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ON THE SO-CALLED MAGNETIC RAYS OF RIGHI; ELECTRICAL OSCILLATIONS IN GEISSLER TUBES, AND THE PERIODIC INTERRUPTION OF SPARK DISCHARGES.[1]

By James E. Ives.

I. Introduction.

IN 1908, Righi[2] described some experiments upon which he based the assumption of the existence of a new kind of ray in a Geissler tube acted upon by a magnetic field. Each ray was supposed to be made up of an electron revolving around a positive ion, each positive ion with its accompanying electron forming as it were a double star. The rays were supposed to be formed under the action of a magnetic field, and under its action to give rise to a number of unusual phenomena in the tube.

The object of the experiments described below was, if possible, to obtain an explanation of these phenomena in terms of well-known principles without having to resort to the assumption of a new kind of ray.

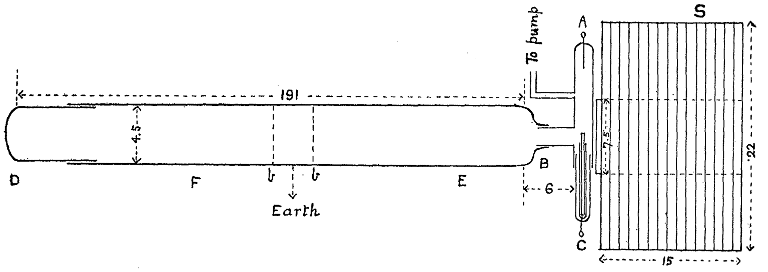

Fig. 1.

The tube which I used in most of my experiments is shown diagram-

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[1] For an abstract of part of this paper, see Physical Review, 7, 407–409, 1916.

[2] Rendiconti della R. Accad. dei Lincei, 2 Feb., 1908; Mem. della R. Accad. della Sci. Bologna, 17, 87–90, 1908; La Materia Radiente e i Raggi Magnetici, Bologna, 1909; Strahlende Materie und Magnetische Strahlen, Leipsig, 1909.

matically in Figs. 1 and 2; Fig. 2 is an enlarged drawing of a portion of Fig. 1. The dimensions are given on the figures in centimeters. The tube, in a general way, is similar to the one used by Righi, but is somewhat simpler in design. It consists of a small tube, Fig. 2, having the anode at *A* and the cathode at *C*. Opening into this, at *B*, is a much longer and wider tube, *BD*, Fig. 1. The tube *AC* I will call the *side tube*, and the tube *BD* the *long tube*. The anode is a platinum wire .046 cm. in diameter; and the cathode is an aluminum wire, .328 cm. in diameter, covered to within a centimeter of its tip with a small glass tube to confine the discharge to its end.

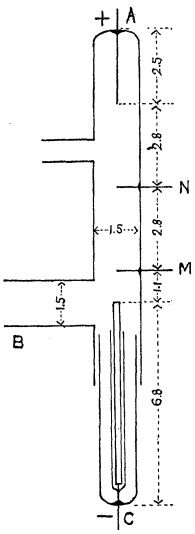

Fig. 2.

The whole tube, which we may call a Righi tube, is connected in series with a high potential battery, *B*, and a non-inductive resistance of from half a million to a million ohms, *R*, as shown in Fig. 3. *kk* is a double switch which connects the battery to the rest of the circuit.

A static induction machine can be used in place of the high-potential battery, but the battery is better as it gives a steadier and larger current. The battery had 2,000 cells, and I usually used about 2,100 or about 2,700 volts.

In all the experiments, I used the air of the room and did not attempt to dry it. To exhaust the tube I used a Gaede rotating mercury pump, or a Gaede oil pump; and to measure the pressure, a MacLeod gauge. The Righi effects were best obtained at pressures varying from .1 to .2 mm. of mercury.

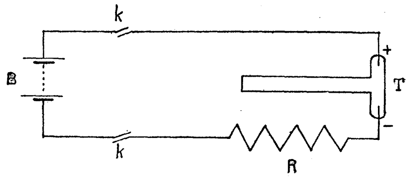

Fig. 3.

To produce the magnetic field, I used a solenoid *S*, Fig. 1, having a soft iron core, which gave an approximately uniform transverse field in the region between the cathode and anode of the tube. Its strength could be varied from zero to 2,600 gausses.

When no magnetic field is present, there is the usual Geissler tube appearance in the side tube *AC*, that is a striated pink glow in the neighborhood of the anode and a bluish-violet glow in the neighborhood of the cathode, but there is no glow anywhere in the long tube. As the strength of the magnetic field is gradually increased, the pink striæ are pressed more and more against the side of the tube, their number increases, and they move downwards until they fill the whole of the Faraday dark space. When the field reaches a certain strength, depending upon the pressure of the air in the tube, the striæ coalesce, forming a continuous pink column, and the discharge through the tube becomes periodic, emitting a note. At the same time, there appears in the long tube, *BD*, a bluish-violet glow extending from the cathode to *E*, see Fig. 1; a pinkish glow extending from *E* to *F*, and a bluish-white glow extending from *F* to *D*. The short bluish-violet column is either attracted to, or repelled from, the north pole of an auxiliary magnet, and produces a spot of fluorescence at the point where it touches the tube. This bluish-violet column Righi assumes to be made up of his magnetic rays. The pinkish column is bent upwards in an arc by the north pole of an auxiliary magnet, and the bluish-white column is bent downwards in an arc. The directions in which these columns are bent seem to show that a current flows away from the region of *F*, on both sides of it. Righi therefore calls this region *F* the "virtual anode." The column from *E* to *D*, we may call the "Righi column." Righi assumes that it is produced by the disintegration of the magnetic rays. He assumes that the magnetic rays under the action of the magnetic field move out along the lines of force. When they have reached the weaker parts of the field they are supposed to disintegrate, producing free positive and negative ions. The positive ions so produced are assumed to form the virtual anode. The portion of the Righi column from *E* to *F*, I shall call the "positive column" because it resembles in color the positive column in the ordinary Geissler tube, and the portion from *F* to *D*, I shall call, by contrast, the "negative column."

In the region of the virtual anode, for several centimeters, the column is often double, there being both a positive and negative column present at the same time. In this case, it presents much the appearance of a vibrating string. Occasionally the column will be double throughout the whole length of the tube: for instance, on one occasion the negative column was of about equal brightness throughout the whole length of tube, and the positive column decreased in brightness from the fixed to the free end of the tube, being very faint towards the free end.

The virtual anode may exist at any point, *F*, along the tube. As the strength of the magnetic field increases, it moves out along the tube toward *D*. Under certain conditions, as for example when an electrostatic induction machine is used, *F* may be close to *E*, and the negative column may occupy nearly the whole length of the tube.

The "magnetic rays" have been investigated by Thirkell,[1] More and

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[1] Proc. Roy. Soc., 83A, 324–334, 1910.

Rieman,[1] More and Mauchly[2] and others. Both Thirkell and More and Mauchly have come to the conclusion that they are negatively charged particles moving in spirals along the lines of magnetic force. In fact More and Mauchly state that they have found that all of the Righi effects can be obtained without a magnetic field by using a Wehnelt hot lime cathode.[3] Recently the Righi effects have been discussed by Holm[4] and Righi.[5]

The bluish-violet column from B to E, in agreement with the investigations of Thirkell and More and Mauchly, we may assume to consist of cathode rays, since it begins at the cathode and makes the glass fluorescent where it touches it. These investigations do not explain, however, the existence of the positive and negative columns, the virtual anode, and the periodicity of the discharge.

I first repeated the experiments described by Righi in his publications, and my experiments confirmed his experimental results. Thus, I found that the length of the Righi column depended upon the strength of the magnetic field, increasing as the strength of the field increased; and that the frequency of interruption of the discharge decreased as the strength of the field increased. The frequency could in this way be varied through several octaves.

2. CAPACITY OF THE LONG TUBE.

Early in my experiments, I noticed that when the finger was touched to a metal band holding the long tube in place the note emitted by the tube became very much louder and the frequency of the discharge was lowered, the frequency normally being very high, about 2,000 a second.

I therefore wrapped a brass band, 10 cm. wide, *bb*, Fig. 1, around the tube and connected it to earth. The frequency was then reduced to about one fourth of its original value. When this band was made twice as wide, the frequency was again reduced. By decreasing the width of the band, and also the strength of the magnetic field, the pitch can be made to vary from zero, or say one discharge every ten seconds, to a pitch above the limits of audibility. In other words, with an earthed metal band on the tube, any frequency that is desired can be obtained.

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[1] Phil. Mag., 24, 307–316, 1912.

[2] Phil. Mag., 26, 252–267, 1913.

[3] R. Reiger, Sitzungsberichte der Physikalisch-medizinischen Sozietät in Erlangen, 37, 20, 21, 1905, states that when using a Wehnelt cathode it is very difficult to get a continuous discharge. This fact, as will be shown later, is probably the reason why More and Mauchly obtained the Righi effects with this kind of a cathode.

[4] Phys. Zeitschr., 16, 79, 80, 1915.

[5] Nuovo Cimento, 9, Gennaio—Febbraio, 1916.

When the band was on the tube, there was a negative column from *bb* to *D*, and, usually, a *double* column from *bb* to *E*. By a "double" column, I mean that the auxiliary magnet divides the luminous column into two parts, one part being bent up and the other down.

These experiments show that the frequency of the discharge depends not only upon the strength of the magnetic field, but also upon the capacity of the long tube. If we assume that the long tube acts as a conducting cylinder, its calculated capacity would be about 20 cm. in electrostatic units. Other experiments, which will be described later, would seem to indicate that this is of the order of the maximum effective capacity of the tube.[1]

The connection between the strength of the magnetic field and the frequency of the discharge probably depends upon the fact that the length and strength of the stream of electrons proceeding from the cathode, into the long tube, increases with the strength of the field, making the effective capacity of the tube greater, that part of the tube only being effective as capacity where the gas has become ionized by the presence of the electrons.

3. Action of the Magnetic Field.

The component of the magnetic field transverse to the side tube, due to the solenoid *S*, Fig. 1, was approximately uniform between the electrodes; not varying more than 10 per cent. along the line joining them. It was transverse to the line joining the electrodes, and in the direction of the axis of the long tube. Its action is twofold: (1) it produces a periodic interruption of the discharge in the side tube, and (2) it sends a periodic charge of electrons into the long tube.

The first fact is shown by the following experiment. I disconnected the long tube from the side tube at *B*, Fig. 1, and closed the aperture so formed with a glass plug. I then examined the action of the magnetic field upon the discharge in the side tube. Using a rotating mirror to observe it, I found that for a certain strength of the field the discharge through the tube became periodic, the frequency decreasing as the strength of the field increased, and varying through several octaves. When the field reached a certain strength, the discharge in the tube ceased. The *periodicity* of the Rhigi effect is, therefore, due to the action of the field upon the discharge through the *side tube*. Its frequency is modified by the presence of the long tube, *BD*, but the periodicity does not depend for its existence upon it.

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[1] For discussions of the capacity of a Geissler tube, see: G. Wiedermann, Die Lehre von der Elektricitat, Bd. 4, 505–511, 1885; J. Borgmann, Phys. Zeits., 2, 651–653, 1901; S. N. Taylor, Phys. Rev., 18, 338–344, 1904; R. Reiger, l.c., 21–39.

The periodic discharge of electrons into the long tube is shown by the existence of the cathode stream, already described, from the cathode to *E*.

Repeated experiments showed that the Righi effects are never present in the long tube unless the discharge through the side tube is an interrupted one.

It was also found that even if the discharge is an interrupted one, the Righi effects are not produced unless the cathode is opposite the opening in the long tube at *B*, Fig. 1. If the distance between the electrodes is kept constant, but the cathode is lowered until it is 3 or 4 centimeters below the opening at *B*, the effects are not obtained. This would seem to show that there must be a projection of the electrons directly from the *cathode* into the long tube. The action of the same field upon the *positive column*, when a portion of it is opposite the opening at *B*, does not produce the same effect.

Table I. shows how the potential difference, between the anode and the cathode, and the current through the tube vary as the magnetic field is increased. Two cases are given, first, when the long tube, *BD*, was *disconnected* from the side tube at *B*, and, second, when the long tube was *not disconnected*. The differences of potential were measured with a quadrant electrometer, and the currents with a milliammeter.

TABLE I.

Pressure in Mm. of Mercury.	Field in Gausses.	Potential Across Tube in Volts.		Difference.	Current in Milliamperes.		Difference.	
		Without Field.	With Field.		Without Field.	With Field.		
.32	200	750	650	−100	1.00	1.09	+.09	Long tube disconnected from side tube.
	245	780	680	−100	1.05	1.15	+.10	
	265	800	700	−100	1.02	1.15	+.13	
	290	Discharge became discontinuous.						
.20	265	1,050	800	−250	.75	.95	+.20	
	300	Discharge became discontinuous.						
.15	340	900	750	−150	1.10	1.20	+.10	Long tube connected to side tube.
	410	Discharge became discontinuous.						
.13	170	1,040	850	−190	.84	1.00	+.16	
	220	1,010	790	−220	.78	.98	+.20	
	280	Discharge became discontinuous.						

To determine the distribution of the potential in the side tube, and the effect of a magnetic field upon it, platinum wires were sealed into the walls of the side tube at the points *M* and *N*, Fig. 2. The wire *M* was in the negative glow, just outside the Crookes dark space, and the wire *N* was just outside the positive striations. The difference of potential between *M* and the cathode was approximately equal to the cathode fall. The results, given in Table II., were obtained when the long tube was *disconnected* from the side tube.

It is seen from the two tables that *as long as the discharge through the side tube is continuous*, the effect of the transverse magnetic field is to considerably *decrease* the difference of potential between the electrodes of the tube, and to correspondingly *increase* the current flowing through it. It is also clearly seen that when the field reaches a certain strength the discharge becomes discontinuous. Readings of the electrometer and milliammeter for field strengths greater than this obviously have no value. Table II. also shows that the cathode fall of potential amounts to about nine tenths of the total fall of potential between the electrodes. Just why the magnetic field for a certain strength should extinguish the discharge, it is difficult to say.[1] The fact that the potential decreases as the magnetic field increases until the discharge becomes interrupted, suggests that the action of the field is to reduce the potential until it becomes less than the "maintenance potential," *i. e.*, the minimum potential necessary to *maintain* the current through the tube. The value of the maintenance potential will depend upon the shape of the tube and its electrodes, the pressure of the air in it, the value of the impressed electromotive force and resistance in the circuit, and probably also upon the strength of the magnetic field.

Table II.

The Long Tube Disconnected from the Side-Tube.

Pressure in Mm. of Mercury.	Field in Gausses.	Potentia Difference Between	Potential Across Tube in Volts.		Difference.	Current in Milliamperes.		Difference.
			Without Field.	With Field.		Without Field.	With Field.	
.20	135	*C* and *A*	1,080	1,020	−60	.80	.84	+.04
		C and *N*	940	890	−50	.76	.79	+.03
		C and *M*	950	860	−90	.78	.80	+.02

The *minimum potential* curve, *A*, and the *maintenance potential* curve, *B*, for varying pressure were obtained for the tube and are shown in Fig. 4. The minimum potential curve, *A*, shows the smallest potential that will *start* a discharge through the tube. Curve *B* was obtained by gradually decreasing the potential applied to the circuit, by a potentiometer arrangement, until the discharge through the tube stopped.

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[1] See Thomson, Conduction of Electricity through Gases, 2d edition, pages 576–579; Riecke, Ann. Phys., 4, 592–616, 1901; Stark, Ann. Phys., 12, 31–51, 1903; Schwienhorst, Diss. Gottingen, 1903; Earhart, Phys. Rev., 3, 103–114, 1914.

There was a non-inductive resistance in the circuit of about half a million ohms, and the current flowing through it varied from .34 to .13 of a milliampere.

4. Sign of the Charges Inside the Long Tube.

The charges on the *inside* of the long tube were examined both with a brass band touching the walls of the tube, and with a platinum wire placed in its axis. The brass band was 5 cm. wide and was attached to a wire sealed into the end of a long glass tube 8 mm. in diameter which could be introduced into a suitable holder at the free end *D* of the long tube. In this way it could be placed at any desired place in the tube. The platinum wire, .046 cm. in diameter and 5.5 cm. in length, was similarly sealed into the end of a long glass tube. The band, or wire, was connected to an aluminum leaf electroscope, and the sign of the charge on it was determined by determining the sign of the charge on the electroscope. The results obtained were the same both for the band and the wire, and were briefly the following.

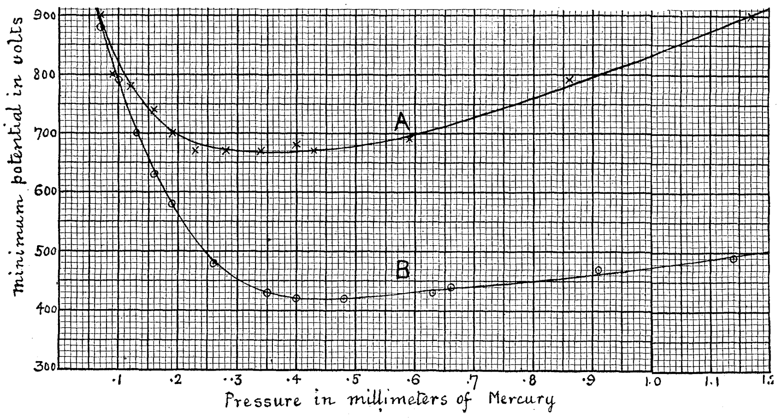

Fig. 4.

If the magnetic field was not strong enough to make the Righi column long enough to touch the brass band, or wire, the behavior of the electroscope was irregular, but if it was strong enough, on closing the high potential key, *kk*, Fig. 3, with no magnetic field, I got a *positive* charge on the electroscope; then with the magnetic field on I got a deflection of *indeterminate* sign, that is a deflection due to a charge rapidly alternating in sign; and finally opening the high potential key, still keeping the magnetic field on, I got a residual *negative* charge. So then, I had an initial positive charge, then a charge rapidly alternating in sign, and finally a residual negative charge. The farther the band, or wire, is from the side tube the more slowly does the leaf charge up for the initial positive charge. The behavior of the electroscope, therefore, indicates that when the magnetic field is strong enough to make the discharge interrupted there is a charging of the tube alternately positively and negatively, and that it probably begins with a positive and ends with a negative charge.

The residual negative charge may be the result of an oscillation due to the capacity of the long tube, or it may be due to the magnetic field diverting a stream of electrons into it. The initial positive charge is explained by the fact that the long tube always has a positive charge, of a greater or less value, when there is a steady discharge through the tube. Since nine tenths of the total fall of potential across the electrodes takes place in the neighborhood of the cathode, the whole of the long tube must be very nearly at the potential of the anode. In order to have this potential it must take on a positive charge. Therefore, when the discharge passes through the side tube, the long tube will begin to take on a positive charge. It will continue to do this until the discharge through the side tube becomes interrupted, when its positive charge will flow back towards the cathode, and may or may not produce a complete electrical oscillation in the long tube. That high frequency oscillations are possible in Geissler tubes is shown by an independent experiment which will be described later in this paper.

If an earthed brass band is placed around the outside of the long tube, causing the separate interruptions to succeed each other very slowly, for instance one every four seconds, the discharge builds up gradually, the glow first appearing faintly in the long tube from *bb* to *B*, Fig. 1, growing brighter and brighter and then suddenly flashing up in the side tube. When this flash takes place, the deflection of the electroscope takes place. Immediately after the flash, all the glow both in the long tube and the side tube goes out, and the action repeats itself.

As seen in a rotating mirror, both the positive and negative parts of the Righi column and the discharge in the side tube appear to be synchronous. If the two parts of the Righi column are not perfectly synchronous, and I do not think that they are, the interval of time between their separate occurrences must be very much less than the audible period of the discharge in the tube, probably less than .0001 second.

It is significant that, even when the magnetic field is not on, every time the high potential key, *kk*, is either closed or opened there is an instantaneous flash of light in the long tube.

5. The Production of the Righi Effects with a Spark Gap.

While experimenting with the arrangement of the circuit shown in Fig. 3, I discovered, accidentally, that all the Righi effects could be obtained without any magnetic field if a suitable spark gap was placed in the circuit. The discovery resulted from the fact that there was a loose contact, and consequently sparking, at one contact of the double switch *kk*. I noticed that when the sparking occurred there was luminosity in the long tube which much resembled the Righi effect. I did not, at first, pay much attention to it, as Righi in his book, and in subsequent papers,[1] has spoken of the importance of not having a loose contact in the circuit, as this would, according to him, produce a spurious effect. I thought, first of all, that I had a spurious effect, but, by putting into the circuit a suitable spark gap on the anode side, and a high resistance on the cathode side of the tube, I found that I could get all the Righi effects without any magnetic field.

At first, not all spark gaps would give the effect. The terminals of the gap must, apparently, be of relatively large area, and be so arranged that the length of the gap remains approximately constant. It is probably necessary that the gap shall be so constructed that the terminals cool off rapidly, preventing arcing. Later I had no difficulty in obtaining the effect with terminals of large surface constructed of zinc, copper or brass. The terminals which I finally adopted were zinc cylinders with flat ends, 9.3 mm. long and 12 mm. in diameter. They were not used end on, that is with their flat faces parallel to each other, but with the flat ends making an angle of 45° with each other, so that the sparking took place between two adjacent edges, as this arrangement seemed to give more regular results.

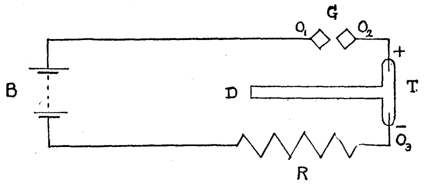

Fig. 5.

The circuit used is shown diagrammatically in Fig. 5. It will be noted that there are four elements in it, the battery *B*, the gap *G*, the tube *T*, and the high resistance *R*. In order that well-developed and characteristic Righi effects shall be produced, I found that the gap must be placed next to the anode of the tube, and the high resistance next to the cathode of the tube. No other arrangement will give the effects completely. For instance, if *G* and *R* are interchanged, the characteristic Righi effects are not obtained, nor are they obtained if *G* and *R* are both put on the same side of the tube. On the other hand, if the

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[1] For this and other interesting matters, see Righi, Phys. Zeits., 15, 528–534, 558–563, 1914.

anode and cathode connections to the tube are interchanged, that is, if the aluminum electrode is made the anode and the platinum electrode the cathode, a good Righi column is obtained, showing that the *shape* of the electrodes and their *position* with respect to the long tube have very little to do with the production of the Righi effects, when these effects are produced with a spark gap.

When the gap is closed, there is, of course, no Righi column, and the discharge through the side tube is continuous. If the gap is now opened and gradually widened, the current through the circuit decreases, remaining continuous, until it has fallen to a certain definite value, when, for a certain critical length of the gap, it becomes periodic. When this happens a short Righi column appears in the long tube. As the length of the gap is further increased the length of the Righi column increases until it fills the whole tube. When the gap becomes too long, the discharge goes out altogether. The frequency of interruption of the discharge decreases as the length of the gap increases. Using 2,700 volts and 800,000 ohms in the circuit shown in Fig. 5, the Righi column appeared when the gap was about .1 mm. long, was brightest at about .3 mm., and went out at about .4 mm.

In most of my experiments, with the spark gap, I used about 2,700 volts in the circuit. For this voltage, the Righi effects appear best at a pressure of about .16 mm. of mercury. For 2,100 volts, they begin to appear at about .2 mm., are brightest at about .13 mm., and disappear at about .05 mm.

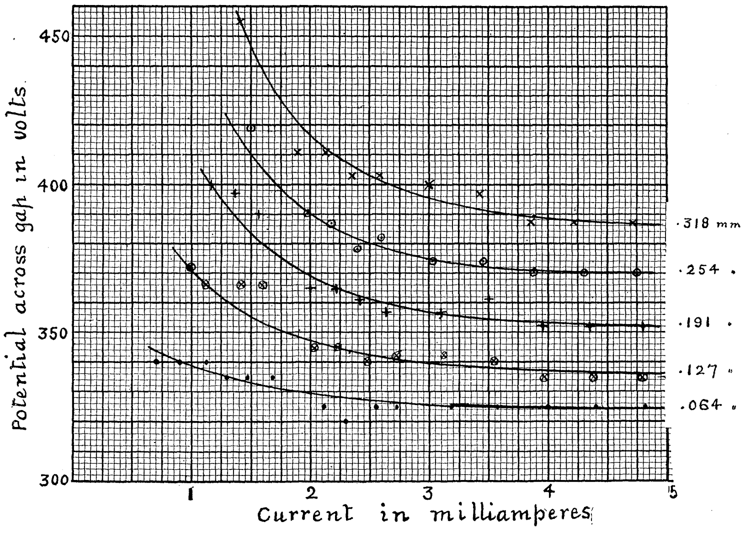

Fig. 6.

I examined the charges on the inside of the long tube, when using a spark gap to produce the Righi effects, just as I did when using a magnetic field to produce them, and I got the same results as before. Also, in this case, I found that if the discharge was stopped before the spark gap was opened, there being therefore no luminosity in the long tube, I got a residual positive charge.

From these results, it now appeared that the Righi effects were not dependent directly upon the action of a magnetic field, and were probably produced by the periodic interruption of the current through the tube. It therefore became necessary to study the properties of the spark gap, and to determine the volt-ampere characteristics both of the spark gap and the Righi tube. The discharge across the gap was examined with both a spectroscope and a microscope and was found to be a true glow discharge, for all lengths, and not an arc discharge. The spectrum observed was, in all cases, the spectrum of nitrogen and not that of the metal of the electrodes. The volt-ampere characteristics for the spark gap, for different lengths of gap, are shown in Fig. 6; and for the tube, for different pressures in the tube, in Fig. 7.

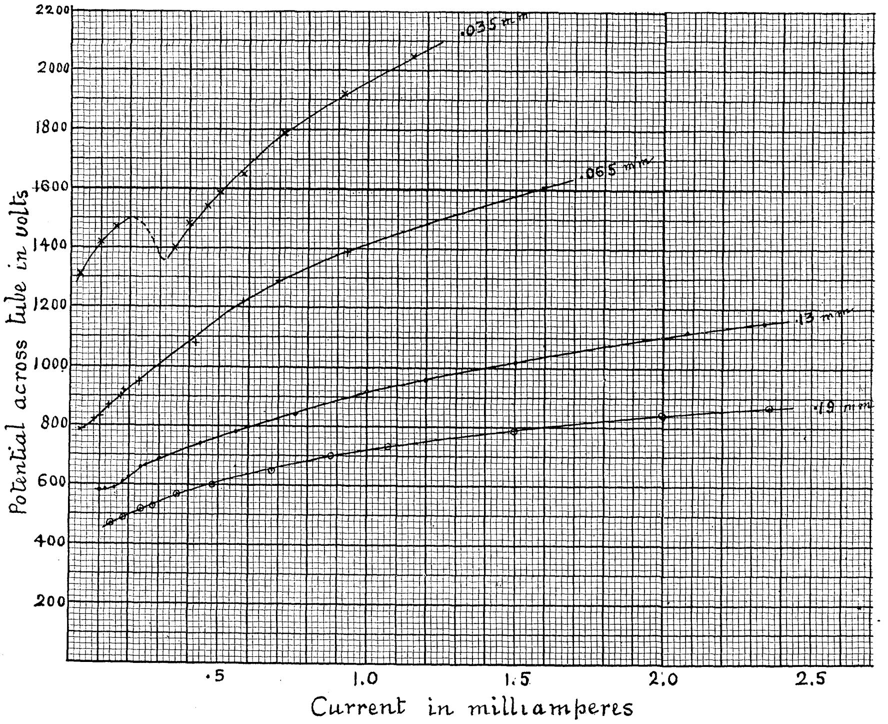

Fig. 7.

Riecke,[1] Stark[2] and Earhart[3] have investigated the characteristic curves for the *glow discharge* for Geissler tubes of special form; and Stark[4] and Malcolm and Simon[5] for spark gap discharges; and my curves agree, in a general way, with those obtained by them. The shape of the characteristic will, of course, depend upon the shape of the tube, and the form of the gap, respectively. The characteristics, as has been shown by Kaufmann,[6] completely describe the behavior of the gap and the tube in the circuit, and enable us to tell whether the conditions in the circuit are stable or not for a given current by the use of his criterion of stability

$$R > -\frac{\partial E}{\partial i},$$

where E is the potential across the gap, or tube; i, the current through it, and R the external resistance in the circuit.

In the circuit shown in Fig. 5, for 2,100 volts and about 500,000 ohms, the discharge becomes discontinuous, or unstable, when the current falls to about 1.8 milliamperes. Now an inspection of Fig. 7 shows that for this current the characteristic for the tube is a rising one, and therefore the conditions are stable so far as the tube is concerned, and the interruption is not due to the tube. An inspection of Fig. 6, on the other hand, shows that for 1.8 milliamperes the characteristic for the gap is a falling one, and that therefore the instability might be due to the gap. However, calculation shows that this possibility must be dismissed as the resistance in the circuit is very large, varying from half a million to a million ohms, and the slope of the characteristic curve, $\partial E/\partial i$, for 1.8 milliamperes is small compared with it, about 30,000 $\frac{\text{volts}}{\text{amperes}}$. Some other cause must therefore be found for the periodic extinction of the spark, as the falling characteristic of the gap is not *alone* sufficient to cause it.

A long series of experiments seems to show that the interruption of the discharge across the gap is due to two facts, (1) that the Righi tube has an appreciable electrostatic capacity, and (2) that the characteristic of the gap is a falling one. The capacity of the tube, apparently, produces an electrical oscillation in it, and this oscillation combined with

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[1] Ann. Phys., 4, 592–616, 1901.

[2] Phys. Zeits., 3, 274, 275, 1902; Ann. Phys., 12, 1–30, 1903.

[3] Phys. Rev., 1, 85–95, 1913.

[4] Phys. Zeits., 4, 535–537, 1903.

[5] Phys. Zeits., 8, 471–481, 1907.

[6] Ann. Phys., 2, 158–179, 1900; see also Barkhausen, Problem der Schwingungserzeugung, Leipzig, 1907.

the falling characteristic of the gap produces the interruption. It is found that if the tube is taken out of the circuit, the discharge across the gap is continuous for all lengths of the gap; and also that if the gap is taken out of the circuit, the discharge through the tube is continuous. The periodic interruption of the current flowing through the circuit is therefore due to the combined action of the gap and tube in series.

Light is thrown upon the problem by the fact that the tube can be replaced, in the circuit, by a *high resistance shunted by a capacity*; thus the Righi tube shown in Fig. 1 may be replaced, approximately, by a high non-inductive resistance, R_1, of half a million ohms, shunted by an air condenser, C, having a capacity of 93 cm., as shown in Fig. 8. The current flowing through the circuit and the periodicity of the discharge were then about the same as when the tube was present.

Further experiments showed that in order to make the discharge across the gap discontinuous, the capacity must be connected directly to the gap. It will not make the discharge interrupted if a high resistance is placed between it and the gap. For instance, a wire, O_2O_5, Fig. 9, 800 cm. long and .062 cm. in diameter, and having a capacity free in air of 39 cm., when attached at O_2 made the discharge discontinuous. If it was attached at O_3, R_1 being a high resistance of half a million ohms, it did not make the discharge discontinuous. Also if attached at O_1, it did not make the discharge discontinuous. Further it was found that the capacity must be attached between the gap and the high resistance. If it is attached at O_2 and the high resistance is placed between O_1 and O_6 the interruption is not produced. Thus it is evident that they must both be on the same side of the gap. It is however indifferent whether they are attached to the anode or the cathode of the gap.

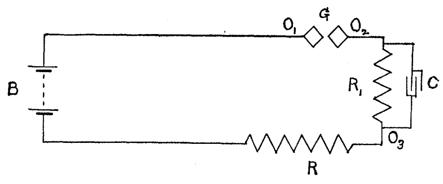

Fig. 8.

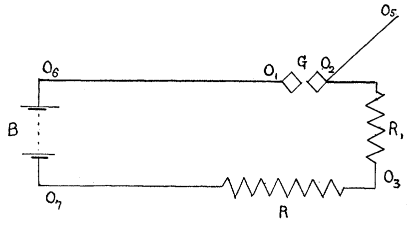

Fig. 9.

If a neon tube is touched to any part of the wire O_2O_5 it glows. This fact, I think, indicates that electrical oscillations are set up in the system $O_5O_2O_1$ by the charging of the wire O_2O_5.

The wire, attached at O_2, can be replaced by a capacity connected *across* the gap; the discharge then becoming discontinuous as before.

Elaborate experiments using capacities across the gap and at different points of the circuit seem to show that the periodic extinction of the discharge is produced as follows.

When the key of the circuit is closed, the system formed by the capacity O_2O_5 and the battery wires O_1O_6 charges up until the potential across the gap is high enough to make the discharge pass across it. The time that this takes will depend upon the time constant, *CR*, of the circuit, where *C* is the capacity of the wire or condenser, and *R* is the resistance of the circuit, and also upon the length of the spark gap. Since R is large, this time will not be very small, but will be of the order of the observed period of the discharge, namely a few ten-thousands of a second.

The resistance of the circuit is so great, and its inductance, .000112 henry, so small, that oscillations cannot take place in it as a whole; but oscillations do take place in the free wire and the gap, $O_5O_2O_1$, Fig. 9; the wire going to the battery, O_1O_6, acting as an earth. In the circuit used, the battery wires going from the double switch, *kk*, Fig. 3, to the battery two floors above were parallel to each other, about 6 inches apart, and 50 feet long. The oscillations are shielded from the rest of the circuit by the high resistances *R* and R_1. The distribution of the oscillations around the circuit was determined roughly by touching a neon tube to different parts of it.

The oscillations resemble the well-known Poulsen and Wien oscillations but differ from them in the fact that in these the supply circuit necessarily has large inductance and small resistance, whereas the Righi circuit has a very small inductance and a very large resistance.

The discharge is put out in the following manner: The condenser, or wire, charges, the spark jumps across, and a damped oscillating current is set up across the gap. At the same time the battery *B* tends to build up a steady current of a few milliamperes or less. The growing steady current, and the damped oscillating current, will be superposed upon each other. Every time the resultant current approaches zero it will be extinguished on account of the falling characteristic of the gap. If the oscillating potential across the gap, due to the condenser, is great enough, the discharge will light up again across the gap in the opposite direction. When, however, the oscillating potential is no longer great enough to do so, the discharge will stop altogether. The action will then be repeated, and the audible periodicity of the discharge will be produced. The same action has already been described by Barkhausen[1] for the case of Wien oscillations.

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[1] Loc. cit., § 46, pp. 94, 95.

The current oscillations were actually observed with a Braun tube and a rotating mirror, for the case in which .095 microfarad and 3.01 henries were connected in series across the gap, the period being, therefore, approximately 3×10^{-3} sec. A strongly damped train of from 1 to 7 half oscillations for every interruption of the spark could easily be observed. The damping as observed in the mirror, or as determined by the position of the maxima on the fluorescent screen of the Braun tube appeared to be *linear* within the errors of observation; the tops of the peaks, in one case, being 2.70, 1.75 and .90 cm. above the point of rest, and 1.75 and .90 cm. below it. I tried to take photographs of the images on the fluorescent screen, but the light was not intense enough.

A calibration of the Braun tube showed that the deflection of 2.70 cm. corresponded to a maximum amplitude of the oscillating current of .33 amperes. The steady current across the gap, when no inductance and capacity were connected across it, was only about .002 ampere. This shows that quite a small capacity would make the discharge interrupted.

I found it to be generally true that if a capacity is put around a spark gap across which a *glow* discharge is passing, the discharge will become discontinuous if the capacity is *great enough*.[1] If the capacity is not great enough, the interruption of the discharge will not take place. For instance, in the case of Fig. 9, the wire O_2O_5 must be about 400 cm. long to produce the interruption. Such a wire has an electrostatic capacity of about 1.25 cm. And for the case of Fig. 8, the air condenser, C, had to have a capacity of at least 2 cm. before it would make the discharge periodic.

There are in these effects two periodicities to be considered, first, the audible periodicity produced by the separate spark discharges and, second, that of the electrical oscillations producing the interruption of the discharge.

The audible periodicity is approximately equal to the time that it takes for the gap to charge up to the sparking potential. This will depend upon the length of the gap. A curve showing the minimum sparking potential across the gap that I used is shown in Fig. 10.

If we neglect the effect of ionization in the gap, the rise of potential across it for the circuit shown in Fig. 9 will be given by the equation

$$V = V_0(1 - e^{-(t/RC)}), \tag{1}$$

where V_0 is the electromotive force of the battery, R is the high resistance in the circuit, and C is the capacity of the wire, or of the condenser around the gap. And the period of the audible periodicity will be given,

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[1] See Hittorf, Ann. Phys., 20, 719–726, 1883; Lehmann, Ann. Phys., 56, 333–336, 1895.

approximately, by

$$t = CR \log_e \left(\frac{V_0}{V_0 - V} \right), \tag{2}$$

where V is equal to the minimum sparking potential across the gap. V for a given length of gap can be determined from Fig. 10. If V, V_0, R and C are known, the audible period can be determined.

I observed that as R, C, or the length of the gap, was increased the audible period was increased. t was calculated from the known values of C, R, V_0 and V, and the values obtained were of the order of the audible period.

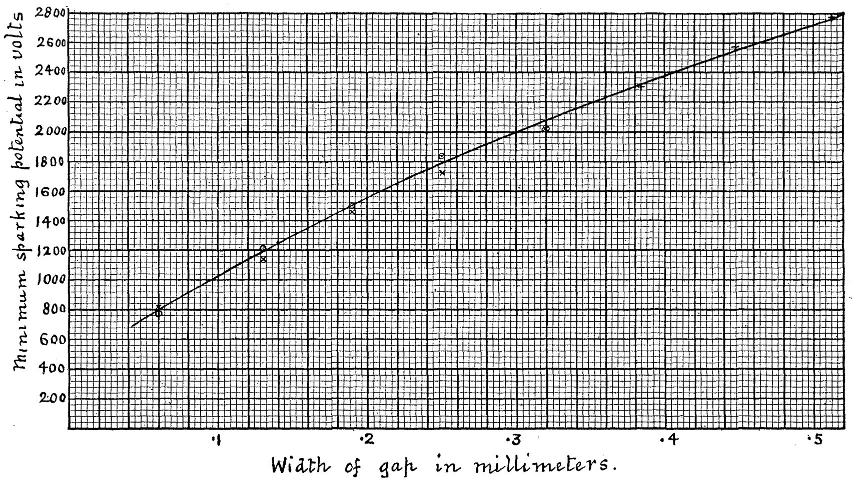

Fig. 10.

If we assume that the discharge across the gap goes out when the oscillatory current is equal and opposite to the steady current, since the maximum value of the oscillatory current, neglecting damping, is

$$V \sqrt{\frac{C}{L}}, \tag{3}$$

where L is the inductance of the circuit, and the value of the steady current is

$$\frac{V_0}{R}, \tag{4}$$

we shall have as the condition for the production of an interrupted discharge

$$V \sqrt{\frac{C}{L}} \underset{>}{\equiv} \frac{V_0}{R}.$$

Solving for C, we get

$$C \geqq \left(\frac{V_0}{V}\right)^2 \frac{L}{R^2} \tag{5}$$

as the equation for the minimum value of the capacity which must be shunted around the gap, or attached to the cathode side of the gap, to make the discharge an interrupted one.

V, the minimum sparking potential, shown in Fig. 10, is related to the length, l, of the gap approximately by the formula

$$V = k_0 + kl, \tag{6}$$

where k_0 and k are constants.

Experiments confirmed (5) except that the value of the inductance, L, of the oscillating circuit seemed to have little effect upon the value of C. If anything, the experiments indicated that the greater L the less C had to be. This may perhaps be due to the fact that the minimum value of C is always very small, and that any inductance that can conveniently be used has a relatively large distributed capacity. So that, when we add inductance to the circuit we add more or less capacity.

The experiments described show, I think, that when the *Righi effects* are obtained without a magnetic field, with a spark gap in the circuit, they may be explained by assuming that the capacity of the long tube and the instability of the spark gap produce a periodic interruption of the current. There is thus produced an alternate charging and discharging of the long tube, the negative column in the long tube corresponding to the charging, and the positive column to the discharging. An actual electrical oscillation takes place in the long tube, made visible by the light resulting from the ionization of the gas. The virtual anode is the region in which the charging and discharging streams are both visible. These two streams probably occur at the other points along the tube, but on account of lack of luminosity at these points, are not visible.

The action is probably as follows: When the double switch leading to the battery is closed, the potential across the gap rises until there is a discharge across it. When this happens, there is a sudden flow of current through the side tube, and the long tube charges up positively. There is then a reaction of the current in the side tube on account of its capacity and inductance, and a flow of current in the opposite direction. This reduces the total current flowing across the gap, and on account of the instability of the gap, the current through it becomes extinguished. It is possible that there may be more than one oscillation of the current in the long tube, but I do not think that there is. The oscillation can only take place in the conducting system DTO_2O_1B, Fig. 5. It cannot extend into the portion O_3R on account of the high resistance R. The luminous column, however, in the side tube from A to M, Fig. 2, when under the action of a transverse magnetic field, is seen to be always pressed against one side of the tube only. If there were an oscillating current from A to M, there would be *two* columns, pressed against opposite sides of the tube. Therefore, I think that there is probably only one oscillation in the long tube, a flow in and a flow out.

It is well known that alternations of current of low frequency can exist in Geissler tubes,[1] and also that if the luminous column of the discharge is subjected to a transverse magnetic field it will be separated into two columns bent towards opposite sides of the tube, corresponding to the opposite currents. The question arose as to whether this would be true for alternations of current in the long tube where the alternations, if they exist, must be of very high frequency, probably several millions a second. I found by experiment that such oscillations of current in Geissler tubes *are* divided into two streams by a transverse magnetic field.

A tube 10 cm. long and 1.5 cm. wide had platinum wire electrodes exactly alike and 7 cm. apart sealed into its ends. It was connected in series with a condenser and the secondary of a small induction coil, and subjected to the action of a transverse magnetic field. A double positive column was obtained, the two columns being pressed against opposite sides of the tube. The two columns were, in many cases, equally bright, indicating, I think, that there must have been several oscillations for each break of the primary circuit. The capacity was varied from 2×10^{-6} mf. to 1.25 mf. When the capacity was increased to 2.5 mf., only one column was present. For 1.25 mf. two columns were present, but one was much less bright than the other. When the tube was connected directly to the terminals of the secondary without any condenser in series with it, there was only a single column when acted upon by the magnetic field.

To examine the action for very high frequencies, a wire 70 cm. long was attached to each side of the tube, and a spark several millimeters long was caused to jump from the secondary of the induction coil to the end of one of the wires, the end of the other wire on the other side of the tube being free in air. The tube then glowed, and when subjected to the magnetic field showed a double column. Since the tube with its attached wires must act as a linear oscillator, or a Hertz oscillator,

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[1] Thomson, Phil. Mag., 32, 321–336, 445–464, 1891; Lehmann, Verh. d. Naturwissensch. Ver. Karlsruhe, 15, 69–71, 1902.

the frequency must be very high. In this case, since the wires were each 70 cm. long, the frequency was probably of the order of 10^8 a second.

The fact that, to get the best results with the Righi tube, the gap must be placed next to the anode of the tube, and the high resistance next to the cathode, is probably explained by the apparent high resistance of the region around the cathode,[1] shown by the high value of the cathode fall of potential. On the other hand, the region of the positive column behaves as though it had a relatively small resistance. If then the gap is placed next to the cathode of the tube, the region of the cathode will act like a high resistance between it and the long tube, and tend to prevent oscillations from being set up in the long tube.

6. A Third Way of Producing the Righi Effects.

While experimenting on the pressure most favorable for the Righi effects, I found that they could be produced without either a magnetic field or a spark gap, if the pressure in the tube was made low enough. For instance, using about 2,100 volts and 500,000 ohms in series with the tube, I got a well-marked column with all the Righi effects when the pressure of the air was reduced to .035 mm. The current through the tube at this pressure was about .2 milliampere. Above this pressure, the discharge through the tube was continuous. Below it, it became discontinuous and the Righi column appeared.

The appearance of periodicity at low pressures is probably explained by the fact that at these pressures the current is very small, and that the volt-ampere characteristic for the tube becomes a falling one for very small currents. The discharge would then become unstable for a certain value of the current according to Kaufmann's criterion. The characteristic for the tube for .035 mm. of pressure, shown in Fig. 7, would suggest that such is the case. The curves given by Riecke[2] and Earhart[3] also show that when the current is very small the characteristic becomes a falling one.

In this case it will be observed that the Righi effects are produced not only without a magnetic field, but even without the presence of a spark gap. So apparently the capacity of the tube and its periodic charging are the only elements that are necessary to produce the Righi effects.

The explanation for this case is probably the same as for the case in which there is a spark gap, except that in this case the instability of the

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[1] See Reiger, l.c., p. 35; Lehmann, l.c., pp. 71–73; Wiedemann and Schmidt, Ann. Phys., 62, 462, 1897.

[2] Loc. cit., p. 596.

[3] Loc. cit., pp. 88–91.

discharge through the tube takes the place of the instability of the discharge across the gap.

7. Conclusions and Summary.

Since I have shown that the Righi effects can be produced without any magnetic field by inserting a spark gap in the circuit, and, if the pressure is low enough, without either magnetic field or spark gap, it may be assumed that the magnetic field does not play a fundamental part in the production of the effects.

In Righi's case, the magnetic field apparently interrupts the discharge. There then follows a rising of the potential across the gap until the discharge takes place again. At this instant, there is a charging of the long tube, and this results in an electrical oscillation in it, in virtue of its capacity and inductance. It may consist of a single oscillation or of several; probably of a single one.

My conclusions therefore may be summarized as follows. The effects observed by Righi in a special form of Geissler tube, and believed by him to arise from a new kind of ray, called by him the magnetic ray, are not due to any new form of ray, but are due to the periodic charging and discharging of the tube.

In support of this view, I have shown:

1. That the long horizontal extension of the Righi tube has an appreciable electrostatic capacity.
2. That the principal action of the magnetic field is to periodically interrupt the discharge through the tube.
3. That for each interruption, charges appear in the long tube, an initial positive charge and a residual negative charge.
4. That the Righi effects can be produced without any magnetic field, by using a suitable spark gap in the circuit.
5. That the current through a circuit of high resistance and small inductance, containing a battery and a spark gap, can be changed from a steady to an interrupted current by attaching a capacity to one of the terminals of the gap; and that this periodic interruption of the current is due (1) to an oscillation across the gap produced by the attached capacity, and (2) to the negative slope of the volt-ampere characteristic of the gap. A theory is given for this action.
6. That alternations of current of very high frequency can exist in a Geissler tube, and that their presence is made evident by a *double* luminous column when the tube is subjected to a transverse magnetic field.
7. That the Righi effects will be produced without either magnetic field or spark gap if the pressure in the tube is made low enough.

In conclusion, I wish to thank the authorities of Clark University, and Professor A. G. Webster in particular, for placing all the resources of the physical laboratory at my disposal during the course of this investigation.

CLARK UNIVERSITY,
WORCESTER, MASSACHUSETTS,
November 15, 1916.