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XII. *Some Experiments on the Velocity of Transmission of Electric Disturbances, and their Application to the Theory of the Striated Discharge through Gases.* By J. J. THOMSON, M.A., F.R.S., Cavendish Professor of Experimental Physics, Cambridge*.

THE velocity of transmission of an electric impulse along a wire is, according to Maxwell's theory, equal to the velocity with which light passes through the dielectric surrounding the wire. The velocity is thus determined by the surrounding dielectric, in which the energy resides, and the function of the wire seems merely to be that of guiding the discharge, which travels at a rate fixed by the dielectric.

The equality between the velocity of light through air and the rate of transmission of an electric impulse along a wire surrounded by air has been roughly verified by observing the lengths along a wire of electric waves generated by an electric vibrator: it was found that the wave-length divided by the calculated time of vibration was very nearly equal to the velocity of light. In order to test Maxwell's theory more fully, and to illustrate the influence of the dielectric and the subordinate part played by the conductor, I have made some experiments to compare the velocity of transmission of electric impulses along wires surrounded by different dielectrics.

If an electric vibrator AC attached to an induction-coil has connected with it a wire AB which bifurcates at B into two circuits, BL, BM, and if the ends L, M are connected to a spark-micrometer the sparking-distance of which can be adjusted by means of a screw, the sparking-distance will depend

* Communicated by the Author.

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upon the relative lengths of the wires BL, BM. If these wires are both surrounded by air, the sparking-distance is a minimum when the lengths are equal. This is the case whatever the material or cross section of the wires. This is also the case if one of the wires is placed between two large zinc plates at a small distance apart; though in this case the electrostatic capacity of one of the wires is very much greater than that of the other.

If $\phi_0 \cos nt$ represents the potential of B, l, l' the lengths of the wires BL, BM respectively, v and v' the velocities of transmission of electric impulses along them, then the potentials of L, M are respectively

$$\frac{\phi_0 \cos nt}{\cos \frac{nl}{v}}, \quad \frac{\phi_0 \cos nt}{\cos \frac{nl'}{v'}}.$$

These potentials will be equal, and the sparks therefore have a minimum length, when $l/v = l'/v'$. When $v = v'$, $l = l'$, which agrees with the effects observed when both wires were surrounded by air. But if v and v' are different, then the lengths of the circuits for minimum spark-length will be unequal, and the ratio of the two lengths will be the ratio of the velocities of transmission of electric impulses along the wires. We have thus a method of finding the rate of transmission of electric waves along different wires*.

In order to compare the velocity along a wire surrounded by air with that along one surrounded by paraffin or sulphur, one of the wires BM was placed inside and insulated from a brass tube connected with the earth at each end. The tube was filled either with paraffin which was poured in in a melted condition and allowed to set, or with sulphur melted down so as to form a solid mass. The length of the circuit BL could be altered by successively adding pieces of wire each $\frac{1}{4}$ of a metre in length. The length of the wires when the spark-length was least are given in the following Table, where the different numbers refer to experiments made on different days :—

Wire surrounded by paraffin.	Wire surrounded by air.
4 metres.	5, 5 $\frac{1}{4}$ metres.
4 "	5.5 "
4 "	6 "
4 "	5 "
Mean . . 4 metres.	5.4 metres.

* I have found since this paper was in type that exactly the same method was used by von Bezold twenty years ago to prove that the velocity of transmission of electricity along wires is not affected by the material or diameter of the wire (Poggendorff's *Annalen*, cxl. p. 541).

The velocity along a wire in air is thus $5\cdot4/4$, or $1\cdot35$ times the velocity along a wire surrounded by paraffin.

Wire surrounded by sulphur.	Wire surrounded by air.
4 metres.	$6\cdot25$ metres.
4 "	$6\cdot5$ "
4 "	7 "
4 "	$7\cdot5$ "
Mean . . 4 metres.	$6\cdot81$ metres.

Thus the velocity along the wire surrounded by air is $1\cdot7$ times the velocity along the wire surrounded by sulphur.

These experiments show that the velocities along wire surrounded by air, paraffin, and sulphur are approximately proportional to the reciprocals of the square roots of their specific inductive capacities.

When the tube surrounding the branch BM of the circuit was filled with powdered glass, the sparks were least when the lengths of the wires BL, BM were equal. This was also the case when the tube was filled with flowers of sulphur. I believe the explanation of this to be that the small pieces of glass and sulphur are coated with a conducting film of moisture which prevents the waves entering the glass or sulphur, so that the waves in this case are really transmitted through air.

Velocity of Transmission along Electrolytes.

To determine the velocity along an electrolyte, an electrolytic cell filled with a solution of zinc sulphate and having zinc electrodes was placed in one of the arms of the fork. The cross section of the cell was about 1 square inch, and the distance between the electrodes about 2 inches. In this case the sparks were least when the arms were of the same length, though the effect produced by increasing the length of one of the circuits was not so great as when both arms were entirely metallic. The velocity of propagation of a rapidly alternating current along an electrolyte surrounded by air can thus not differ much from the rate along a wire.

When a vacuum-tube was substituted for the electrolytic cell, the sparking-length did not seem to be affected, however the relative lengths of the arms BL and BM were altered. I believe that this, however, is not because the velocity of the discharge through a vacuum-tube is very much less than the velocity along a wire, but on account of the retardation of the discharge at the electrodes. The velocity across an air-space cannot be very different from that along a wire, otherwise the periods of electrical vibrators would vary with the length of

the spark very much more rapidly than seems to be the case. I am endeavouring by the aid of a rotating mirror to measure the velocity of the discharge along a vacuum-tube 50 feet long, and though the experiments are not yet completed, they have gone far enough to show that the velocity through the gas is comparable with that of light. The results of experiments on the rate of propagation of electricity along wires leads us to regard the conductor as merely guiding the discharge, the correlation between the æther and the conductor compelling the discharge to travel along the latter with the velocity of light.

The very rapid rate with which the electric discharge is propagated through a rare gas compels us to admit that the electricity is not carried by charged atoms moving with this velocity. For if it were, then if the discharge were to take place in air at atmospheric pressure between two parallel plates one centimetre apart, charged to a potential difference of approximately 30,000 volts, the kinetic energy which would have to be communicated to the atoms to make them move with this velocity would be greater than the original potential energy of the charged plates : assuming that the charge on each atom is that deduced from electrolytic considerations.

The evidence in favour of the view that the conduction of electricity takes place by means of the atoms of the substance through which the discharge passes appears to me to be so strong, that I think it important to see whether this view of the electric discharge cannot be reconciled with the very rapid rate at which the electric discharge passes through a gas. The following view of the behaviour of the gas seems to explain both the rapid propagation of the discharge and some of its most striking features, such as stratification.

Before the electric field is intense enough to cause discharge, the induction in the field polarizes the gas. We may regard this polarization as being equivalent to the formation of chains of molecules analogous to the "Grotthus chain" in electrolysis. As the intensity of the field increases, suppose the molecules in one of these chains near an electrode, say the negative, interchange their atoms ; and that *it is not merely those molecules which are next the electrode which split up, but that the decomposition of the molecules extends along an appreciable length of the chain.* The positively electrified atoms will cling to the negative electrode, and after a time, depending upon the number of free atoms, the distance between them, and their mutual attractions, the chain will resume its original molecular condition. This time may vary slightly from atom to atom. Let us, however, for the sake of clearness, suppose

that the atoms recombine simultaneously after a time T . Then, when the atoms have recombined as far as possible, since there are a certain number, say N , of positively electrified atoms sticking to the negative electrode, there must be N negative atoms left free : in order that the discharge should travel with the velocity V , these N negative atoms must be situated along the line of discharge at a distance VT from the negative electrode. Hence if we suppose that the molecules along a length VT of the Grotthus chain were split up before discharge commenced, the free negative atoms would appear at the end of this chain, and the discharge would travel with the velocity V ; and thus, by properly choosing the length of the chain, we can make the velocity what we please.

The N free atoms at the end of the chain would act as a new negative electrode, and other Grotthus chains of length VT would decompose at the end of this, and so on. The discharge would thus be broken up into a series of separate currents, each of length VT ; and in this way the discharge through each element would be able to satisfy the condition imposed on it by the surrounding dielectric and travel with the velocity of light.

According to our view, this breaking-up of the current into a series of separate pieces shows itself in the stratifications observed when the discharge passes through a gas at low pressure. The behaviour of a striated discharge in a magnetic field seems almost to prove that it is made up of a series of separate discharges. For "if a magnet be applied to a striated column, it will be found that the column is not simply thrown up or down as a whole, as would be the case if the discharge passed in direct lines from terminal to terminal, threading the striæ in its passage. On the contrary, each stria is subjected to a rotation or deformation of exactly the same character as would be caused if the stria marked the termination of flexible currents radiating from the bright head of the stria behind it, and terminating in the hazy inner surface of the stria in question. An examination of several cases has led the authors of this paper to conclude that the currents do thus radiate from the bright head of a stria to the inner surface of the next, and that there is no direct passage from one terminal of the tube to the other." (Spottiswoode and Moulton, *Phil. Trans.* 1879, part i. p. 205.)

Goldstein, and Spottiswoode and Moulton, from the study of the behaviour of the striated discharge, have independently arrived at the conclusion that each stria represents a separate discharge. Thus Goldstein (*Phil. Mag.* [5] x. p. 183) says :—
"By numerous comparisons, and taking account of all appa-

rently essential phenomena, I have been led to the following view :—

“The kathode-light, each bundle of secondary negative light, as well as each layer of positive light, represent each a separate current by itself, which begins at the part of each structure turned towards the kathode, and ends at the end of the negative rays or of the stratified structure, without the current flowing in one structure propagating itself into the next, without the electricity which flows through one also traversing the rest in order.

“I suspect, then, that as many new points of departure of the discharge are present in a length of gas between two electrodes as this shows of secondary negative bundles or layers—that as, according to experiments repeatedly mentioned, all the properties and actions of the discharge at the kathode are found again at the secondary negative light and with each layer of positive light, the intimate action is the same with these as it is with those.”

Spottiswoode and Moulton (Phil. Trans, part i. 1879, p. 201) express much the same opinion :—“If, then, we are right in supposing that the series of artificially produced hollow shells are analogous in their structures to striæ, it is not difficult to deduce from the explanation above given the *modus operandi* of an ordinary striated discharge. The passage of each of the intermittent pulses from the bright surface of a stria towards the hollow surface of the next may well be supposed, from its inductive action, to drive from the next stria a similar pulse, which in its turn drives one from the next stria, and so on. Thus the procession in the naturally and artificially striated columns are precisely similar ; save that in the case of the latter the pulses from the several striæ are excited by induction from without the tube, while in the case of the former the induction is that of the discharge itself in its passage from stria to stria. The passage of the discharge is due in both cases to an action consisting of an independent discharge from one stria to the next ; and the idea of this action can perhaps be best illustrated by that of a line of boys crossing a brook on stepping stones, each boy stepping on the stone which the boy in front of him has left.”

The laws governing striation seem to be in accordance with those which follow from the view expressed above, that the distance between two striæ is the distance passed over by light during the time taken by the atoms split up in the chain to recombine.

Thus the distances between consecutive striæ increase when the pressure of the gas diminishes ; but when the pressure

diminishes the mean distances between the atoms increase, and therefore T , the time required for recombination, will increase; but as on the above view the distance between two striæ is VT , where V is the velocity of light, the diminution of the pressure will cause a separation of the striæ. Again, the distance between two striæ increases as the diameter of the tube in which the discharge takes place increases; since in the wider parts of the tube we have the same number of molecules split up as in the narrower, the average distance between the atoms will be greater in the wide part of the tube than in the narrow, so that the time required for recombination, and therefore the distance between two striæ, will be greater in the wide part of the tube than in the narrow.

We have not the requisite data for calculating the time required for the recombination of the atoms, but we may perhaps suppose it is of the same order as the time required for a particle moving with the average molecular velocity to travel over half the average distance between the molecules: this time for air at the pressure of 1 millim. of mercury is about 2×10^{-11} seconds, which would correspond to a distance between the striæ of 6 millimetres, which is a length quite of the same order as the actual one.

An interesting point arises when the electrodes are separated by a distance less than VT . In this case the discharge cannot be propagated from one electrode to the other with the velocity V unless the velocity of the atoms is very much increased. This increase in the energy which has to be communicated to the gas to allow the spark to pass will increase the resistance which the gas opposes to the passage of electricity along the line joining the electrodes; that is, it will require a greater electromotive intensity to produce the discharge. If, however, instead of taking the straight line of force between the electrodes, we consider one of the longer curved lines, and choose one whose length is VT , or a multiple of it, then along this line a Grotthus chain could be formed, which would convey the discharge with the velocity V ; and since in this case it is not necessary to increase the velocity of the atoms in order to attain the requisite velocity of propagation, the resistance opposed by the curvilinear path per unit length will be less than that offered by the straight path. Thus, when the electrodes are separated by a shorter distance than VT , the shortest distance between them need not be the path of least resistance, and we might expect to find the discharge taking place along curvilinear paths of such length as would enable the discharge to travel at a rate V without increasing the kinetic energy of the molecules.

Very striking examples of this effect have been given by Hittorf and others. Hittorf (*Wied. Ann.* xxi. p. 90) describes an experiment in which when the electrodes were very near together the discharge passed along a curved path of very much greater length, leaving the short space between the electrodes free from glow. In Lehmann's *Molekularphysik*, vol. ii., many illustrations of the discharge between electrodes very near together are given. Some of these are very remarkable, the space immediately between the electrodes being free from glow, while the discharge when the electrodes are plane passes between the faces of the electrodes which are most remote from each other.

The view we have taken of the electric discharge requires the molecules to be split up for a finite distance along the line of force: the electromotive intensity has to maintain over this length the value required to split up the molecules; thus, if the field of force is not uniform, it will require a greater electromotive intensity at the surface of the electrode to produce a spark than if the field were uniform. However, at ordinary pressures VT is so small that it would be very difficult to produce a sufficiently rapid variation of the field to make this effect felt.

The striations on this view of the electric discharge may be regarded as forming little electrolytic cells, the beginning and end of a stria corresponding to the electrodes of the cell. Let us consider one of these cells. Suppose the unit of electricity passes through it, then the work done by the electric field is $F\lambda$, if F is the electromotive intensity, and λ the length of the stria. The passage of this unit of electricity will be accompanied by definite chemical changes in the space between two striations. Let w be the increase in the potential energy due to these changes, then, if there is no increase in the kinetic energy of the gas, we must have

$$F\lambda = w.$$

Thus, when the chemical change is the same, the electromotive intensity varies inversely as the distance between two striæ. Thus, if we can diminish in any way the distance between the striæ without altering the chemical action, the electromotive intensity required to force electricity through the gas will be increased. If we have gas at the same pressure in tubes of different diameter, after the exhaustion has passed a certain point, the distance between the striæ will be greater in the wide tubes than in the narrow ones, so that the resistance offered to the discharge ought to be greater in the narrow tubes than in the wide ones. Hittorf (*Wied.*

Ann. xxi. p. 90) has observed this effect to a very striking extent: at a pressure of .03 centim. of mercury it took 1100 elements of his battery to force the discharge through a tube 1 centim. in diameter, while 300 elements were sufficient to force it between similar electrodes in a tube 11 centim. in diameter.

In the structure round the negative electrode, consisting of the glow over the electrode, Crookes' dark space, and the negative glow, which, according to our view, is only a stria differing from other striæ merely by the special arrangement of the lines of force near the electrode, the chemical and other changes produced by the discharge seem to be more complicated than those which take place in the rest of the field: one obvious reason for this is the presence of the metal, which makes many chemical changes possible which could not take place in striæ where nothing but gas is present. This stria is thus under special conditions, and may differ in size, fall of potential, &c. from the remaining striæ.

Hittorf's experiments show that there is an exceptionally large change in potential close to the kathode. If we take the preceding view of the spark-discharge this will explain the very striking increase in the electromotive intensity necessary to produce a spark across a layer of air when the thickness of the layer is diminished beyond a certain amount. For let us consider the case when the spark passes between two infinite parallel planes; the discharge, according to the view enunciated above, goes first across the stria next the negative electrode, where the rise in potential is K , and then across a number of other striæ, the rise of potential across each stria being w ; thus if n be the number of such striæ, V the difference of potential between the plates when the spark passes,

$$V = K + nw.$$

If l is the distance between the plates, λ_0 the length of the stria next the kathode, λ the length of the other striæ, then

$$n = \frac{l - \lambda_0}{\lambda}$$

$$V = \left(K - \frac{\lambda_0}{\lambda} w \right) + \frac{l}{\lambda} w. \quad . \quad . \quad . \quad (1)$$

This may be written

$$V = K' + al.$$

On this view the curve representing the relation between difference of potential and spark-length is a straight line not

passing through the origin. The curve given by Paschen (Wied. *Ann.* xxxvii. p. 69) for the relation between spark-length and potential when the electrodes were spheres 1 centim. in radius is very nearly straight, and would correspond to the above formula if K' were between 600 and 700 volts.

If R is the electromotive intensity required to produce a spark of length l , we see from the above since $R = V/l$ that

$$R = \frac{K'}{l} + \alpha.$$

Thus the electromotive intensity required to produce a spark increases as the spark-length diminishes; in other words, the electric strength of a thin layer is greater than that of a thick one.

The curve on this hypothesis representing the relation between the electromotive intensity and the spark-length is a rectangular hyperbola; the curves given by Dr. Liebig (*Phil. Mag.* [5] xxiv. p. 106) for air, hydrogen, carbonic acid, and coal-gas seem to approximate to hyperbolas.

The distance between the striæ is proportional to the time taken by the atoms in the Grotthus chain to recombine; this time will be greater the greater the distance between the atoms; if we assume that it is proportional to the distance travelled by an atom between two collisions, the distance between the striæ will be proportional to the mean free path, and therefore inversely proportional to the density: thus we may write in equation (1) $\lambda = \beta/\rho$, where ρ is the density of the gas. With this substitution equation (1) becomes

$$V = K' + \frac{l\rho w}{\beta}. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Paschen's observations on the electric strength of air, hydrogen, and carbonic acid at various pressures seem fairly accordant with this formula; they show, however, that K' is not quite independent of the density but increases slowly with it. If we are dealing with sparks so long that the second term on the right-hand side of equation (2) is large compared with the first, then the spark-potential for the same gas depends only upon the product $l\rho$. Paschen's experiments seem to show that this law holds with great accuracy; it would, however, be interesting to have experiments with smaller values for $l\rho$ than those used by him.

In the preceding equations we have supposed the field to be uniform and the striæ of the same length; if the field is

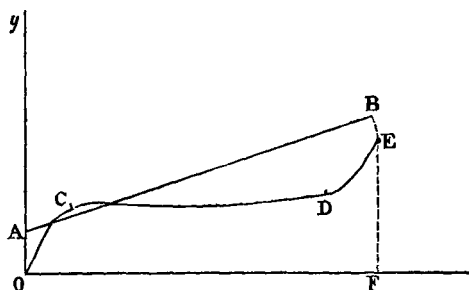
variable the striæ may be of slightly different lengths, and (2) will only be approximately true; the accurate equation will be

$$V = K + w \int_{\lambda_0}^l \frac{dl}{\lambda}.$$

According to this view the discharge takes place when the value of the potential difference has the value given by either (1) or (2) and not when the maximum electromotive intensity has a certain value. Dr. Schuster's reduction of Baille's and Paschen's experiments shows that the maximum electromotive intensity when the spark passes is by no means constant.

If by the combination of the atoms at the end of a stria sufficient heat is produced to dissociate the adjacent gas without the aid of the electric field, the gas dissociated will, as the experiments I described in the *Philosophical Magazine* for April and May 1890 prove, be able to conduct the electricity, even though the potential difference is very small. We should then have a region in the gas where the potential charges are small compared with those in other parts of the gas: the dark space between the negative glow and the positive column seems to be such a region, and it is situated near to the negative glow, the hottest part of the field.

When the dimensions of the electrodes are not large compared with the sparking-distance, the connexion between the sparking-distance and the difference of potential is not linear. The experiments of De La Rue, Hugo Müller, and Freiberg have shown that with pointed electrodes, or small spheres, the sparking-distance for the same difference of potential is greater than with larger electrodes. This is what we should expect from the preceding considerations, for according to them when the spark passes from the negative electrode the



distribution of potential must be represented by the straight line AB, where the abscissæ represent the distance from the

electrode, and the ordinates the excess of potential over that of the negative electrode.

A spark will pass when the curve representing the potential before discharge cuts the curve AB. When the field is uniform the potential curve before discharge is a straight line passing through the origin, and if OF represent the distance between the electrodes OB will be the position of the potential curve before discharge when it first intersects AB; in this case FB is the potential necessary for discharge, and the relation between it and the sparking-distance is represented by equation (2). When, however, the electrodes are small the electric field is very far from uniform; there are great changes in the value of the potential near the electrodes, but at some distance from them the potential changes very slowly. The potential curve before discharge in this case will be somewhat of the form OCDE, and we see from the figure that this may intersect the line AB (when a spark will pass) when the difference of potential between the electrodes FE is less than FB, the difference when the field is uniform. We see in this way that the sparking-distance will be greater for small electrodes than for large ones, and will increase more rapidly with the difference of potential. We notice, too, that in this case the maximum electromotive intensity is greater than in a uniform field.

XIII. *On the Diurnal Variation of the Magnet at Kew.* By W. G. ROBSON and S. W. J. SMITH, of the Normal School of Science and Royal School of Mines*.

THE multiplication of magnetic observatories makes it extremely desirable that the methods of reducing the observations should be as similar as possible. It is, however, practically impossible that all observatories should determine the diurnal variations of the elements by the elaborate method in use at Greenwich, which, in the case of any one element, necessitates the measurement of the hourly ordinates of the curves at 24 points on all but a very few days of the year under discussion.

Dr. Wild (Rep. Brit. Assoc. 1885, p. 78) advocates the determination of the mean diurnal range from measurements on the comparatively small number of days of very small disturbance, and points out that the inclusion of disturbed

* Communicated by the Physical Society: read June 6, 1890.