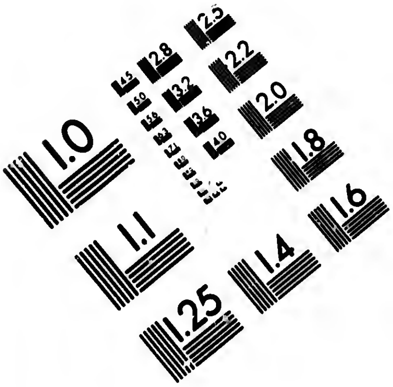

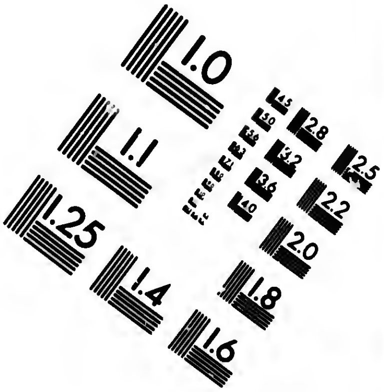

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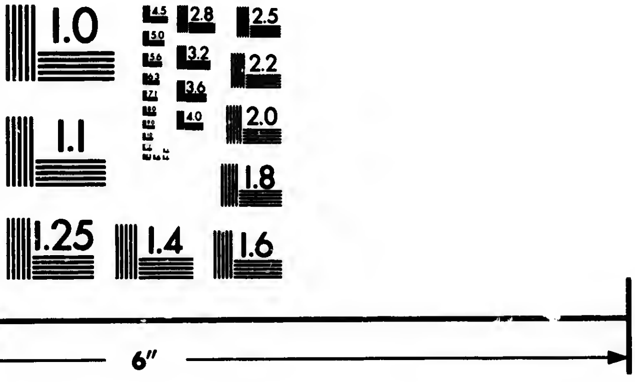

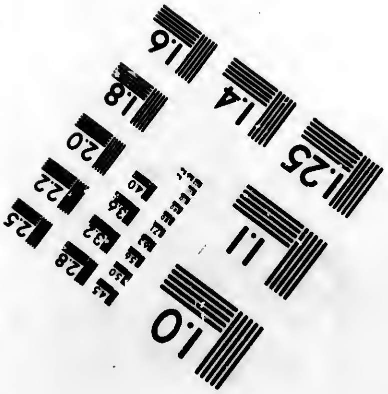

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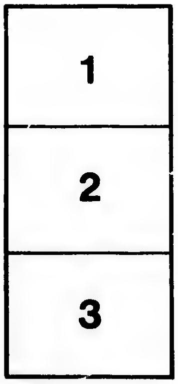
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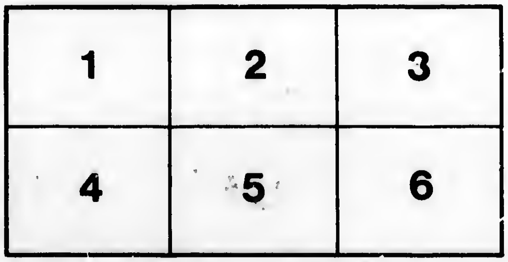
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ELECTRICAL WAVES.

BY

SAMUEL J. SAUNDERS.

A THESIS
PRESENTED TO THE FACULTY OF CORNELL UNIVERSITY FOR THE
DEGREE OF DOCTOR OF SCIENCE.
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THERE is a great deal of artificiality in any of the methods of explaining the processes that go on in the electric or magnetic field, but since we do not know what actually takes place, we can not resist the help of analogies and models as a convenient means of getting a more vivid picture of these processes. We know that a line of force is something more than a mere geometrical conception. It must be a definite something going on in a certain region of space, and whatever may be its real nature, we must accord to it a definite physical character as much as we ascribe to a current flowing in a given circuit.

In planning the experiments on "Electrical Waves," and in the explanations here given of attendant phenomena, a method of reasoning is employed, which is based upon Faraday's lines and tubes of magnetic induction. During the winter of 1888 the author wrote a brief paper for Dr. E. L. Nichols, of Cornell University, entitled "A Method of Determining the so-called Direction of Current." Portions of that paper are here repeated, inasmuch as some such view is necessary to explain certain phenomena, such as, for instance, the production of sparks in a Hertz resonator. If the resonator be a linear one there is no complete circuit, while if it be a circular or rectangular one, a rotation of it about its centre, in certain planes, changes the length of spark in it, though there has been no change in the number of magnetic lines of force threading through it; consequently, in neither case can we estimate the tendency to spark across the air gap by calculating, according to Faraday's rule, the increase or diminution of the number of lines of force passing through the circuit.

It is usual to consider a conductor, which carries current, as being surrounded by lines or loops of magnetic induction, these being circles for a straight wire situated in a medium of uniform permeability, the return portion of the circuit being infinitely distant. These loops of induction may be regarded as radiating outwards from the wire during the growth of current in it, somewhat similar to the outward movement of waves from the spot where a pebble has been dropped in still water. The first-formed waves spread outward, and new ones make their appearance at the centre until the current has reached its steady state. The relation between the direction of the current and its lines of force being the same as that between the thrust and twist of a right-handed screw.

It is also assumed that there is a tendency on the part of lines of force to contract, like stretched elastic strings, along the direction of their length, and to push one another apart when parallel and running in the same direction. In other words, each loop behaves as if it were an opened elastic ring subjected to more or less pressure from within. It thus requires the expenditure of energy to expand these rings, and in this state they represent a definite quantity of energy measurable in ergs per cubic centimeter of field. When the force which sustains them is removed, these rings collapse inwards upon the wire and disappear, or at least shrink to molecular dimensions, their energy being restored to the circuit in the form of an induced current. Since the direction of the lines remains unchanged, the direction of the current induced by their collapse is the same as that of the current giving rise to them. In every case the loops, or portions of them, disappear into the conductors which they encircle, when the force sustaining them is removed.

When two lines or loops run in opposite directions, they attract each other and when they come together at any point of their path, they coalesce to form a single loop, which, from its tendency to contract, urges the sources of the loops towards each other. These loops might be considered as having neutralized each other at the point of contact, leaving free ends which run together in such a manner as to form one loop out of the two, unless they can coincide throughout their entire length, when the neutralization is complete. It is so in the case of a circuit composed of a tube with the return lying along the axis of this tube. This breaking and running together of the lines of force applies to the attraction between the unlike poles of magnets, to the mutual attraction between a conductor which carries current and a magnet, and also to the attraction between circuits carrying currents in the same direction.

A conductor offers resistance to lines of force cutting across or through it which varies with the conductivity; the better the conductivity the slower will be the progress of lines cutting through it. Moreover, if a sufficient delay has been caused in any portion of one of the loops or lines by an interposed conductor, that portion is broken out of the loop, the remainder being pulled away from it, leaving it encircling the conductor with no force to sustain it opened out, consequently it shrinks up and disappears in the conductor, producing in it an induced current. In Fig. 1 let N represent the north and S the south seeking pole of a permanent magnet. The positive direction of the lines of force will be from N to S across the air gap. Let B be the cross-section of a conductor which is perpendicular to the plane of the paper, and which is made to suddenly cut across this magnetic field from above downwards. The lines of force will be carried or pushed ahead of the conductor for the instant, owing to the resistance which it offers to their cutting through it (see Fig. 1) and, as the conductor is moved on, these encircling portions are broken out of, and pulled away from, the main lines. They are then in a position to shrink in upon the conductor B, thus setting up an induced current in it. The conductor being encircled left-handedly, the induced current will be out from the paper or towards

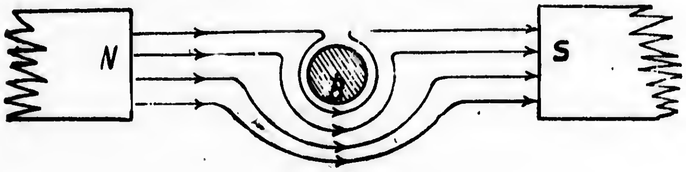

Fig. 1

us. If the direction of motion be reversed, the direction of the current is also.

Let us now consider the case where a current flows in B towards us, or up out of the paper. The induction loops encircle it left-handedly as we view it. Suppose B to be situated as in Fig. 1 with regard to the magnetic field; the lines on the upper side of the conductor run in the opposite direction to those of the field. As has been explained, when one of these lines comes in contact with one of the field lines running in the contrary direction, they break at that point and run into one, as shown in Fig. 1. This contracting along its length urges the conductor upwards through the field. The conductor is thus robbed of its lines, which disappear in the manner described, and the energy which they represented is transformed into the energy of motion of the conductor. The lines thus destroyed are being continually replaced by new ones sent out by the current which flows in B.

Next we come to currents induced by currents. In Fig. 2 let A be the cross-section of a conductor which carries current down through the paper. The lines of force will encircle it as shown in the figure. These lines travel outward from the wire at the same rate, when current is made, but some go further than others. The first ones go out to the most distant portions of the field, and the succeeding ones

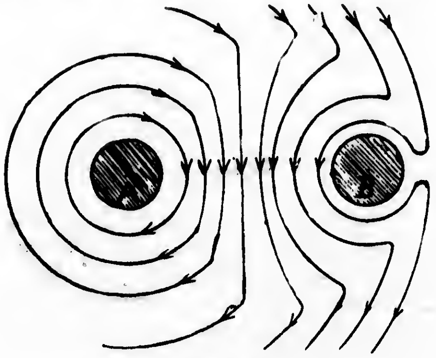

Fig. 2.

to intermediate positions. As the current grows, new lines are sent out at a rate depending upon the rate of increase of the current. Let B be the cross-section of a wire which is parallel to A. When current is sent through A, the loops of force expanding outwards reach B, by which their motion is delayed, so that they momentarily encircle it as shown in Fig. 2, and the main portions of these loops expanding still further outward from A, break away from the parts which encircle B. These parts are then free to shrink in upon B, causing an induced current to flow in it, and since the direction of the loops around B is left-handed the induced current is towards us.

Suppose now that circuit A is suddenly broken, all of its lines collapse inward, those to the right of B, in Fig. 2, have to cut through B on their way in, and it is readily seen that they will momentarily encircle it right-handedly. The induced current in B is away from us, or is in the same direction as the primary current in A. If the secondary circuit B is moved up nearer to A, the number of lines cutting through it when current is started or stopped in A, is increased and reaches a maximum when B exactly coincides with A, that is, the starting or stopping of a current in a conductor induces an inverse or direct current in the wire itself. From the point of view adopted, we must consider this self-induction as due to the lines of force cutting through the substance of the conductor, while the current is being made or broken in that conductor. We might suppose it to be made up of an indefinitely great number of very small parallel filaments and the loops as originating at the centre, so that each one upon opening out must cut through the whole number of filaments, the currents thus induced being opposed in direction to that producing the loops. From this point of view, the thicker the wire the greater its self-induction. A current of given strength is capable of sending out these loops only until each square centimeter of space is filled with a given number, which depends upon the permeability of the medium, and the distance from the circuit. The total number associated with any circuit depends, then, upon the shape of its contour and not upon its length. For the cases considered thus far, the coefficient of self-induction may be defined as being the number of lines associated with the circuit when unit current flows, or, as the quantity of induced electrification which is developed in the circuit, assumed to be of unit resistance, when unit current through it is made or broken. Calling this coefficient L, we see that it may represent, either a number of lines of force set up by a certain current, or the current set up by the opening or collapsing of a certain number of lines. If the current be of strength I there will be LI lines of force set up, and conversely if LI lines of force come in upon the wire in a very short time, they will produce an instantaneous current I.

Let A and B of Fig. 2 be similar circuits, that is, the resistance and self-induction of each being the same, and suppose B to have such a form and position that unit current in A sends out lines so that M of them cut once through B. M is called the coefficient of mutual induction. A current I being made in A, MI lines will cut through B, and, when A is broken suddenly, these MI lines again cut B on their way in upon A. Since LI lines cutting such a circuit produces an instantaneous current I, MI lines will produce a current i, which is to I as MI is to LI, or $i = MI \div L$. [See Fleming's Alternating Currents, or Bedell and Crehore for mathematical treatment of this.] There are, however, $(L - M)\,I$ lines which can not cut or disappear in B on break of circuit A, inasmuch as they do not encircle it, these of necessity must go in upon A causing the instantaneous current $(L - M)\,I$ in it. The nearer M is to being equal to L the less will be this current.

On making current in A, the outward movement of the lines being delayed by their having to cut through the closed circuit B, they accumulate rapidly to their limit in the space between A and B, and anything which lessens the number of lines of force sent out by any circuit, in a given time, hastens the rise of the current in it to its full value. A method of thus getting rid of the self-induction in the coil of an electromagnet has been patented quite recently. A closed coil is wound alongside of the magnet coil, this being of a given conductivity and capacity, the self-induction is entirely neutralized.

It is found that the presence of a closed secondary circuit causes both the primary and secondary currents to establish themselves by a series of oscillations. The result is the same as if a condenser of the proper capacity were in connection with the primary. These oscillations of the primary current have much to do with the effects obtained in the secondary. As in the Hertz experiments, the electric surgings in the primary or exciter, set up similar ones in the secondary or resonator and cause the spark to pass across the air gap.

We have said that the delay in the progress of lines of force cutting broadside through a conductor is proportional to, or dependent upon, the conductivity. If the circuit be open the conductivity is practically zero, consequently the delay is very slight, and the conductor gets no hold upon any portion of a line sufficiently good to break it out of, or away from, the main one. There is in this case but little more energy expended than if there were no secondary circuit present, though the eddy currents in the substance of the conductor dissipate some, even on open circuit. If, instead of making and breaking the primary circuit in a leisurely manner, we set up electrical oscillations in it of sufficient rapidity, the lines of force which are sent out to the greatest distance from the conductor become distorted in shape, owing to non-uniform permeability, and their tendency to contract increases this distortion, until finally a portion of each of the outer lines detaches itself as a self-closed line of force, which advances independently into space while the remainder of the lines sink back into the oscillating conductor. The number of receding lines of force is the same as the number which proceeded outwards, but their energy is necessarily diminished by the energy of the detached portions. These portions which do not return to the system, but are radiated into space, constitute the true electrical or electromagnetic waves, which possess all the properties of light waves.

EXPERIMENTS ON INDUCTION.

The first experiment upon the effect the arrangement of circuits had upon the induced currents was as follows:—Upon a long straight board were placed four wooden wheels of four inches in diameter, having their planes at right angles to the base-board, and four feet apart. Around the circumference of these wheels, at equal distances, eight wires were fastened, these being parallel to each other and to the base-board. The wires were sixteen feet long and were connected together at each end to a single wire which formed the return circuit. Through the centres of the wheels another wire was passed, equivalent in resistance to the eight in multiple. In circuit with this and the source of current was a Poggendorff switch, so that the rate of make and break could be changed at pleasure. A second switch was put in the secondary circuit. This was carried upon the same shaft as the first one, and had brushes supported by an adjustable ring so that the time of completing the secondary circuit could be regulated at will. The make and break induced currents were thus separated and either could be sent through a galvanometer in the circuit. When the central wire was used as the primary and the circumference wires as secondary the same readings were obtained as when the eight wires were used as primary and the central one as secondary. When the wires upon the rims of the wheels were all placed together at one point, instead of being separated by equal distances, the readings were unchanged.

The effect of making the secondary in the form of a tube completely surrounding the primary was next tried. For the eight wires, twelve strips of zinc were substituted, each strip being sixteen feet long and 1.05 inches wide. These were tacked upon the circumferences of the wheels, making a zinc pipe or cylinder four inches in diameter, which surrounded the central wire. After taking a number of readings, using first one of the circuits as primary, and then the other, eleven of the strips were removed and all placed upon the twelfth one. This arrangement was again modified by sawing radial slits in the circumferences of each wheel one-half an inch in depth and 1.05 inches apart. In these slits the zinc strips were placed. They were thus edgewise to the central wire, and their centres at the same distance from it as before. Finally each strip was rolled up in the form of a wire. The induced currents, however, were the same for each case, showing that a single wire lying at a given distance R from the primary is the same in effect as a tube of equivalent resistance which entirely surrounds the primary, the radius of the tube being R.

A much more complete arrangement of the circuits is as follows: An insulated wire thirty-five feet long, which will be called circuit 1, had a copper tube of same length slipped over it. Over this tube, which will be called circuit 2, was put a rubber tube and then another copper tube, circuit 3, and so on until there were five concentric circuits. The thickness of these tubes varied so that the resistances were equal. The ends of these circuits were brought very nearly together, by bending them into a circle of about twelve feet in diameter.

The wires leading from these terminals to the battery, galvanometer and telephone were carefully insulated and twisted closely together so that there should be no effect except from the concentric system of circuits. The tables on page 12 give the readings obtained. A word or two in explanation of the tables might be in place. In the fourth column headed "other circuits" the letter "O" is used to denote that the circuit is open, while "S" denotes that it is shut or closed. For instance, 3 S signifies that the ends of circuit 3 have been joined by a short copper staple dropped into the mercury cups at its terminals. For convenience in writing out the table the sounds heard in the telephone are given numerical values, 10 representing the loudest sound heard during the experiments. The brilliance and loudness of snap of the sparks in the primary upon breaking circuit are represented numerically upon the same basis. Further than this the tables explain themselves.

For the readings in which the galvanometer was used in the secondary circuit, the primary current was made and broken by hand. When the telephone was used in the secondary the makes and breaks of the primary were made by a Foucault mercury interrupter. Readings (22) (32) and some others are interesting, and were not as expected. It was hoped that these experiments would show something regarding the direction of propagation of the electromagnetic waves, that is, whether they radiate outwards from the wire when current is up, or come in upon the wire from outside space. Also, whether a secondary circuit in the form of a tube, through which the primary passes, has any greater E. M. F. induced in it, than has a single wire of equal resistance, the distance between the circuits being the same for

No.	Circuit used as primary	Galv'n'r or telephone in circuit.	Other circuits.	Galv'r defl'x's in mm.	Sound in telephone.	Spark in primary.	Galv'r defl'ns when galv'r and battery are interch'g'd	Sound when telephone and battery are interchanged.
1	1	2	3O 4O	155	10	9	145	9
2	1	2	3S 4O		4	3		4
3	1	2	4S 3O		6	5		5
4	1	2	3S 4S		2	2		2
5	1	3	2O 4O	140	9	9	125	8
6	1	3	2S 4O		3	2		3
7	1	3	4S 2O		4	4		5
8	1	3	2S 4S		2	1		2
9	1	4	2O 3O	125	8	10	120	8
10	1	4	2S 3O		2	2		3
11	1	4	3S 2O		3	3		3
12	1	4	2S 3S		1	1		1
13	2	3	1O 4O	135	9	10	130	9
14	2	3	1S 4O		4	3		4
15	2	3	4S 1O		4	5		3
16	2	3	1S 4S		3	2		2
17	2	4	1O 3O	125	8	10	120	8
18	2	4	1S 3O		4	3		4
19	2	4	1O 3S		3	4		3
20	2	4	1S 3S		2	2		2
21	3	4	1O 2O	125	8	10	120	8
22	3	4	1S 2O		5	4		5
23	3	4	2S 1O		4	3		4
24	3	4	1S 2S		3	2		3

No.	Current in circuit.	Returning through circuit.	Telephone in circuit.	Other circuits.	Sound in telephone.	Sound when telephone and battery are interch'g'd.
25	1	2	3	4O	0	0
26	1	2	3	4S	0	0
27	1	2	4	3O	0	0
28	1	2	4	3S	0	0.4 (?)
29	1	3	2	4O	0.2	1
30	1	3	2	4S	0.2	1
31	1	3	4	2O	0	0
32	1	3	4	2S	5	5
33	1	4	2	3O	6	6
34	1	4	2	3S	4	5
35	1	4	3	2O	3	3
36	1	4	3	2S	5	5
37	2	3	1	4O	1	2
38	2	3	1	4S	0.8	1.5
39	2	3	4	1O	0	0
40	2	3	4	1S	4	5
41	2	4	1	3O	1	[illegible]
42	2	4	1	3S	0.5	1.5
43	2	4	3	1O	0.8	1
44	2	4	3	1S	0.8	1
45	3	4	1	2O	0.8	1
46	3	4	1	2S	0.2	0.5
47	3	4	2	1O	1	1
48	3	4	2	1S	0.7	0.8

each case. In determining the position of nodes for Hertz waves in parallel wires, a resonator was made and used, the sides of which consisted of hollow tubes threaded over and insulated from the primary wires. The spark gap was between adjustable points attached to zinc discs, which were inserted at the middle point of one of the sides. The experiments show that there is no advantage in this form for slow alternations, but actual trial showed that for the Hertz waves it was a very great improvement over the ordinary wire form. This remark applies to the experiments previously described, that is to say, a wire may be surrounded by parallel wires so that no energy can get out, and the closeness of the grid necessary depends on the rate of alternation in the primary.

HERTZ WAVES.

Although much time was given to experiments on Hertz waves only brief mention will be made of them here. Linear exciters or oscillators and linear resonators of different sizes were first tried. The oscillators had cylindrical, telescopic ends, the capacity of which could be modified at will. The wave length was calculated from the dimensions of the oscillator. The spark gap was between points, one of which could be adjusted by a micrometer screw. The spark was viewed by a low-power microscope. To make the discharge between the knobs of the oscillator as sudden as possible, they were frequently polished. A strong air blast was tried, also a powerful electromagnet, but these seemed to have but little effect. The electrostatic effects alone were obtained by attaching large metal sheets to the ends of the oscillator and then holding the linear resonator end-on towards these.

These effects were almost entirely eliminated and the electrodynamic only obtained by placing the oscillator directly in front of a large earth-connected metal screen, the capacity-ends being bent around behind the screen, leaving only the straight wire portion in front.

When the waves were set up in parallel wires, the oscillator was circular in form, at the ends of which were condenser-plates quite near together, the distance between them, and therefore the capacity, being variable. The long wire circuit was threaded through a hard rubber tube and thus was capable of being put very close to the oscillator circuit throughout its entire length. The resonator, as has been already described, consisted of hollow tubes threaded upon the wires, and prevented from touching them by glass tubing. The end portions of this resonator consisted of ordinary wire. More brilliant sparks were obtained than when the resonator was merely inserted between the wires. Another advantage of this form was that it needed no other support than the wires in which the Hertz waves were set up. The wave length, however, was found to vary with the size of the resonator. And a decided disadvantage is the difficulty of calculating even approximately the capacity of this form. Considerable time was spent in trying to determine whether the exciter gave out waves of different lengths, or only one wave length which depended upon its dimensions.

Under proper conditions any resonator will respond to any exciter. Poincaré says (see Electricité et Optique, Vol. II, p. 250): "In the vibrations emitted by any exciter two things must be considered, the period and the logarithmic decrement. Different reasons lead me to think that this decrement is many times greater for the exciter than for the resonator. The vibrations would diminish in intensity very rapidly for the exciter, they would thus be very short and little capable of interference. This does not hold for vibrations proper to the resonator. The resonator would be set in motion by the exciter, providing the periods were nearly the same, and it would continue to vibrate after the exciter had entirely ceased but it would vibrate then with its own period, and these are the vibrations of long duration, which being capable of interfering, we observe." That is, the case is somewhat analogous to ringing a bell, if the rope be suddenly pulled and let go, the bell will continue to swing with its own period, which is totally independent of that of the impulse, but if the pulling be a series of impulses then to ring properly the bell must be chosen of such a size that its period is the same as that of the impulses.

It was thought that if two different-sized resonators were placed in the path of the radiations, so that each gave sparks, and then a number of resonators, similar to one of these, placed between them and the source, that particular wave length proper to these interposed resonators should be absorbed and no other, thus the sparks should cease in one and not in the other. If, on the other hand, these resonators should absorb all the energy radiated, as held by Hertz and others, then the sparks should cease in both at the same time. A number of rectilinear resonators were made and attached to a thin board. Six of these were of a total length of 1m. each, and were placed 7.5cm. apart, between these a number of shorter ones were placed, the shortest of which was 20cm. in length. When this board was held flatwise in the path of the waves sent out by the mirror all the resonators gave sparks, but when it was turned edgewise so that one was behind the other only the three or four long ones nearest the source gave sparks and the short ones seemed to be also slightly affected, the sparks being weaker but not cut off. If now, beginning with the resonator nearest the source, the spark gaps were lengthened so that sparks could not pass, the sparking in those farthest from the source was increased. The sparks in the short resonators were very capricious, frequently ceasing altogether and then suddenly starting up they would continue vigorously for a long time, though no change had been made in the apparatus or surroundings. This behaviour makes the results indefinite to a large extent, however the experiments seemed to prove that the oscillator emitted waves of all lengths, and that to obtain satisfactory results for the velocity of propagation of these waves it is necessary to obtain the period of the resonator rather than that of the vibrator. Several turns of wire were used as a resonator in place of the single turn, but trials in different ways gave no results, the sparks ceasing to pass in every case where more than one turn was used. An extended bibliography was prepared but has been omitted inasmuch as the whole ground has been so thoroughly covered by recent publications, the most important, next to Hertz's own work, being that by Prof. J. J. Thomson entitled "Recent Researches in Electricity and Magnetism."

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