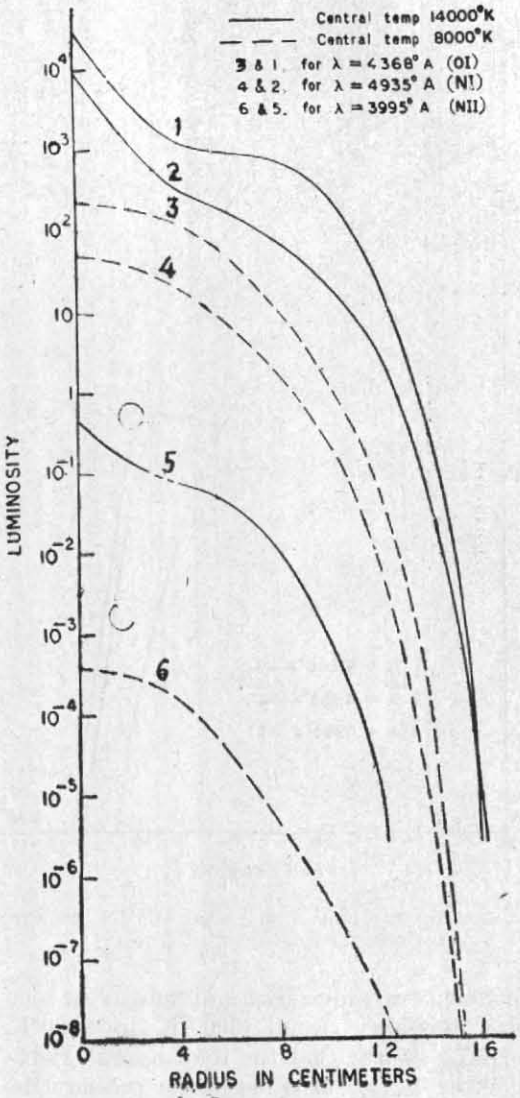

Fig. 3
Variation of luminosity (in arbitrary unit) with radius of the return stroke channel

to 0·5 cm (Oetzel 1968; Uman 1969), the lower values being for subsequent strokes. It is evident from the figure that the subsequent return strokes are more luminous than the primary one. It is evident from the above discussions that though the primary return stroke channel is less luminous than the subsequent one, the luminosity of the former remains relatively for longer time. This is only because the luminosity for larger channel radii decays slowly than for smaller one as in Fig. 2. Hence the luminous life of the primary return stroke is more compared to that of subsequent return strokes.

Fig. 4 shows the decay of luminosity with decreasing temperature. Morris *et al.* (1966) reported that the continuum radiation from air at atmospheric pressure at wavelengths above 2000°A

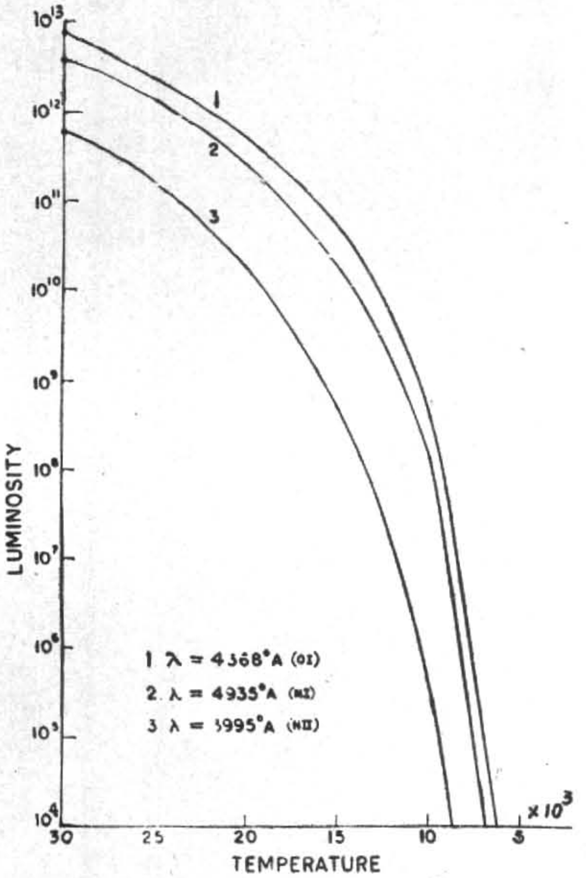

Fig. 4. Variation of return stroke luminosity (in arbitrary unit) with temperature of the stroke

falls off about two orders of magnitudes as the temperature decreases from 16000°K to 9000°K. Allen (1965) showed that the total optical radiation emitted by air at atmospheric pressure decreased about two orders of magnitude as the temperature is lowered from 14000°K to 9000°K and about three orders of magnitude as the temperature is lowered from 9000°K to 4000°K. The change in total luminosity from the peak lightning temperture (about 30,000°K) to the 2000°K to 4000°K range is expected to be at least five orders of magnitude. Since the thermodynamic properties of dry air and of moist air do not differ appreciably (Uman *et al.* 1964), our theoretical results may be compared with the experimental values for dry air and they are found in good agreement. The change in luminosity for the higher wavelengths is even greater, (*See* Table 2), since a larger part of the radiation is due to singly ionized nitrogen atoms, which do not exist at low temperatures.

TABLE 2

Wave length	Fall of temperature (°K)	Fall of luminosity (in order of magnitude)	References
2000 A	16000-9000	2	Morris *et al.* (1966)
Visible light	14000-9000	3	Allen (1965)
Do.	9000-4000	3	Do.
3395 A	16000-9000	4	Authors
4935 A	16000-9000	5	Do.

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