ART. XXIX.—*On the Oscillations of Lightning discharges and of the Aurora Borealis;* by JOHN TROWBRIDGE. (With Plate IV.)

IT is well known that when air is subjected to a sudden strain at the moment of an electrical discharge it acts like glass or a similar elastic solid and is cracked in zigzag fissures: indeed the resemblance between the ramifications of lightning and the seams produced in plates of glass by pressure has been commented upon by various observers. Photographs of powerful electric sparks lead one to conclude that a discharge of lightning makes way for its oscillations by first breaking down the resistance of the air by means of a disruptive pilot spark; through the hole thus made in the air the subsequent surgings or oscillations take place.

In examining the early photographs of electric sparks by Feddersen one perceives indications that the electric oscillations tend to follow for at least some hundred thousandths of a second the path made by the pilot spark; and there are observers who believe that by rapidly moving a camera they have obtained evidence that successive discharges of lightning follow the same path. Professor Lodge has protested, with reason, against the conclusions drawn from the method of "waggling" the head or camera: for the movement of the head or camera certainly requires the hundredth of a second while the discharge of lightning is over in less than one hundred thousandth of a second.

The method of the photography of electrical discharges by means of a revolving mirror seems to be the best method of studying the behavior of air suddenly subjected to the electric strain. I have therefore examined this behavior with more powerful means than those employed by previous observers; and it may be well to recall here the fact that usually in lightning discharges, high electromotive force and great quantity are frequently combined in a very short interval of time. The modern alternating machine and the device of the transformer enables one to study the character of lightning more successfully than is possible by means of an electrical machine: for both the electromotive force of the discharge and its quantity can be adjusted over a wide range. In my study of this subject I employed an alternating machine giving from three hundred to four hundred alternations per second, with a current from fifteen to twenty amperes, and the photographic apparatus was the same as that which was used in my investigation on the damping of electrical oscillations on iron wires.* By means of a step-up transformer and an oil condenser, discharges of high electromotive force and great quantity could be readily obtained. The method of the excitation of a Ruhmkorf coil or transformer by means of an alternating dynamo, due originally to Spottiswode, has placed in the hands of the experimenter, as I have said, powerful means of studying electrical discharges.

Since my object was to study the photographs of sparks having both great electromotive force and great quantity I limited myself to discharges of about two centimeters. By the device of an air blast and other contrivances for obtaining a quick break in the continuity of the electrical discharges, Professor Elihu Thompson has shown how sparks of many feet in length can be obtained. Figures 1 and 2 are reproductions from untouched negatives not enlarged, and ten to twelve oscillations can be counted on each photograph. The interval between the oscillations is about one hundred thousandth of a second; and it will be noticed that the electrical discharge follows exactly the same path in the air for three hundred thousandths of a second. During this length of time every sinuosity in the air path is exactly reproduced. I employed terminals of tin; and on figure 1 it will be noticed that a mass of melted and vaporized tin remained suspended in the air for at least three hundred thousandths of a second before it was dissipated in a comet-like tail. During the three hun-

* Phil. Mag., Dec., 1891.

dred thousandth of a second, therefore, the air remained passive while the electrical oscillations took place. During this time it is fair to conclude that the heat produced by the passage of the spark was not sensibly conducted away. If conduction of heat had taken place the electrical resistance of the air path would have been sensibly altered and the path of the discharge would have changed in form. Here I think we have an interesting limit to the time it takes atmospheric air to respond to the phenomenon of heat conduction.

I have said that the discharges I employed were powerful both in regard to electromotive force and to quantity. Iron terminals one-quarter of an inch in diameter were raised to a white heat by the continuous passage of the sparks and globules of the melted metal were formed. When the sparks were passed through the secondary of a transformer of about thirty seccohms of self induction, three fifty-volt Edison lamps placed in multiple in the primary of the transformer, which consisted of merely two layers of thick wire, were lighted to full incandescence. The spark from two large glass condensers of 5000 electrostatic units each, excited by an electrical machine, passed through the same step-down transformer barely raised a six-volt lamp to a red heat. The study of the efficiency of step-down transformers in thus transforming transient currents of high potential to transient currents of low potential and comparatively large current enables one to obtain an estimate of the high potential of lightning and of the current which accompanies its fall of potential. Thus if C denotes the current in the lightning discharge and E the electromotive force, C′ and E′ the corresponding quantities in circuit of the primary of the step-down transformer and A the efficiency of the transformer we shall have

$$C'E' = ACE$$

The element of time and the mode of transformation must be considered in any estimate of the amount of energy in lightning discharges. Although a powerful spark of electricity from two Leyden jars each of 5000 electrostatic units is incapable of decomposing water directly; yet by its passage through the secondary of a suitable step-down transformer it can decompose the water in the primary with great evolution of gases, and it is probable that an ordinary discharge of lightning of a few hundred feet in length could light, for an instant, many thousand incandescent lamps if it were properly transformed by means of a step-down transformer. Indeed the ringing of electrical bells and the melting of electrical fuses are of common occurrence during thunder storms and manifest the energy of lightning discharges. During a recent visit at a summer hotel which was lighted by incandescent lamps, I was much interested to observe that the lamps blinked at every discharge of lightning, although the interval which elapsed between the blinking and the peals of thunder showed that the storm was somewhat remote. This effect was doubtless due to induction produced by the surging of the lightning discharges. On the occasion of a heavy discharge the lights were completely extinguished, although no fuse was burned. My observation of this effect of lightning upon electric light circuits also leads me to believe that the system of carrying electric light wires along gas fixtures where both gas fixtures and electric light fixtures are combined is fraught with great danger. If there is a leakage of gas at the joints of the gas pipes or through a sand hole in the casting of the pipes electric sparks arising through resonance effects or from ordinary passage to earth of an electric charge brought into the building by the electric wires can ignite the escaping gas and produce a mysterious conflagration. Such a conflagration was averted in the hotel in which I noticed the blinking of the lamps only by the careful scrutiny of an attendant who noticed a jet of gas from a pin hole in the gas fixtures impinging on the wood work. During the storm a minute electric spark had ignited the escaping gas. Electric light wires and gas pipes should never be contiguous; for no lightning guard or protector can ensure that minute sparks, due in some cases to resonance effects, may not arise.

The study of the disruptive or oscillatory discharge of lightning is closely connected with that of the brush discharge and that of the phenomenon of the Aurora Borealis; for the disruptive discharge if it is an oscillatory discharge ceases to be disruptive after a few hundred thousandths of a second, as figures 1 and 2 show, and partakes of the nature of a brush discharge. The zigzag fissures in the air disappear and only the spark terminals glow. Recent experimenters have exhibited, as a marvel, the lighting of a vacuum tube through the human body by grasping one terminal of a suitable transformer with one hand and by holding the vacuum tube in the other hand. It must be remembered, however, that the lines of force proceed from the hand which holds the vacuum tube through the air and the walls or floor of the room to the other terminal of the transformer. We can change this brush discharge or luminosity at either terminal of a transformer into a disruptive discharge by lessening the distance between the terminals or by increasing the electromotive force.

I am fully aware that the oscillatory discharge of lightning with its disruptive effects I have noted—its permanence of path and the fading of the disruptive discharge into the brush discharge or mere luminosity at either of the spark terminals, is a far simpler phenomenon than the luminosity produced in rarefied tubes; for in the latter phenomenon we have the dissociation and impact of molecules, and we must consider all the problems of atomic motion in addition to those of the oscillatory nature of electrical waves. It is not my purpose to enter into a consideration of the molecular movements involved in oscillatory discharges in vacuum tubes; but having discussed some of the general features of discharges of electricity in air at the ordinary pressure I shall endeavor to trace the connection between such discharges and the phenomenon of the Aurora Borealis. To my mind the luminosity in a vacuum tube held in one hand while the other hand grasps the terminal of a Ruhmkorf coil, closely represents the phenomenon of the northern light, for we have in this case a discharge of electricity from a higher level to a lower through a rarified medium. Although in this paper I restrict myself to a discus sion of the general relations between discharges of lightning and the phenomenon of the Aurora Borealis, and do not enter into a study of the molecular movements excited by electrical discharges, I am impelled to devote a few words to the subject of the stratified discharge and to show that it has no connection with the oscillatory discharge of electricity such as we are considering. The distances between the stratifications do not seem to be changed by modifying the period of forced oscillation given to the transformer over a wide range. I have produced the stratifications by employing an interrupter of a Ruhmkorf coil giving from sixty to one hundred vibrations per second, and by the use of two alternating machines, one giving 300 to 400 alternations per second and the other 900 to 1000 alternations per second. The distances between the stratifications do not seem commensurate with the rate of alternation of the exciter of the transformer. On the other hand the distance between the stratifications is not dependent upon the amount of self induction in the circuit. In one case quadrupling the self induction reduced the distance between the stratifications one-half. This reduction was due not to the increased self induction but to the increased resistance; for the introduction of a water resistance of some megohms diminished in a similar manner the distance between the stratifications. In short I could not discover any connection between the law $t = 2\pi\sqrt{LC}$ and the phenomenon of stratification.

I have said that we can pass by insensible gradations from the condition of the brush discharge to that of the disruptive discharge. By intercalating a non-inductive water resistance and a vacuum tube between the terminals of a suitable transformer we can exactly imitate the phenomena observed when the vacuum tube is held in one hand while the other hand grasps one terminal of the transformer. In this case the water resistance takes the place of the resistance of the air of the room. The intensity of the discharge being thus much diminished one can readily study various manifestations of stratification which may perhaps be termed transitory stratifications in distinction to the stationary wave-like forms observed in narrow tubes. The transitory stratifications can be produced at will by touching suitable points of a vacuum tube with the finger or by connecting such points with the ground. Such stratifications are stationary as long as the ground connection is maintained, and are independent of the rate of the alternating machine which excites the transformer. It is evident that the condenser action of the vacuum tube plays an important part in this phenomenon. In observing the striæ and waving columnar form of the light excited in this manner in tubes filled with rarefied gases, one is led to believe that the stratified form of the Aurora Borealis is produced in a similar manner. Fig. 3 is a form of the northern light noticed by me. Let us suppose that a discharge of electricity takes place in rarefied air between A and B, and that C is a region of cloud or moisture. C can be regarded as the finger or earth conductor which is applied to the tube of rarefied air and which seems to throw the discharge into transitory stratification, and to give the waving form of the Northern light.

The pulsation, therefore, of the Aurora Borealis is in no way, I believe, connected with any oscillatory discharge; yet certain writers have intimated that the glowing of vacuum tubes which are connected with one terminal of a transformer and the light of the Aurora is due to millions of electrical oscillations per second. Now it is impossible to study the question of the rate of oscillation of the brush discharge, by means of Federsen's method for the light of the discharge is not sufficient to produce a photograph. A brief consideration, however, of the laws of electrical oscillations shows, I think, that such writers are mistaken. The rate of decay of the amplitude of such oscillations is expressed by the well known factor

$$E^{\frac{Rt}{2L}}$$

Now in the case of a brush discharge R is enormously large. A resistance of thirty or forty ohms was sufficient to completely damp the oscillations of the sparks studied by me in the research on the damping produced on iron wires. In the case of the brush discharge although we may be dealing with very small values of self induction and small values of time, we have on the other hand great values of R. I believe therefore that the brush discharge is reduced to the case of one throb which is analogous to the pilot spark in disruptive discharges. In regard to the Aurora, it may be urged that the resistance of the rarified air is not enormous. In answer to this, it can be said that the phenomenon of the Northern light can be best reproduced by intercalating a tube of rarefied air with some megohms of a water resistance between the terminals of a suitable transformer. The supposition that the Northern light is produced by the action of extremely rapid electrical oscillations on molecules of rarefied air is not borne out by the theory of transient currents and experiment shows that the phenomenon of the waving and apparent stratification observed at times in the Aurora is due to the re-distribution of the lines of force which is produced by suitable earths in the shape of regions of cloud and moisture.

The comparatively small resistance of the electric spark in air noticed by many observers is due I believe to the permanence of path, for this path is intensely heated and is practically a charred hole in the air. When this path no longer becomes such a hole and the heated air rises and is dissipated, the oscillations of the electric spark become rapidly damped, and we have the phenomenon of the glow at each of the spark terminals without the disruptive discharge; that is, we perceive what is termed a brush discharge. The lines of force crowding from one terminal seek through the air of the room the other terminal, and in passing through rarefied air the energy along the lines of force is manifested by molecular actions which are apparently protean in form. I see therefore no evidence for believing in the rapid oscillation of the Aurora.

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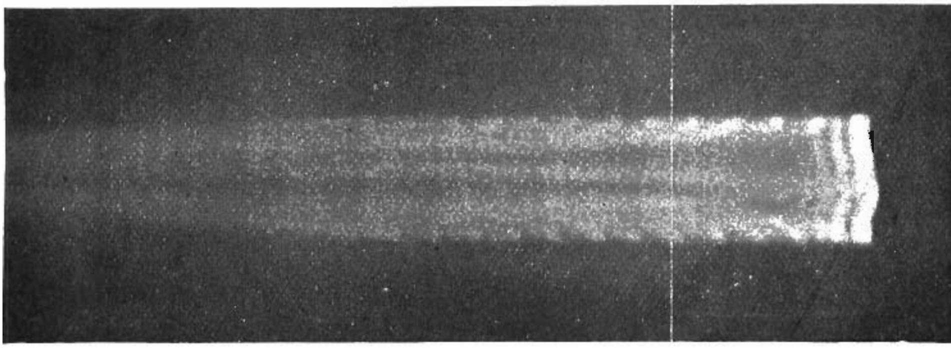
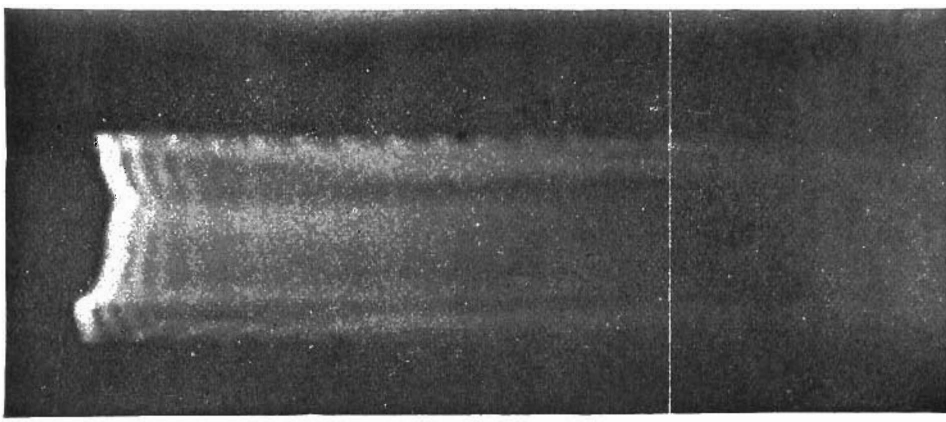


2.



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