VI. *On the Sensitive State of Electrical Discharges through Rarefied Gases.*

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[PLATES 15–20.]

CONTENTS.

I.—*Definition and description of the sensitive state.*

It has frequently been remarked that the luminous column produced by electric discharges in vacuum-tubes occasionally displays great sensitiveness on the approach of a finger or other conductor to the tube. The exact effect of such approach varies considerably with the circumstances of the discharge. In many instances the luminous column is repelled; in others, and especially when the finger is brought into actual contact with the glass, the column is severed; and in the latter case, in addition to the luminosity previously present, there often appears proceeding from the interior of the tube, at the point where the finger rests, the blue haze which usually characterises the negative end of a discharge. In some cases the discharge is so powerfully affected that the well-known green or blue fluorescence appears on the side of the tube opposite to the point touched.

The degree of sensitiveness varies between wide limits. Discharges frequently occur in which close observation is necessary to detect any trace of it, while others may be produced so sensitive that the magnetic action of a powerful electro-magnet is hardly more marked than the action which is due to it as a conductor. The condition in question does not appear to be confined to any particular gaseous medium or to any special form of tube; and it is in fact probable that in almost any tube sensitiveness may be produced by adopting suitable precautions.* This state of sensitiveness may be exhibited by stratified discharges, but it is more commonly associated with those which show no clear traces of stratification. It is not however universally present in either kind of discharge.

The state in which the discharge is affected by the presence or approach of a conductor will be called the *sensitive state;* while that in which it is not so affected will be called the *non-sensitive state.* The former is the subject of the present inquiry.

The attention of the authors of this paper was drawn to this form of vacuum discharge, partly by the striking character of the phenomena which it presents and partly by their own earlier observations which led them to connect it with an interruptedness or intermittence in the current. Although there are a great variety of methods by which the sensitive state can be produced, they all agree, as will presently be seen, in causing a rapid intermittence in the current. The experiments of Mr. De La Rue and others have furnished strong evidence for concluding that vacuum discharges are never continuous in the same sense that the flow of electricity along a metallic conductor is continuous, but that they are always disruptive and periodic with an extremely high rate of periodicity. Such being the case, it appeared desirable to subject to special examination a form of discharge in which periodicity (though much less rapid) is

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* Subsequent experiments have removed all doubt on this point. So long as the tube permits any traces of a luminous column to appear, this column can be rendered sensitive.

produced by artificial means, and where the periodicity is therefore capable of being varied at will. Moreover, the usefulness of an investigation into the phenomena of discontinuous discharges is not wholly dependent on the theory which regards all vacuum discharges as discontinuous; for, as the mathematician is often obliged to reason from the discontinuous to the continuous—from the polygon to the curve—so the physicist may ultimately be best able to arrive at the causes of the phenomena accompanying the ordinary vacuum discharges (whether these be absolutely continuous or only relatively so) by a study of the phenomena which rapidly intermittent discharges present. And the importance of this method is greatly increased when we consider that no one of the usual phenomena of ordinary vacuum discharges is necessarily absent from or incompatible with the discontinuous discharge; and that if the theory of the discontinuous character of the ordinary vacuum discharge be correct, this method offers us the prospect of constructing a continuous chain of phenomena, extending from the single flash of a Leyden-jar discharge to the steadiest striated column which can be produced by a battery-current.

II.—*The sensitive state is due to a periodic intermittence in the discharge of considerable rapidity and regularity, the quantity of electricity in each individual discharge being sufficiently small to permit the discharge to be instantaneous.*[*]

In order to establish this proposition we shall first describe all the modes known to us of producing sensitive discharges, and shall show that in all cases the circumstances of the discharge give great probability to the idea that it is discontinuous or intermittent in the manner above described. We shall then give direct experimental evidence that in all these cases such intermittence actually exists in the resulting discharge. And lastly we shall examine the cases in which we know that intermittence actually exists in non-sensitive discharges, and shall show that such intermittence has not the requisite characteristics stipulated for above, but is of a wholly different type from that which we have described as the cause of sensitiveness in vacuum discharges.

The simplest method of producing the sensitive state is by conducting through the exhausted tube a current from a HOLTZ machine or some other constant source of

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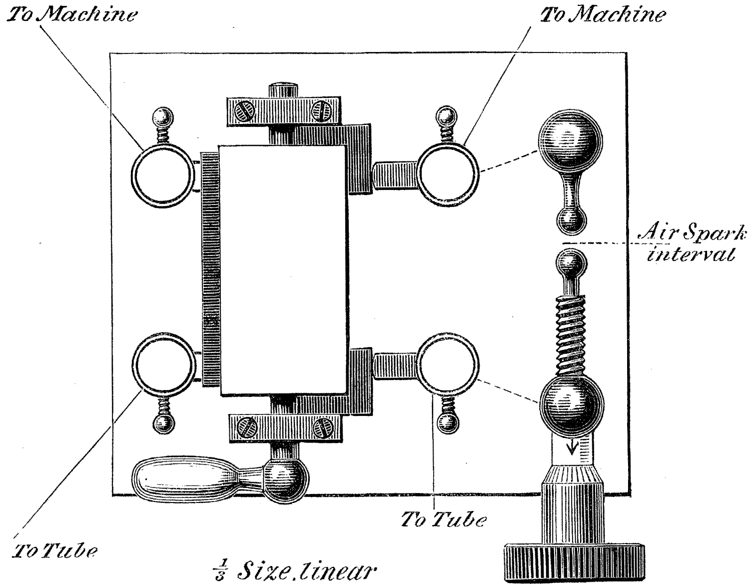
[*] In speaking of the sensitive state as being due to an intermittence in the discharge, the authors of this paper are treating of discharges lasting for a finite time. It was, naturally, in this form that sensitiveness was first known to them; but in the course of the inquiry they have discovered, as will hereafter appear, that each individual discharge is sensitive, and that the sensitiveness of the intermittent discharge is due solely to the sensitiveness of its individual members. The effect of the intermittence is only to change through rapid iteration the instantaneous phenomena presented by each discharge into an appearance which to the eye is steady and continuous.

electricity of high tension, and interposing a small air-spark in the path of the current from one of the terminals of the machine to the tube. The following plan will sufficiently describe the apparatus used. So soon as the air-spark is made to intervene (see Plate 15, fig. 1), the discharge in the tube becomes sensitive; and this sensitiveness may in general be increased by increasing the length of the air-spark, until the discharge becomes visibly intermittent, so as no longer to appear to the eye as a steady continuous discharge. Although this is by no means the only way in which the sensitive discharge can be produced, it is the one which is the most generally convenient for the purposes of experiment; and it may on that account be regarded as the typical mode of production. That the discharge within the tube should be intermittent when the supply of electricity is rendered intermittent by the air-spark is so obvious as not to need discussion, and though we cannot positively assert (without experimental evidence of the fact) that the pulses of free electricity of which the discharge is composed pass into the tube instantaneously, it is difficult to imagine any circumstances under which we should less expect the individual discharges to have a prolonged or continuous character than when, as in the present case, they are due to charges of free electricity that come suddenly to the terminal of the tube after leaping in the form of a disruptive discharge across the air-spark interval.



Another method of producing a discharge which shows indications of sensitiveness is by using an induction coil in connexion with a large condenser, such as that described in a paper "On Stratified Discharges, V." (Proceedings of the Royal Society, xxvii., p. 60). If the discharge be allowed to pass through the tube while the coil is at work, a certain amount of sensitiveness will usually be visible. (See Plate 16, fig. 6.) But if the coil be stopped and the current allowed to flow from the condenser through the tube without disturbance from the entrance of the coil-discharges, the discharge will be found to have lost all its sensitiveness. The explanation of this we believe to be that so long as the coil was at work its pulsations produced sudden periodic elevations of tension in the condenser, which caused corresponding discharges through the tube. It is probable that in these cases the periodic discharges are only superposed upon the continuous discharges which we see upon stopping the coil, and which are caused by the mean tension in the condenser, so that it would be more strictly accurate to say that the discharge is subject to intermittent or periodic variations of intensity than to say that it is itself intermittent. But, as all the phenomena agree with the supposition that the discharge is partly sensitive and partly non-sensitive, and that the sensitive portion is wholly caused by the pulsations produced by the coil, it is better to look upon it as a superposition of two discharges, and to regard the sensitive one as intermittent.

It is not, however, universally the case that the discharge from the condenser is non-sensitive when the coil is not acting. When the tension in the condenser becomes low, it is very usual to find sensitiveness in the discharge. This phenomenon, however, does not in any way make against the view that sensitiveness arises from intermittence; for the very last stages of the discharge from the condenser are intermittent even to the eye, and it is not strange therefore that the stage immediately preceding should also be intermittent, though with a much more rapid period. That such is the true explanation of the phenomenon can also be shown directly, either by means of a rapidly revolving mirror, or by interposing a telephone in the circuit, as will be more fully described hereafter.

Again, certain tubes appear to render the discharge from a continuous source sensitive without the necessity of artificially producing intermittence in the current. Such cases will, however, be found to offer no difficulties. They are merely instances of tubes which at higher tensions of the condenser give the phenomenon already described as being so common when the tension is low. No doubt, if the tension in the condenser, or perhaps, more strictly speaking, if the quantity of electricity discharged (strength of current) were still further increased, the sensitiveness could in all cases be made to vanish.*

Again, a sensitive discharge may be produced by connecting one terminal of

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* It is worthy of remark, that the correlative proposition has been found to be in general true of the tubes examined by the authors of this paper for the purposes of this investigation. Though the greater number of them exhibit no trace of sensitiveness when the current is produced by the full power of a large twelve-plate HOLTZ machine, yet they can be made to show sensitiveness (without the introduction of an air-spark) by throwing some of the plates out of work, so as to reduce the quantity of electricity in the current.

the machine with one terminal of the exhausted tube, and the other terminal of the machine with the outside of the tube, as in Plate 15, figs. 2 and 3. If the current be then permitted to pass between the terminals of the machine by leaping a considerable distance (say half an inch) in air, so that the discharges in the tube are caused partly by conduction from one terminal of the machine, and partly by induction due to the rapid alternations of high and low tension in the wire from the other terminal of the machine to the outside of the tube, the resulting discharge will be found to be sensitive. The arrangement here described, and which may be represented by the subjoined diagram, was devised by Mr. P. WARD, in order to show the phenomena of "CROOKES' Lines."* When the sparks passed to P, the outer surface of the glass near P was traversed, over an area of an inch or more in diameter, by irregular bright lines branching out from P as a centre. From the point of the inner surface adjacent to P, CROOKES' radiating lines shot out in various directions across the tube, and made themselves visible by fluorescence on the opposite side in the neighbourhood of R. The fluorescence figure, usually in the form of a cross, could be made to revolve about its centre by the action of a magnet; the direction of the rotation being reversed when the polarity of the magnet was reversed. In this case the principal discharges in the tube take place when the passage of a spark from the one terminal of the machine to the other has caused a sudden relief of tension in the wires leading to the tube, so that the discharge has the same intermittence as the disruptive discharge between the terminals of the machine; in other words, it has the same intermittence as a long air-spark, and direct experiment with a revolving mirror has shown that the luminous phenomena in the tube opposite to the wire are synchronous with the passage of the sparks from one terminal of the machine to the other.

Again, rapid intermittence and sensitiveness in what would otherwise be a continuous discharge may be produced by the use of a "wheel-break," such as is described (see Plate 15, fig. 3) in a paper "On Stratified Discharges, III." in the Proceedings of the Royal Society for February 15, 1877. This instrument consists of a wheel platinized at the edge, on which a platinum spring rests. In the circumference of the wheel a number of slots are cut, and filled with ebonite plugs, so as to interrupt the current. If the wheel-break be interposed in the circuit of a HOLTZ machine when producing a luminous discharge in a vacuum-tube, and the break be worked at a considerable speed so as to cause the current to be interrupted some 400 to 2000 times per second, the discharge becomes highly sensitive. This instrument is used as a shunt, viz., so as to divert from the tube the current given by the machine by permitting it to pass through a continuous metallic circuit during the time that the platinum wire rests upon the metallic portion of the circumference. In this way the current is never actually broken, and one great advantage of this arrangement is

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* See Proceedings of the Royal Society, December, 1878.

that it simply produces intermittence in the discharge through the tube without interfering with it in any other way.

Another method of producing a sensitive discharge is by the use of a very rapidly vibrating break, such as that described in a paper "On Stratified Discharges"*

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* The following is an extract from the paper in question:—

"In the stratified discharges through rarefied gases produced by an induction-coil working with an ordinary contact-breaker, the striæ are often unsteady in position and apparently irregular in their distribution. Observations made with a revolving mirror led me to conclude that an irregular distribution of striæ does not properly appertain to stratification, but that its appearance is due to certain peculiarities in the current largely dependent upon instrumental causes.

"Having reason to think that the defects in question were mainly due to irregularity in the ordinary contact-breaker, I constructed one with a steel rod as vibrator, having a small independent electro-magnet for maintaining its action. The natural vibrations of the rods which were tried varied from 320 to 768 per second; while under the action of the battery-current and electro-magnet they varied from 700 to 2500, or thereabouts, per second. The amplitudes of the vibrations were exceedingly small, in fact not exceeding ·01 of an inch; and it is to this fact, coupled with the extreme rapidity and consequent decision of make and break, that I mainly attribute the steadiness of the results.

"With a contact-breaker of this kind in good action several phenomena were noticeable; but first and foremost was the fact that, in a large number of tubes (especially hydrocarbons) the striæ, instead of being sharp and flaky in form, irregular in distribution, and fluttering in position, were soft and rounded in outline, equidistant in their intervals, and steady in proportion to the regularity of the contact-breaker. These results are, I think, attributable more to the regularity than to the rapidity of the vibrations. And this view is supported by the fact that, although the contact-breaker may change its note (as occasionally happens), and in so doing may cause a temporary disturbance in the stratification, yet the new note may produce as steady a set of striæ as the first: and not only so, but frequently there is heard, simultaneously with a pure note from the vibrator, a strident sound, indicating that contacts of two separate periods are being made; and yet, when the strident sound is regular, the striæ are steady. On the other hand, to any sudden alteration in the action of the brake (generally implied by an alteration in the sound) there always corresponds an alteration in the striæ.

"It is difficult to describe the extreme delicacy in action of this kind of contact-breaker, or 'high break,' as it may be called. The turning through 2° or 3° of a screw, whose complete revolution raises or lowers the platinum pin through ·025 of an inch, is sufficient to produce or to annihilate the entire phenomenon. A similar turn in a screw forming one foot of the pedestal of the brake is enough to adjust or regulate the striæ; and a slight pressure of the finger on the centre of the mahogany stand, apparently rigid, or even on the table on which the contact-breaker stands, will often control their movements.

"The discharges described above are usually (although not always) those produced by breaking contact; but it often happens, and that most frequently when the strident noise is heard, that the current produced by making contact is strong enough to cause a visible discharge. This happens with the ordinary as with the high break; but in the latter case the double current presents the very remarkable peculiarity that the striæ of one current are so arranged as to fit exactly into the intervals of the other; and, further, that any disturbance affecting the column of striæ due to one current affects similarly, with reference to absolute space, that due to the other, so that the double column moves, if at all, as a solid or elastic mass. And this fact is the more remarkable if we consider, as is easily observed in a revolving mirror, that these currents are alternate, not only in direction, but also in time, and that no one of them is produced until after the complete extinction of its predecessor. And it is also worthy of note that this association of striæ is not destroyed even when the two currents are separated more or less towards opposite sides of the tube by the presence of a magnetic pole. There seems, however, to be a tendency in that case for the

(Proceedings of the Royal Society, June 10, 1875). If such an instrument be used with an induction coil, the discharge, though often beautifully stratified, is intensely sensitive. The lowest limit of rapidity with which we have produced *stratified* sensitive discharges in this way is 240 breaks per second.

We will now consider the direct experimental evidence that the current is intermittent in all cases in which the discharge is sensitive. This evidence is derived from the revolving mirror and the telephone. If the body of the tube containing the discharge be hidden by an opaque screen which contains a narrow longitudinal slit, and the image of this slit be observed in a rapidly revolving plane mirror, a series of bright and black bands appear whenever the discharge is sensitive, showing that there are

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striæ of one current to advance upon the positions occupied by those of the reverse current, giving the whole column a twisted appearance. But as there is no trace, so far as my observations go, of this association of alternate discharges when produced by the ordinary break, we seem led to the conclusion that a stratified discharge, on ceasing, leaves the gas so distributed as to favour, during a very short interval of time, a similar stratification on the occurrence of another discharge, whether in the same or in the opposite direction.

"The column of striæ which usually occupy a large part of the tube from the positive towards the negative terminal have hitherto been described as stationary, except as disturbed by irregularities of the break. The column is, however, frequently susceptible of a general motion or 'flow,' either from or towards the positive pole, say a forward or backward flow. This flow may be controlled, both in velocity and in direction, by resistance introduced into the circuit, or by placing the tube in a magnetic field. The resistance may be introduced in either the primary or the secondary circuit.

"When the striæ are flowing they preserve their mutual distances, and do not undergo increase or decrease in their numbers. Usually one or two remain permanently attached to the positive electrode; and as the moving column advances or recedes, the foremost stria diminishes in brilliancy until, after travelling over a distance less than the intervals between the two striæ, it is lost in darkness. The reverse takes place at the rear of the column. As the last stria leaves its position, a new one, at first faint and shadowy, makes its appearance behind, at a distance equal to the common interval of all the others: this new one increases in brilliancy until, when it has reached the position originally occupied by the last stria when the column was at rest, it becomes as bright as the others. The flow may vary very much in velocity; it may be so slow that the appearances and disappearances of the terminal striæ may be watched in all their phases, or it may be so rapid that the separate striæ are no longer distinguishable, and the tube appears as if illuminated with a continuous discharge. In most cases the true character of the discharge and the direction of the flow may be readily distinguished by the aid of a revolving mirror. In some tubes, especially in those whose length is great compared with their diameter, the whole column does not present the same phase of flow; one portion may be at rest while another is flowing, or even two conterminous portions may flow in opposite directions. This is seen also in very wide tubes, in which the striæ appear generally more mobile than in narrow ones. But in all cases these nodes or junction-points of the flow retain their positions under similar conditions of pressure and current; and it therefore seems that, under similar conditions, the column in a given tube always breaks up into similar flow-segments.

"These nodes will often disappear under the action of a magnetic pole. Thus if the first segment, measured from the positive terminal, be stationary and the second be flowing backwards (*i.e.*, from − to +), a magnetic pole of suitable strength, placed at the distant end of the latter, will stop its flow, and the whole column will become stationary throughout. An increase in the strength of the magnet, or a nearer approach of it to the tube, will produce a general forward flow of the column."

intervals between the luminous discharges, during which the tube is dark.* If the ordinary non-sensitive discharge be observed in a similar way there are no such dark bands, and no available speed of the mirror suffices to show any break in the uniformity of the luminous image of the slit. The occurrence of these dark bands shows conclusively that the discharge in which they appear is intermittent and discontinuous, and it may be stated as a general proposition that a revolving mirror has thus invariably shown intermittence in the discharge whenever a sensitive column has been examined by it through a slit of proper dimensions, whatever may have been the particular means by which the sensitiveness has been produced.

We have said that the telephone, as well as the revolving mirror, may be made to show that there is intermittence in the discharge in vacuum tubes so long as there is sensitiveness. The evidence it gives to us is as follows: When a telephone is in circuit with a non-interrupted, non-sensitive discharge, a rushing sound is frequently although not always heard. In a very large number of cases there is absolute silence. But as soon as the discharge becomes sensitive the silence is broken by a shrill sound, or if the rushing sound of which we have spoken previously existed, there is a sudden change in the character of the sound, which usually becomes musical. The pitch of the note is always high, and naturally varies with the circumstances of the discharge. When the air-spark is again abolished the note ceases, or gives way to the rushing sound mentioned above.† Occasionally, in the sensitive discharge, the rushing sound and the musical note are heard simultaneously. This may arise from rapidly succeeding periods of interruptedness and non-interruptedness; but it is not a phenomenon of any particular importance at the present stage of our inquiry.‡

It will have been noticed that at the outset we defined the intermittence capable of causing sensitiveness to be such as would permit only so small a quantity of electricity to pass at each individual pulsation as not to interfere with the instantaneous character of the discharge. This is necessary in order to exclude such cases of intermittence or fluctuation of current as are observable within a single-coil discharge when a compara-

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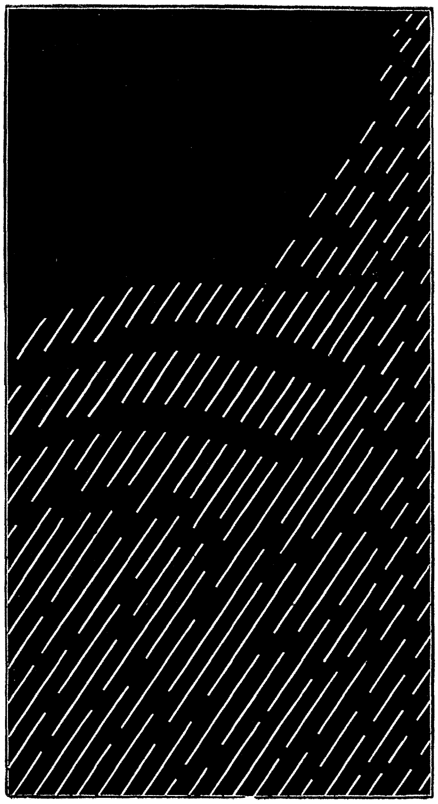
* This experiment is more fully described in § 10.

† It may fairly be objected that this test shows only the intermittence of the current in the circuit external to the tube, and does not directly tell us anything of the discharge through the tube. We shall, however, show later on how the telephone may be made to give us more direct evidence of the intermittence of the discharge through the tube. But to render clear the nature of this evidence would require that the theory of the sensitive discharge should be more fully developed than is possible at this early stage.

‡ When the air interval is increased beyond striking distance, a silent discharge takes place across the interval; and the discharge through the tube is the same in character as that produced without an air-interval; it is also non-sensitive. And instead of the shrill whistling which is heard with an air-spark proper, nothing is in this case audible but a soft rushing sound. A similar result is obtained when an arc is formed across the air-spark interval, which is found to be the case under certain circumstances which will be referred to later on.

tively slow break is used. Some observations were published ("On Stratified Discharges, II.," Proceedings of the Royal Society, May 18, 1876) by one of the authors of this paper, relative to the appearance of the coil discharge when viewed in a large revolving mirror moving through one revolution between each contact made by the break.* The rapidity with which the contacts followed each other was necessarily slow in comparison with the rapidity of intermittence of which we have been speaking; but, what is of more importance, the duration of the discharges, consequent upon the nature of the contacts, was far greater. Moreover, it was found that each discharge was of a very complicated character. The discharge opened with a sudden rush,



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* The break here used was a mercurial one, the plunger of which worked on a cam attached to the axle of the mirror, so that the action of the contact-breaker was regulated by the motion of the mirror, and the image was always formed in the same position in the field of view. An opaque screen with a slit in it was usually placed on the tube so as to face the mirror. In order to convey a clearer idea of the phenomena alluded to in the text than could otherwise be obtained without reference to the paper itself, one of the diagrams is reproduced. This represents the appearance (in the mirror) of a carbonic acid tube with the slit attached. This tube, viewed by the eye, shows flake-like fluttering striæ, with a slight tendency to flocculency near the head of the column. The commencement of the discharge is at the right hand, and the negative terminal at the top. The drawing fairly represents the appearance of the upper part or head of the column of striæ during one complete coil-discharge. When the battery-surface exposed is small, the whole consists of, first, three or four columns of striæ of decreasing length, and afterwards of an almost unbroken field of striæ. Each of the initial columns is perfectly stratified; and the same disposition of striæ prevails throughout the entire discharge. The striæ which fill the main part of the field present a proper motion nearly uniform, but slightly diminishing towards the end. These striæ are for the most part unbroken, but are occasionally interrupted at apparently irregular intervals. When the battery-surface is increased, the elementary striæ are more broken, and near the head of the column the interruptions occur as in the figure. The separation of the earlier part of the discharge into striated columns divided by intervening rifts does not, excepting in the case of the first, extend far towards the positive terminal. Nevertheless, even as far as the positive terminal itself, there seems at times to be a fuller development of discharge than is subsequently maintained.

The first rift in the discharge, following the first outburst, is sometimes distinguishable even as far as the positive terminal; and perhaps in those cases indicates a real cessation of the discharge. This is corroborated by the fact that a similar interruption is then perceptible in the glow surrounding the negative terminal; but after this the negative glow retains its unbroken character throughout the entire discharge.

usually followed by an apparently complete cessation of discharge; it then recommenced, and continued to exhibit during its entire period of existence variations of a very irregular kind. It is, in fact, probable that during the period subsequent to the first outburst and the momentary cessation of discharge that often follows it, the state of the tube is much the same as it would be during a continuous discharge, in consequence of the absence of any regularity of pulsation. The tube is always conducting a discharge, although perhaps the consequent disturbance is more violent in one part than in another. There is no alternation of a sharply-defined discharge and electrical emptiness. So important is the distinction between what may be called irregularly fluctuating and periodically intermittent discharges, that in the case of a fairly rapid coil discharge it is frequently found that, while the striæ in the main luminosity give but very slight traces of sensitiveness, the faint ghostly striæ which are seen to project far beyond the end of the positive column proper show very great sensitiveness (see Plate 16, fig. 6).* And the experiments above referred to with the revolving mirror show that this faint column of luminosity is due solely to the first outburst of which we have spoken; so that such outbursts form a sensitive system, while the fluctuating discharges that follow are non-sensitive. As the action of the break gets more rapid it is found that the fluctuating portion of the discharge becomes less and less developed, and the discharge more and more nearly consists of the first portion only. It is a matter of observation that as we attain to still higher rapidity of break-action this becomes more and more the case, and that at very high speeds the discharge reduces itself to this first portion alone; and thus we understand how it is that with a very high-speed break we obtain the most intensely sensitive discharges from a coil.

It will thus be observed that all the methods of producing the sensitive state agree not only in the intermittent character of the discharge, but also in the shortness of duration of the individual discharges themselves,† and this it is which has induced the authors of this paper to consider brevity of duration as much an essential feature of the individual discharges that produce the sensitive state, as rapidity or regularity of interval between these discharges. The latter characteristics are, in fact, of more importance for maintaining the persistence of the sensitive state during a finite interval of time than for actually producing it, since careful experiments fail to show any inferior limit of rapidity of the periodicity necessary to produce such a discharge. In

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* These faint sensitive striæ projecting beyond the luminous column in a coil discharge, are the only case of a sensitive discharge of which the authors of the present paper are aware which is not produced by one or other of the methods previously described.

† These remarks may seem to be inapplicable to the case of the HOLTZ machine with the wheel-break; for here the intervals during which the tube forms part of the circuit are usually equal to those during which it is not so. But it does not follow that the electricity is passing through the tube during the whole of the time that the tube is in circuit. For it will not commence to pass until there has been such a charging up of the terminals as is sufficient to effect a discharge.

truth, there is no impossibility in producing by a single flash a discharge having the characteristics of sensibility. If a charged Leyden jar* ("On Stratified Discharges, IV.," Proceedings of the Royal Society, March 22, 1877) be employed with a suitable tube, the instantaneous discharge that passes through the tube on the jar being connected with it will show all the symptoms of sensitiveness during its passage through the tube.

This direct evidence of the connexion between intermittence of discharge and the sensitive state will, we believe, derive further support from the accordance of the various phenomena with the theory of the sensitive state which will be developed in the course of this paper, and which rests upon the hypothesis that the sensitive state is due to such an intermittence—a hypothesis which the authors of this paper venture to hope is sufficiently demonstrated by the experimental facts already stated.

In conclusion, the authors of this paper desire it to be understood that, in claiming intermittence as an essential of the sensitive discharge, they do not intend to exclude all ideas of intermittence from the non-sensitive discharge. The experiments of Sir W. GROVE,† Mr. DE LA RUE, and others, have shown almost to demonstration that there is intermittence in the most stable and non-sensitive discharges. But such intermittence must be of an order almost incomparably higher than that of which we are speaking. Though sensitiveness has been found to co-exist with intermittence at the highest speeds attainable by the mechanical or chemical means above referred to, and even in many cases to increase with the rapidity of intermittence, it is by no means necessary that it should continue to do so when this rapidity is increased, say, many hundred or thousand fold. Indeed, with the rapidity given by a short and rapid air-spark, the sensitiveness is not so marked in its features as with a longer and less rapid air-spark. Nor, as will be seen, does our view require that very great rapidity of intermittence should necessarily produce very great sensitiveness. On the contrary, so far from its being an advantage that the discharge should be divided into a very large number of small discrete discharges, it would seem that the most favourable condition for the production of sensitiveness is that the individual discharges should be as large (and therefore as few in number) as is compatible with an absence of the prolonged or fluctuating phases observed in the ordinary coil discharge.‡ And therefore, in order to avoid any misconception, the terms *interrupted* and *uninterrupted* will be used to describe the condition of the currents causing the sensitive and non-sensitive state respectively, instead of the terms *intermittent* and *continuous*, which might otherwise have been adopted.

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* This experiment will be found more fully described on p. 208, and properly belongs to a later portion of the investigation, and is referred to here only in passing.

† Phil. Mag., 1858, July-December, p. 18.

‡ It will be found that this conclusion, which was arrived at from observation, is a necessary consequence of the theory of sensitiveness which the authors of this paper desire to put forward.

III.—*The effect produced on a sensitive discharge by the approach of a conductor, is directly due to the relief given by its presence to the instantaneous electric tension within and around the tube, caused by the individual discharges in their passage through the tube.*

In the case of the sensitive or interrupted discharge we have seen that there are discrete pulses of electricity passing between the terminals. It is, therefore, not an improbable supposition that the pulse of positive electricity leaving the positive terminal in the form of free electricity, and consequently exercising electric induction in every direction round it, may cause that electric tension or (as Professor MAXWELL would call it) displacement, which, so far as we know, is the universal accompaniment of free electricity. Such induction would cause an electric tension upon the outer surface of the glass and in the space beyond; but, inasmuch as the glass is a non-conductor, it could not cause any redistribution of the electricity within it or on its surface. It is somewhat difficult to ascertain the effect on the space around the tube, occupied as it is with the mobile and rapidly-moving particles of air; but there can be little doubt that the induction from the discharges would only occasion redistribution of the electricity in this part of the field to a very slight extent. If, however, we place a conductor on or near the glass, the induction can readily occasion a redistribution of electricity in the conductor. The state of the electric field in the neighbourhood of the conductor would then be different to that at any other part of the tube; and this would in its turn react upon the discharge or upon the gaseous matter which exists within the tube. We shall now show that the observed effect is due to such a redistribution of electricity in the conductor; and shall subsequently proceed to examine the cause of this redistribution and its *modus operandi* in producing the observed effect.

In order to demonstrate that the phenomena of sensitiveness are primarily due to a redistribution of electricity in the conductor caused by alterations in the electric condition of the interior of the tube, it is only necessary to observe that a non-conductor, however highly charged, does not affect the sensitive discharge. Nor will a conductor of small size, in contact with the tube (such as a piece of tinfoil), affect the discharge so long as it is insulated. But if the tinfoil be connected to earth, or to a distant conducting body, it at once produces a marked effect on the sensitive discharge.

A consideration of these experimental facts leads to the following conclusions: (1) that the effect is due to a redistribution of electricity in the conductor; and (2) that such effect is periodic. If a continuous electric state in the external body were the necessary condition, the observed effect could be produced by charged non-conductors. But as this is not the case, we must look to the facility of change in electric state afforded by conductors for an explanation of their effect on the sensitive discharge. This conclusion is supported by the fact previously stated that a small piece of tinfoil placed upon the tube produces no effect so long as it is insulated. Such a piece of tinfoil would give but little scope for redistribution of electricity—at all events, in such a way as to affect the space around it. But if it be connected metallically with a distant conducting body, so that positive or negative electricity can be driven from it to a sensible distance from the tube, the case is different; and if this be done it is at once found to affect the sensitive discharge.

If, then, the effect on the sensitive discharge is caused by the facility for a redistribution of electricity within the portion of the electric field occupied by the conductor, it follows that there must be a varying electric action upon it from the discharge in the tube. And that such is the case may be shown by connecting a ring of tinfoil placed round the glass with the earth, and interposing a telephone in the circuit between the tinfoil and the earth. So soon as the current becomes interrupted by an air-spark, a sound is heard in the telephone corresponding with the sound of the air-spark causing the intermittence. This shows conclusively that at each pulsation there is an electrical redistribution within the system composed of the earth, the wire, and the tinfoil. And as this continues indefinitely, without producing any charge upon the tinfoil, it is clear that there must, during the complete period of each pulsation, be a flow of one kind of electricity from the tinfoil, followed by its return or a similar flow of the opposite kind of electricity from the tinfoil.

Now, since this periodic redistribution is effected by the pulsations of electricity within the tube, it follows that we may regard the conductor as affording a kind of relief to the tension in the electric field round the portion of the tube with which it is in contact. And that such is the nature of its action can be shown by numerous experiments, such as the following: If, instead of connecting the tinfoil to earth, a wire leading to earth be placed almost in contact with it, sparks will be seen to pass, showing the state of electric tension to which the tinfoil is from time to time subjected. And further, if the effect upon the sensitive discharge be examined closely, it will be found to be stronger in proportion as the circumstances in which the tinfoil is placed are more favourable for giving more complete relief. So long as the wire does not touch the tinfoil, or permit sparks to pass from or to it, the tinfoil is unable to affect the sensitive discharge. But if the wire be near enough for sparks to pass, the sensitive discharge will be affected, but to a decidedly less extent than would be the case were the wire in actual contact with it. In the latter case the relief which it could afford would be perfect; in the former it would be imperfect, since the sparks would not be able perfectly to equalize the potentials of the tinfoil and the wire. Again, the effect of the tinfoil when in electrical connexion with the conducting body will be found to vary in proportion to the capability of the system to relieve the tension of the tinfoil. If the conducting body be large or distant, the effect will be nearly the same as though the tinfoil were joined to earth; if, on the other hand, it be small and near to the tube, the effect will be much less. The same remarks apply to cases in which, though the tinfoil is not absolutely disconnected from earth, yet its connexion is electrically very imperfect. Thus, if the wire from the tinfoil be allowed just to touch the finger, it will give less effect than if it be tightly held, and similiarly for other imperfect connexions. Even in the case of the telephone in circuit between the tinfoil and the earth, if the telephone be not too far from the tube a marked diminution in loudness will be observed when the connexion between the telephone and the earth is severed, so that the displaced electricity, no longer able to escape to the earth, is compelled to re-arrange itself in the telephone and the wire connected with it.

There is no need to place the conducting body in actual contact with the glass in order to affect the sensitive discharge. If the body be near the tube it will produce nearly the same effect as though it were in contact, as in Plate 15, fig. 5; if it is farther off it will produce less; and, as in the former case, if it is large and capable of permitting displaced electricity to remove to a considerable distance from the tube, it will produce a much greater effect than if the contrary be the case. In short, it may generally be stated that the completeness of the effect of a conducting body upon the sensitive discharge depends on the completeness of the capability it possesses of permitting a displacement of electricity within it (caused by the electric disturbances in the tube) without any material alteration of its potential.

Such experiments as those of the telephone in circuit with the tinfoil and the earth may not unnaturally suggest the idea that these effects may be due to electro-magnetic and not to electro-static induction. But careful examination negatives this supposition. In the first place it is not necessary that the tinfoil should have any considerable length in the direction of the tube, which is presumably the direction of the current through it. A narrow ring of tinfoil round the tube will give all the results above described. Again, if a coil of insulated wire be placed near or round the tube, no difference is produced by joining the ends of the wire. In fact, no difference of effect is observable whether the conductor be made up of insulated wire or be a mere mass of metal; the whole seems to owe its effect to its being a conductor of considerable size. No form of conductor possesses greater effect than a narrow ring of tinfoil connected to earth by a single fine copper wire perpendicular to the tube, and no conducting system could be devised more unfavourable to the production of electro-magnetic inductive currents by the original current in the tube. Moreover, the effect is far too great to be attributable to electro-magnetic induction in circuits so unfavourable to its action. In short, every feature of the case, upon examination, tends to render it less probable that any of the electric phenomena in the external conducting system are due to electro-magnetic induction; and the supposition has been noticed here rather with the view of showing that it has not escaped consideration, than because it was considered to have any valid claims to notice.

The arrangement in which the tinfoil is connected to earth is that which affords the most complete relief to the periodic changes of electric tension produced by the periodic pulsations of electricity through the tube. And, considering that the earth may be regarded as an infinite conducting body of potential zero, it seems justifiable to use the term *complete relief* in connexion with its effect. But in order to render the relief complete, it is not necessary that the potential of the relieving conductor should be zero; it is the relief to the periodic alternations of electric tension which produces the effect. If a Leyden jar be connected with the tinfoil, its effect on the sensitive discharge is the same whether it be charged or not. In short, any conductor of sufficient size connected with the tinfoil will produce the same effect as the earth, at whatever potential it stands.

It is so important to establish clearly that the effect of a conductor is independent of the potential at which it stands, and is due only to the facility for redistribution of electricity which it affords, that we shall here refer to an experiment which very clearly demonstrates such to be the case. Let a HOLTZ machine be taken as the source of the current, and an air-spark be interposed at some part of the current outside the tube, say, for example, in the part between the tube and the positive terminal of the machine, and let a ring of tinfoil be placed round the tube and connected with the earth and the relief-effect duly noted. It will be found that no effect is produced either upon the current* or the relief-effect by connecting either of the terminals of the machine to earth. That no effect should be produced upon the current is not surprising, as the whole effect, like all other electro-dynamic effects, must be due to the difference of the potentials of the two terminals and not to their absolute values. But it is very remarkable that the relief-effect is the same in both cases, inasmuch as in one case the tinfoil is of the same potential as the positive terminal of the machine, which is of higher potential than any other part of the whole circuit (including the tube), and in the other case it is of the same potential as the negative terminal of the machine, which is necessarily of lower potential than any other portion of the circuit. No stronger proof could, we think, be given that the effect is completely independent of the potential of the relieving system.

From this follows a remarkable result, the accuracy of which is, however, fully

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* So far as the current is concerned, the actual experiment when made by the authors of this paper would not support this statement, owing to a peculiarity in the source of electricity then used. This source was a large HOLTZ machine, and it was discovered that there was a large excess of positive electricity in the currents produced by it, so that when the terminals were metallically connected, sparks of a considerable length could be obtained from them. The obvious consequence was that the current through the tube was stronger when the negative terminal was connected to earth than when the positive terminal was so connected. But when allowance was made for this instrumental peculiarity the experiment fully supported the above statement. The peculiarity itself was doubtless due to an escape of negative electricity into the air within the machine.

confirmed by experiment. It is a matter of common occurrence in physics, that where a cause having one period acts upon a subject having a different period, the result is, on the average, the same as though the former remained constant at its mean value. Applying such considerations to the present case, we see that if the tinfoil be joined to a conductor whose electric state periodically changes, but whose period is not the same as that of the discharge in the tube, we may expect the effect to be the same as though it remained constant at its mean value; that is to say, it will be the same as though the tinfoil were connected with the earth (supposing the conductor to be of sufficient capacity), since it is a matter of indifference at what potential the relieving conductor actually stands. Thus to whatever conductor of sufficient capacity the tinfoil be connected, the effect will be the same as though it were connected to earth, unless the conductor have an electrical period identical with that of the discharge in the tube. The effect produced by joining the tinfoil to earth therefore naturally becomes our standard effect, with which all others may be compared. We shall in future call this effect the *to-earth* or *relief-effect.*

We have said that experiment fully confirms the theoretical result that any conductor of sufficient capacity not having the same electrical period as the discharge in the tube will give the *to-earth* or *relief*-effect. And this is so. If the tinfoil be connected with either terminal of the HOLTZ machine when the current is obtained therefrom,* or to an independently working coil or to a wire carrying a current with an independent air-spark, the relief-effect will be produced exactly as though the tinfoil had been connected with earth. It must, of course, be understood that if the changes of tension in the conductor be sufficiently violent, they will of themselves produce inductive discharges in the tube, just as they would in the case of a tube with no discharge through it, and the total effect will be the sum of the relief-effect and these inductive discharges. But allowing for such independent effects of the variations in the electric state of the conductor, we have not found any exception to the rule enunciated above, viz., that any conductor of sufficient capacity whose electric state does not suffer variations of like period with the interrupted discharge in the tube will, when connected with the tinfoil on the tube, produce the relief-effect, that is say, the same effect as though the tinfoil had been connected with the earth.

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* There is sometimes, however, a slight heightening of the relief-effect when the tinfoil is joined to the terminal of the HOLTZ machine nearest to the air-spark. This is due, no doubt, to a slight periodic variation of tension there, caused by, and synchronous with, the pulsations of the air-spark, and its period is, therefore, the same as that of the discharge in the tube, so that it presents no exception to the general rule enunciated above.

IV.—*The relief-effect (when the intermittence is effected near the positive terminal)* assumes the form either of repulsion or of discharge from the interior surface of the glass. These two effects are identical in nature, and the form actually assumed depends, in the same tube, solely on the intensity of the action which calls it forth.*

We shall in the present section suppose that the air-spark or wheel-break, or other contrivance used to cause intermittence, is placed between the positive terminal of the tube and the source of electricity. This being so, the most cursory examination of vacuum-tubes enables us to distinguish two types of effects when a conductor is made to approach to the tube. In the one case the luminous column is repelled by the conductor; in the other the luminosity appears to leap towards the conductor, usually in two tongues, which approach, but do not necessarily touch the glass, one on each side of the place where the conductor most closely approaches the glass, while between the two tongues there appears a luminous haze similar to that which ordinarily surrounds the negative terminal. We shall call these respectively the *repulsion-form* and the *discharge-form* of the *relief-effect* (Plate 16, fig. 7).

Further examination shows that these two forms of the relief-effect† include all cases. It is not uncommon to find both forms present at once. The luminous column is not always wholly interrupted; the two tongues which branch from it towards the conductor being often connected at their bases by the remains of the luminous column. This connecting piece usually shows signs of having been repelled by the conductor, and though not remarkable in other respects, it is in most cases less bright than the remainder of the luminous column. The *discharge-form* again is often destitute of one or other of its members; the two tongues may be very feeble, and the haze may be so faint as to be practically invisible. The magnitude of the repulsion-effect also varies greatly, depending, as will be seen, upon all the causes which are at work in producing the sensitive discharge. In many cases the sensitiveness is only indicated by a slight depression of the luminous column when the finger is placed on or very close to the glass; in others, the finger cannot be brought anywhere near the glass without the luminous column being strongly repelled. But these variations do

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* In thus examining the effects produced when the air-spark is in the "positive circuit" (*i.e.*, between the positive electrode and the source of electricity), before dealing with the matter in its more general form, the authors of this paper are following the actual course of their investigations. It has been thought advisable so to do because the class of effects examined in this section fully merit a separate treatment, and are more conveniently dealt with in this way than in connexion with the more general theory.

† By using the term *relief-effect*, the authors of this paper do not mean anything further or other than the effect, on the luminous discharge, of a neighbouring conductor, whose condition is such that its potential remains more or less completely unchanged by the electric disturbances in the tube. No theory of the *modus operandi* of these effects upon the luminous discharge is intended to be conveyed in the term. It was selected because the electric strain in the tinfoil was *relieved* by the process of joining it to a larger conductor, and has been retained because no more convenient term has been found.

not affect the truth of the statement that the effects of bringing a conductor near to the tube consist in all cases of one of the above described types or of a mixture of the two; and the doubtful cases can be shown to be cases in which the faintness of the effect creates a difficulty in recognizing their true features rather than cases in which a foreign element is present in the appearances themselves. We shall presently examine the causes which increase sensitiveness, but we wish first to examine the relationship in which the two forms of the relief-effect stand to one another.

Take a tube exhibiting a sensitive discharge, and find a spot where on contact with the finger the discharge-effect is manifested. Instead of placing the finger on the glass, commence with the finger at so great a distance from the spot that no visible effect is produced on the sensitive discharge. Now slowly approach the finger to the spot chosen on the tube. The first symptom of sensitiveness will in all cases be a slight repulsion of the luminous column; this will, on nearer approach of the finger, become more decided, and at length a slight haze will become visible between the repelled luminous column and the spot on the glass. This will, if the process be continued, rapidly develop into the ordinary discharge-effect. The change from the state of greatest repulsion to that of the discharge-effect is usually extremely rapid, so much so as to give rise to the idea that there is an absolute discontinuity at this point; but if care be taken to get a steady current, and the approach be very gradual, it can be shown that there is a continuous graduation from the one state into the other.

A more accurate method of trying the experiment consists in fixing a piece of tinfoil or thin metal, bent to the curvature of the tube, at the end of a glass rod, and connecting it to earth by a thin wire running along the rod. If this be made to work through a socket in a stand so as to admit of complete control, it will be found that the luminous discharge may be made to pass continuously through all gradations from almost imperceptible repulsion to the discharge-effect merely by diminishing the distance of the tinfoil from the tube. Actual contact is, as may easily be imagined, the most favourable arrangement for the production of discharge-effect, but it is by no means essential to it, nor is there indeed any discontinuous or even very rapid change in the effect when contact commences. The experiment fully bears out the principle previously enunciated, that the more complete the relief the greater the effect on the sensitive column, understanding for the future that the discharge-effect must rank higher than the repulsion-effect, or, in other words, must be considered as an intensified form of it (Plate 16, fig. 8).

A very slight modification of the arrangement last described will serve for an experiment which yet more clearly demonstrates that the intensity of the relief-effect depends on the completeness of the relief afforded to the static induction caused by the free electricity in the tube, and that for this purpose the discharge-effect must be taken as an intensified form of the repulsion-effect. If the tinfoil, instead of being connected to earth, be connected to any system of conductors insulated from earth, it will be found that by increasing the capacity of the system we can cause the relief-effect produced to vary from slight repulsion to the full to-earth effect. A very striking way of exemplifying this is by taking a thin copper wire, some 18 inches or 2 feet in length, and fixing its two ends on two glass rods. Coil the wire round one till it is all wound round it, and place the other so that the end of the wire is in electrical contact with a piece of tinfoil placed on the tube at some spot where the discharge-effect is strongly manifested when the tinfoil is put to earth. The capacity of the system in such shape is so small that it will only produce a slight repulsion. If now the rod which is in contact with the tinfoil be held stationary, and the other be removed from it, the wire being allowed to uncoil itself as the rods separate, it will be found that the repulsion gradually increases and passes almost imperceptibly into the discharge-effect. The removal of the other end of the wire from the tube has simply had the effect of increasing the capacity of the system to give relief to the tinfoil when under the action of the static induction of the electricity in the tube, and this, after causing the effect on the column to increase from faint to strong repulsion, further intensifies it by making it pass into the still stronger form of discharge-effect.

There are other ways of passing continuously from the repulsion-effect to the discharge-effect; and these not only support our view of the identity of the two effects, but by comparison with the results just obtained throw some light upon the causes of these phenomena. If the finger be passed along a tube containing a discharge of considerable sensitiveness, it will usually be found that from the positive terminal to a certain distance from it the discharge-effect is produced, but beyond that the repulsion-effect. If we stop at any point where the discharge-effect is produced and vary the effect by substituting for the finger some conducting system capable of giving only imperfect relief, we shall find that the nearer we are to the positive terminal the more difficult it is to reduce the effect to mere repulsion; in other words, the relief-effect tends to assume its more intense form the nearer we approach to the positive terminal.

A third method of causing the repulsion-effect to pass continuously into the discharge-effect is by increasing the violence of the interruptions which render the current sensitive. If a very small air-spark be introduced into the "positive circuit" of an uninterrupted discharge, the luminous column will be rendered slightly sensitive, but such sensitiveness will be manifested solely in the form of the repulsion-effect. If the air-spark be increased so that the pulsations become more violent but less frequent, this sensitiveness will increase, and the relief effect near the positive terminal will assume the discharge form, while the rest of the luminous column will only show repulsion. If the air-spark be still further increased, it will be found that the limits of the discharge-effect gradually extend themselves further and further along the tube until the whole column is capable of manifesting it; and this state of things remains until the interruptedness of the discharge becomes so great by reason of the length of air-spark, and the consequent slowness of the intermittence, that the discharge becomes flickering and unsteady, and ceases to be, in the proper sense of the term, a sensitive discharge.

It appears, then, that we can pass continuously from the repulsion to the discharge form of the relief-effect in any one of three ways:

(1.) By keeping the relieving system fixed at the same spot on the tube, and varying the completeness of relief, the discharge remaining the same;

(2.) By keeping the relieving system constant, and varying its position on the tube, the discharge remaining the same;

(3.) By keeping the relieving system constant and fixed in position, and varying the interruptedness of the discharge.

It is probable that there is a fourth way, viz.: by varying the quantity of the discharge, all other things remaining the same. The only phenomenon bearing on this point at present observed is that when the condenser is allowed to run down, the discharge-effect appears where previously there had only been repulsion. This might be supposed to show that decrease of quantity tends to give the discharge-effect, but it is probable that the reverse is the case, and that the phenomenon in question is due to the increased interruptedness—the greatly longer period of the intermittence of the discharge—which accompanies the falling of the tension in the condenser, and which, as we have seen, would tend to give the discharge-effect. The importance of slowness of intermittence in giving the discharge-effect is shown by the fact that on working the coil with a very high-speed break the sensitive discharge thereby produced only gives repulsion-effects, while so great is the tendency of the coil discharge when a slower break is used to give the discharge-effect, that it will often appear in a luminous discharge when the condenser and coil are used under circumstances which, from the size of the air-spark, would lead us not to expect it, but will vanish when the coil is stopped and the condenser allowed to work alone; thus showing that its appearance was due to the pulsations of the coil making themselves felt in the discharge, and by their slowness and violence causing the discharge-effect in places where the more rapid and equable intermittence of the air-spark would not have produced it. No doubt some portion of the above effect is due to the greater violence of the coil pulsations, but on the whole it tends to support the other experiments which show that the discharge-effect is intimately connected with great interruptedness of current.

It must not be thought that all tubes give both forms of relief-effect. So far as the observation of the authors of this paper has extended, all tubes give a repulsion-effect; but it is comparatively rare to find tubes which present both the forms. Speaking generally, the typical effect, especially with tubes of high resistance, is a repulsion not very great in amount. A further discussion of the signification of those forms of relief-effect will be necessary when we consider the analogues to them which exist in ordinary vacuum discharges.

In accordance with what has previously been stated, when the air-spark is on the positive side, the same effects are obtained by connecting the tinfoil to the negative terminal, or to any independent source of electricity of sufficient magnitude, as by connecting it to earth. In such cases, therefore, the question whether the effect will assume the discharge or the repulsion form will be decided by the same circumstances that control it in the case of the connexion to-earth ; viz., the position of the tinfoil relatively to the positive terminal, and the nature of the discharge, or, as the latter may in all probability be expressed, its magnitude and degree of interruptedness.

We therefore have, as has before been pointed out, a standard phenomenon at every point of a tube illuminated by a sensitive discharge, viz., the *to-earth* or *relief*-effect. We can get other effects connected with this, and to a great extent dependent upon it, by varying the completeness of the relief afforded. These effects form a continuous series from zero up to the complete relief-effect ; and this series can easily be passed through continuously by some such process as that above described, in which two glass rods and a connecting wire were employed to form the relieving system. Hence, if at a point of the tube we obtain by any process an effect on the sensitive luminous column, we can at once ascertain whether it belongs to the category of relief-effects or not. If it does not, there must exist some foreign element other than the mere facility for granting electrical relief in the influences brought to bear upon the tube. We now proceed to examine these special or non-relief effects.

V.—*On the special or non-relief effects produced on the sensitive luminous discharge by connecting it with the air-spark terminal.*

In the present section we shall at first suppose the intermittence to be caused by an interruption in the circuit between the source of electricity and the positive terminal of the tube. For convenience we shall express this fact by calling the positive terminal *the air-spark terminal.*

If we connect a wire with a piece of tinfoil placed upon the tube, and connect the wire with any independent conducting system, we shall obtain, as we have seen, more or less complete forms of the relief-effect. Both the wire and tinfoil will, in the majority of cases, repel the luminous column. But if the wire be connected with the positive terminal a sudden change takes place in the phenomenon. Instead of the luminous column being repelled by the wire, the course of the latter along the tube (supposing it partly to rest upon the tube) will be marked by a bright line of luminosity on the inner surface of the glass as though it had attracted the luminous column instead of repelling it. And the effect of the presence of the tinfoil is changed in a no less remarkable manner. Instead of the former repulsion, a tongue of luminosity will be seen apparently starting from the actual inner surface of the glass under the tinfoil and stretching toward the negative terminal of the tube, while the luminous column on the positive side of the tinfoil is usually depressed or repelled, and is often well nigh severed in two. If the tinfoil be in the form of a ring round the tube the appearance of the phenomena is very striking. In many cases the luminous column extending from the positive terminal is brought to an abrupt termination and ends in a sharply defined head, somewhat rounded at the extremity. Around this there is a well marked hollow cone of luminosity, springing from the inside of the tube immediately beneath the tinfoil, bright and sharply defined on the outside but hazy and blue on the inside, which is turned to and in fact surrounds the termination of the positive column above described. This hollow cone does not come to an apex on its external surface, but passes into a luminous column which stretches away towards the negative terminal of the tube, and supplies the place of the former luminous column, which it resembles in all respects (Plate 16, fig. 10). When the air-spark is considerably increased the truncated luminous column is very much altered; but as the various forms presented by the phenomena will require a close examination at a later stage we shall not detail them here.

The one thing to which it is necessary to call attention at the present stage in regard to these effects is their complete dissimilarity to those we have described as relief-effects. As we have shown in a previous section, each part of a tube in which a sensitive discharge is passing has a standard relief-effect called the *to-earth* effect, produced by connecting it with a conducting system of practically infinite capacity. A continuous gradation of relief-effects from zero to this *to-earth* effect can be obtained by limiting the capacity of the relieving system so that it can no longer be subjected to the influence of the electrical disturbances that take place in the tube without its potential undergoing material alteration. Now, if we compare the appearances described in this section with any member of this chain, we see they are wholly dissimilar, so that we at once learn that these effects are not due to the relieving capacity of the system with which the tinfoil is now connected, but to some special electrical interference to which the new arrangement has given rise. It is on the ground of this dissimilarity that we shall call these effects *special* or *non-relief* effects; and it must be borne in mind that these effects are only obtained when we connect the tinfoil with the air-spark terminal or make use of an arrangement electrically equivalent to this.

If the negative be the air-spark terminal, there will be found to be an equally great contrast between the effects obtained by joining the tinfoil to earth and to the air-spark terminal. As before, the relief-effects can be obtained by joining the tinfoil to any conducting system of sufficient capacity, whatever be its potential, provided that it does not undergo variations of potential co-periodic with those within the tube. The special or non-relief effects can, on the other hand, be only obtained by connecting the tinfoil with the negative terminal. It will not, however, be necessary here to examine or contrast these effects, as they will subsequently be shown to fall under a general rule; and it suffices here to state that the contrast above referred to is found to exist.

VI.—*On the nature of the electrical actions by which the relief and non-relief effects are respectively caused or accompanied.*

It is clear, as we have seen, that tinfoil placed upon the tube and connected to earth produces its effect on the luminous discharge by permitting the electric forces caused by or arising from the discharge within the tube to produce electric displacement within it and the system connected with it. And as it is immaterial how the actual displacement is produced, we may, without affecting the result, suppose that there is a suitable charge of electricity sent into the tinfoil from some source without the tube. This charge will, of course, be the same in quantity, but opposite in sign, to that which passes out of the tinfoil to the earth. We may thus discard all thoughts of relief or non-relief, and consider both states as being due to charges sent into the tinfoil from external sources at the proper times. And in the case of the relief-effect it is evident that these charges will be co-periodic with the electrical changes in the tube since they are caused by them.

In considering this subject we are at once struck with the fact that the non-relief-effect has been, up to this stage of the inquiry, produced only by connecting the tinfoil electrically with the air-spark terminal. It is evident that the peculiarity possessed by this source of electricity does not arise from its high or low potential, for we have seen that the potential does not affect the power of the conducting system to influence the luminous discharge; nor, as we have also seen, would mere fluctuations of potential in the wire produce any other than the relief-effect, or interfere with or destroy it, unless they were of like period with the pulsations in the tube. Hence the special effect in question must be due to the fact that connexion with the air-spark terminal interferes in a special manner with the electrical state of the tinfoil, and the peculiarity must consist in the fact that the period of the charges (and consequent variations of potential) is such that they keep time with the pulsations in the tube.

Now the displacement of electricity, which would otherwise give the standard relief-effect, may be interfered with either by exaltation, or by reversal, or by diminution. The last alternative is excluded by the experimental fact that these special or non-relief-effects do not resemble any of the series of relief-effects which we have described, and which range from zero to the complete to-earth effect.

To decide between the remaining alternatives we may adopt a similar course. Like the relief-effect, the special or non-relief-effect may be obtained in other than the complete form we have already described. In that form a piece of tinfoil placed upon the tube is connected with the air-spark terminal. If, instead of resting on the tube, the tinfoil (still connected with the air-spark terminal) be fastened to an insulated rod and made to approach the tube, a series of special effects are produced which pass from zero to the complete non-relief-effect. Now if this complete non-relief-effect were merely an intensification of the relief-effects we should expect to obtain the ordinary relief-effects, or some close approximation to them, at some part of this chain of special effects. But such is not the case. From the commencement to the end the special effects are wholly dissimilar to the relief-effects, showing clearly that the special effects cannot be due to an alteration in intensity of the same kind of electrical pulses that produce the relief-effects, but must be due to pulses of an opposite character.

This is, of course, not the only proof that the electrical pulses that produce the two effects are of opposite kinds. In fact, an examination of the appearances of the two effects is almost enough to convince the observer that it is impossible that one can be a mere heightening of the other, so radical is the dissimilarity, especially in their more marked forms. But the proof given above is the simplest and most direct experimental proof, and it is sufficient at the present stage, even when taken alone. It will, however, be subsequently found that there is strong confirmation of the correctness of this view.

We conclude, therefore, that the displacements of electricity in the tinfoil caused by joining it with the air-spark terminal are the same in period but opposite in character to those which produce the relief-effect. But it is evident, taking the positive terminal to be the air-spark terminal, that the former consist of periodic pulsations of positive electricity at the moments when the air-spark passes.* Hence in the case of the non-relief-effect, the tinfoil receives a pulse of positive electricity each time a spark passes. This must be, as we have seen, of the opposite character to that which causes the relief-effect. Hence to every pulsation coming from the air-spark there corresponds in the case of the relief-effect a pulsation of negative electricity to the tinfoil; that is to say, a pulsation of positive electricity *from* the tinfoil.

This conclusion is exactly what we might have expected on the assumption that when the positive is the air-spark terminal the positive electricity passes intermittently through the tube in pulses of the same period as the air-spark. If each time the air-spark passed there were a sudden charging-up of the positive terminal and the portion of the circuit metallically connected therewith, causing a sudden discharge of positive electricity into and through the tube, this positive electricity, on reaching the part near to the tinfoil, would, by its induction, tend to drive away positive electricity from the tinfoil, and to attract negative electricity to it. This is what we find to be the case, and similar reasoning will apply to the case when the negative is the air-spark terminal. Therefore we shall assume that in the relief-effect there is a pulse from the tinfoil of the same character as the excess of electricity within the part of the tube opposite to it, or as it may be more simply stated, a pulse of electricity to the tinfoil of the opposite character to the electricity which is discharged from the air-spark terminal; and that in the non-relief-effect there is a pulse to the tinfoil of the same kind as the electricity which is discharged from that terminal.

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* If it is necessary to give an experimental proof for a conclusion so obvious, it is sufficient to connect this portion of the circuit to earth, placing a telephone in circuit, when the air-spark note will distinctly be heard, showing that there are periodic variations of potential accompanying each spark.

The first takes place at the moment that the electricity in the tube passes the spot where the tinfoil is; the second keeps time with the charging-up of the terminal which leads to the discharge, and is therefore most intense at the moment of discharge. And, further, we have the experimental fact that under ordinary circumstances these effects are of a diametrically opposite kind.

This is, perhaps, the most suitable place for explaining the connexion between intermittence and sensitiveness in vacuum discharges. The effects observed in sensitive discharges have been traced in the preceding part of the paper to the effect of static induction from the free electricity that passes into the tube at each pulse. Now, in order that this static induction outside the tube may be strong, it is clearly necessary that the quantity of free electricity within the tube while the discharge is passing should be great. In other words, the current must pass in large pulses and not in driblets. This is exactly what intermittence effects. The electricity is penned back until it has accumulated in large quantities, and then in one pulse it bursts into and sweeps through the tube. In the so-called continuous current, also, the electricity doubtless passes into the tube in pulses, but as these pulses are perhaps many thousand times more numerous in any given time than is the case with the sensitive discharge, the quantity in each pulse is proportionately smaller, and is thus insufficient to produce a static induction which is of sufficient magnitude to be capable of causing in its turn discharges within the tube. Hence the so-called continuous current is really a sensitive current of infinitely small sensitiveness. The difference between the two is much the same as between the effect of letting the superfluous waters of a river overflow a weir each moment, and of penning them back for a whole day and then suddenly letting them free.

VII.—*Examination and interpretation of the special or non-relief-effect when the positive is the air-spark terminal.*

For the purposes of this section we shall take first the form of special or non-relief-effect already described. It is a very marked form, but by no means an unusual one, and indeed it is probable that it can be obtained in a more or less complete form in most vacuum tubes; and it possesses, as we shall see, the important property of being the typical form from which all others can be derived by modifications of known and definite kinds corresponding to peculiarities in the circumstances of the tube or the discharge.

If we place round the tube a narrow ring of tinfoil, and connect it with the positive terminal (where the air-spark is supposed to be) by a wire passing at a sufficient distance from the tube to prevent its directly affecting the luminous column, the following appearances will be noticed:—

(1.) The column which starts from the positive terminal will be found suddenly to terminate at the tinfoil ring in a bright column of small diameter occupying the centre of the tube. This column is usually striated, and ends in a stria with rounded head.

(2.) On the side of the tinfoil towards the negative end of the tube a conical column of luminosity is seen to start from the inside of the tube immediately beneath the tinfoil, and to stretch towards the negative terminal. This cone, in fact, forms the base of the new positive column.

(3.) On examination, this luminous cone is found to be hollow, the interior having an ill-defined and hazy surface in strong contrast with the somewhat sharp and regular outline of the exterior (Plate 16, fig. 10).

Let us consider what is the explanation of these appearances. We know that strong pulsations of positive electricity pass to the positive terminal of the tube and the tinfoil, keeping time with the passage of the air-sparks. These pulsations, when they arrive at the terminal, are of sufficient intensity to cause a discharge to pass through the tube, and the pulsations that reach the tinfoil must be of exactly the same strength as those that go to the terminal. Such pulsations must drive off positive electricity in corresponding pulsations from the interior parts of the tube contiguous to the tinfoil. These latter pulsations are similar to the discharges that take place from the positive terminal, and they seek relief in the same manner, viz.: by rushing towards the negative terminal of the tube. In this process they form the hollow luminous cone mentioned above. These discharges of positive electricity from the inner surface of the tube leave behind them an excess of negative which would be held prisoned by the positive charge in the tinfoil if that were permanent; but just as the latter was generated by the momentary charging-up due to the passage of the air-spark, so it is released by the relief given to such charging-up by the discharge through the tube. On such discharge taking place, the negative on the interior of the tube is set free, and in its turn satisfies the positive electricity of the discharge that meets it in its passage from the positive terminal. Thus we naturally get the termination of one positive column on the side of the tinfoil nearest to the positive terminal, and a complete discontinuity between it and the second, which starts in a hollow cone from the edge of the tinfoil nearest to the negative terminal.

To show more clearly that this is the true interpretation of the phenomena, and that the effect of the arrangement is thus to substitute for the original discharge two independent discharges occupying different parts of the tube, take two or three such rings separated from each other by spaces somewhat less than the diameter of the tube and connect them as before with the positive terminal. Each of these will be found to be the base of a hollow cone similar to that above described; and each such cone will form the base of a luminous column having all the features of a positive column, and terminating sharply behind the next tinfoil-ring or at the borders of the usual negative dark space near to the negative terminal of the tube. These sectional positive columns will be small in diameter and bright, and will or will not be striated according as their length is sufficient to permit of striæ or not. If they are not striated the hollow cone will end in a blunt rounded head of considerable brightness (Plate 16, fig. 9, and Plate 17, fig. 11). Each of these hollow cones will have its hazy irregular internal surface turned towards the bright end of the sectional positive column immediately behind it, *i.e.*, towards the positive terminal of the tube. If now we bring the finger or a conductor to the side of the tube these columns will all display sensibility, but each will move independently of the others and of the remainder of the positive column and behave as though it started from the tinfoil ring at its base, still preserving, however, its position relative to the sectional columns on each side of it. If a magnet be used, it deflects all these columns, but each column still moves independently and as though it had its tinfoil ring as base. The magnet also shows, as might be expected, that the discharge through each of the columns is in the same direction, viz.: the positive passes from the hollow cone towards the bright termination of the column of which it forms the base or commencement.

Now, taking a tube in which the above phase is clearly marked, let us gradually increase the air-spark interval, so as to render the electrical pulsations more violent. The sharply-defined head of the terminated column will be found to flatten and widen out, growing less bright in the centre till it becomes almost an annular ring of light. As the air-spark interval is still further increased, this annular ring widens and gets less definite, until at last the column on the positive side of the tinfoil assumes somewhat the form of a hollow cone pointing towards the positive terminal of the tube. The base of this cone is however not quite close to the tinfoil,* and is formed, as above stated, of the last phase of the annular luminous ring formed out of the head of the terminated positive column (Plate 17, fig. 12).

If the air-spark interval be too small these phenomena will not be obtained, but only a more or less faint foreshadowing of them mixed with diffused luminosity. This is not to be wondered at, as in such cases the electrical pulsations to the outside of the glass are probably insufficient to produce within it discharges of sufficient intensity to give complete satisfaction to the discharge from the positive terminal, and hence we have an effect produced by the superposition of an ordinary luminous discharge and one interrupted in the way above described. But careful examination of various tubes has convinced the authors of this paper that the forms above described are the truly typical forms of the special or non-relief-effect when the positive is the air-spark terminal.

VIII.—*Examination and interpretation of special and relief effects in general in the case of interrupted discharges.*

We have hitherto confined our examination of these effects to the single case in which the air-spark or other cause of the interruptedness of the current is situated in

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* The authors of this paper believe that such is always the case, but the phenomenon is complicated by the presence of a reverse current which accompanies the use of a large air-spark in the positive circuit.

the positive portion of the external circuit: that is to say, between the positive terminal of the tube and the source of electricity, and of this case we have only attempted to interpret one of the two classes of effects. But, as we have already remarked, it is not only in this case that we get sensitiveness, or that the relief and non-relief-effects in the luminous discharge are observable. All these phenomena are similarly manifested when the air-spark or cause of intermittence is situated in the negative portion of the external circuit, although, as we shall see, the characteristics of the two effects are quite changed. We shall now proceed to examine the appearances in the four cases, viz.: the relief and non-relief-effects when the air-spark is in the positive and the negative respectively, and to trace the connexions and the resemblances which exist between them.

To do this satisfactorily it is necessary to examine the various forms which these effects assume as we vary the intensity of the causes which give rise to them continuously from zero up to the highest limit practically attainable with the instruments used. This variation may, as we have seen, be made in several different ways, of which the following are the most convenient:—

(1.) We may vary the air-spark from zero up to the limit of striking distance; or if the interruptedness of the current be arrived at by other means, some equivalent mode of altering the character of such interruptedness may be adopted.

(2.) We may vary the distance of the tinfoil which produces the effect upon the tube from the greatest distance at which an effect is observable to actual contact.

(3.) We may move the tinfoil up and down the tube so as to be at a greater or less distance from the air-spark terminal.

Supposing, then, the tinfoil to be in the form of a narrow ring surrounding the tube, and taking first the *non-relief-effect* with the air-spark in the *positive*, we obtain the following results by these respective methods:—

(1.) As we increase the air-spark from its initial value, zero, there appears first of all a brightening of the central portion of the positive column in the part of the tube close to the edge of the tinfoil on the same side of it as the positive terminal of the tube. As the air-spark gets bigger this becomes a more or less marked division of the column into two parts, the details at the place of division shadowing forth the effect we have already described of the hollow cone and bright termination of the positive column. As the air-spark is still further increased this effect grows clearer and clearer, till it comes to its greatest perfection. Increasing the air-spark still more, the terminal stria or head of the column gets wider, or more nearly of the same diameter as the tube, and the brightness is greatest round its edges, so that it in reality becomes annular. It then grows shadowy and gets very close to the tinfoil, and finally disappears or becomes from its position so difficult to observe that its presence cannot be satisfactorily ascertained, so that the column on the positive side of the ring appears hollow, as it is on the negative side.

(2.) As the ring contracts from a large size, so that we get at first only the inductive effects from a comparatively distant conductor, the first appearances are those we have described for a small air-spark, and the others come in turn as the ring is decreased in size.

(3.) As the ring is moved away from the air-spark terminal the stria-effect is turned into the double hollow-cone-effect, and to reproduce the former effect the ring has to be widened.

Next, taking the air-spark in the *negative* and observing the *relief-effects,* they are found to be as follows :—

(1.) An increase of the air-spark from its initial value, zero, produces exactly the same series of effects as that just described under (1), with minor differences in the definition of the various phases. The bright and sharply-defined termination of the positive column of pointed or annular shape according as the air-spark is smaller or larger is often very beautifully shown.

(2.) Increasing the ring was equivalent to decreasing the air-spark.

(3.) Moving away from the positive made a pointed termination become annular. But this phenomenon is generally very difficult to observe.

This identity of effect in the two cases is the strongest confirmation possible of the correctness of the conclusions previously arrived at. We know that the special effect when the positive is the air-spark terminal is caused by pulses of positive electricity passing to the tinfoil co-periodic with the elevations of potential at the positive terminal produced by the passage of charges of electricity across the air-spark interval. And we find that such pulses of electricity in the tinfoil produce the hollow-cone discharges in the tube, and these form the base of a subsequent positive column while the original positive column stops short within the hollow cone and its discharge apparently finds satisfaction in the negative electricity set free there. Applying the knowledge thus obtained to explain the exactly similar effects which we obtain by connecting the tinfoil to earth and making the negative the air-spark terminal, we see that we must ascribe the pulses of positive electricity which give these effects to the inductive action of the negative charges which rush through the tube from the negative terminal at each passage of electricity across the air-spark interval. These pulses set free positive electricity within the tube, which rushes from the glass in its normal form of the hollow-cone discharge to satisfy the negative discharge which by its inductive action originated it, and the negative electricity on the inner side of the tube, set free again by reason of this satisfaction of the original discharge, passing from the interior of the hollow cone, continues the discharge through the tube. It will be observed, therefore, that the interior of this luminous hollow cone is taken to act the part of a negative terminal in both cases.

One difference between the two cases must be noticed here. The positive pulses in the latter case are directly due to the inductive action of the *actual electric variations within the tube near the tinfoil*, and will thus be proportional to the extent of these variations. In the former case they are directly due to the elevations of potential at the positive terminal which cause the discharge. In this case, therefore, they will be of equal strength throughout the tube; in the other case they will be so only if the extent of the electrical variations is the same throughout the tube, which we shall hereafter show is in all probability not the case. And hence we find, on comparing the observations given above, that while in the *special effect* the intensity increases *cæteris paribus* with the distance from the air-spark terminal, in the *relief-effect* it is stronger the nearer it is to that terminal. We shall show hereafter that the instantaneous variations of potential produced by the discharges are greater nearer the air-spark terminal than at a greater distance from it, so that it is natural that the relief-effects should be most marked in the neighbourhood of that terminal, while it is not strange that the non-relief-effects, in which the forces at work outside the glass are the same whatever part of the tube be selected, should be most marked at the parts of the tube where the electrical actions in opposition to which they act are the weakest.

Having thus demonstrated the identity of these two classes of effects there remain the other two, viz.: the *relief-effect* when the *positive* is the air-spark terminal, and the *special* or *non-relief-effect*, when the *negative* is the air-spark terminal. Both these should be produced, according to the theory, by pulses of negative electricity rushing to the tinfoil, caused in the one case by the inductive action of the positive discharge within the tube, and in the other case coming directly from the terminal of the tube which is in metallic connexion with the air-spark interval.

To examine these effects a tube was taken, and a narrow ring of tinfoil placed round it which was connected with the negative terminal, and the air-spark interval was placed in the part of the external circuit leading from the machine to the negative terminal of the tube. The effect was to constrict the luminous column by the formation of a dark space between the part of the interior of the tube directly under the tinfoil and the luminous column (Plate 17, fig. 13). The section of this dark space through the axis of the tube was in the form of a segment of a circle of which the centre would be in or near the tinfoil or within the glass immediately beneath it, so that the whole figure was that of a section of an anchor-ring by a co-axial cylinder. As the air-spark was increased the dimensions of this space also increased, till nothing was left of the luminous column within the part of the tube surrounded by the tinfoil but a very bright central line (Plate 17, fig. 14).

It will be observed that this phenomenon is precisely what would be produced by a repulsion of the luminous column, the peculiar form being occasioned by the fact that the tinfoil was used in the form of a ring, so that the repulsion must take place symmetrically from all sides, and hence must produce constriction of the column instead of displacing it entirely. We shall, however, see that some caution is necessary before we identify it with the familiar phenomenon of repulsion which has been described as so characteristic of positive relief-effects.

To establish the identity of this effect with the relief-effect when the air-spark is in the positive, the connexion between the negative terminal and the tinfoil was removed, and the tinfoil was connected to earth and the air-spark placed in the positive external circuit. On varying the size of the air-spark as in the case just described, precisely the same series of phenomena were presented except for very minor peculiarities of definition.

Inasmuch as in neither of these effects had there been any appearance of the blue discharge which, as we have seen, is so characteristic of the relief-effect when the air-spark is in the positive circuit, we examined the tube and found that it did not give this effect, or, at all events, it did not give it with the kind of current that was then being used. We therefore took a nitrogen tube in which we had often observed it, and repeated the experiment. No sooner was the air-spark interval of sufficient length than the blue discharge appeared, whether the one or the other of the two effects was being observed. In both cases the effects were at first repulsion, but when the action became more violent it passed into the blue discharge effect. The identity of the effects in the two cases was thus placed beyond all doubt. Indeed, the only difference that can be detected is that the definition is not equally sharp in the two cases.

On testing these tubes by moving the ring of tinfoil up and down the tube it was found that the blue discharge had a greater tendency to appear when the ring was near the positive than when it was near the negative terminal of the tube, thus confirming the law arrived at in the former case: that relief-effects are strongest near to the air-spark terminal, and non-relief effects are strongest at a distance from that terminal.

On looking closely at the blue discharge under the tinfoil, it is seen that it does not lie close to the glass, but is separated from it by a little blank space, precisely as the luminosity on the negative terminal of a tube is separated from the terminal itself by the small non-luminous space known as CROOKES' space. Thus the inside of the glass beneath the tinfoil acts precisely as a negative terminal. In contrast to this we find that in the cases in which the effects are produced by positive pulses, the luminosity starts sharply from the surface of the glass itself, just as the glow on the positive terminal appears to start from the very surface of the terminal itself. Nor is this the only point of resemblance between the effects produced by external negative pulses and the appearances of negative terminals. Any one familiar with the appearances presented by negative terminals shaped like a ring will know that they form round them a blank space, driving off the glow till it at length appears at the centre of the ring only, where it forms a bright line. The resemblance between these appearances and the effects above spoken of, produced by negative pulses, is so close that, so far as the authors of this paper are able to judge, these last-named effects are substantially identical with what would be produced were there a terminal in the tube consisting of a flat metallic ring fitting close to the inner surface of the tube immediately beneath the tinfoil, and this terminal were connected with a source of electricity and played the part of a negative terminal to discharges within the tube.

It is necessary here to make a remark, the purport of which has to some extent been assumed in what has already been stated. Although we have ascribed the sensitive effects directly to pulses of electricity which pass to the tinfoil or the parts of the conducting system nearest to the tube, we do not mean to imply that the free electricity in the tinfoil, or conducting system, affects the discharge by the direct action of the free electricity in the one upon that in the other. According to the theory of the authors of this paper, the effect of the pulses of electricity passing to the outside of the tube is always directly spent in causing a discharge, or its equivalent, to proceed from the interior of the tube, and it is the effect of this upon the luminous discharge already existing in the tube which produces the appearances observed. In the case of positive discharges to the outside of the tube there is no difficulty in accepting this, as the discharge is visible; but in the case of negative pulses the truth of the theory is less obvious. Those tubes which only give a slight repulsion require no special notice; the space formed by such repulsion is in all respects analogous to CROOKES' space, and the interior of the glass beneath the tinfoil is analogous to a ring-shaped negative terminal. But those which commence with very considerable repulsion and, as the air-spark is increased, pass suddenly into what we have called the discharge-relief-effect, require a separate examination.

In such tubes, if the air-spark interval be very great, the appearance is substantially the same as in other tubes. The space separating the blue luminosity from the interior surface of the tube is considerable, and is shaped as we have already described. We may assume then that we have here a case of a negative ring-terminal. When we decrease the air-spark interval, the luminosity draws closer to the tube, until it is separated from it only by a small interval, and the interior of the section of the tube surrounded by this blue luminosity is nearly dark, such darkness not being symmetrically disposed, but extending beyond the tinfoil on the side nearest to the positive terminal of the tube, thus appearing to drive back the positive luminous column. If this be carefully examined, it is impossible to resist the conclusion that we have here the analogue of the familiar negative dark-space, so that the ring-shaped terminal formed on the interior of the tube has its full complement of CROOKES' space, negative halo, and negative dark space. And the correctness of this conclusion is further demonstrated by an examination of the appearances produced by placing a small piece of tinfoil on the tube (not surrounding it, but forming a small patch upon it) and joining it to earth when the air-spark is in the positive. As has been previously described, the blue luminosity will appear between two bright tongues which seem to issue from the luminous column in the tube and stretch towards the blue haze beneath the tinfoil. The space between these two tongues is dark. On closely examining the phenomenon it is seen that the dark space extends from beneath the blue haze to a point considerably on the same side of the tinfoil as the positive terminal of the tube, so that the bright tongue on that side is separated by it from the blue haze for a considerable interval. The other tongue, on the contrary, seems to proceed from a point close to the blue haze. The magnet shows that both these tongues are formed by currents where the positive electricity is passing in the same direction as that in the tube. It is therefore evident that the interior of the tube beneath the tinfoil acts as a negative terminal to the tongue first described, and that this tongue is a positive luminous column, which is separated, as in ordinary cases, from the halo or glow of its negative terminal by a dark space. The other tongue is a positive discharge which proceeds from the interior surface of the tube after the satisfaction of the negative discharge therefrom in the manner just described. This positive discharge is doubtless due to the positive electricity that was fixed on the interior of the tube by the same negative pulse in the tinfoil which caused the negative discharge from the interior of the tube.

This leaves unexplained only the state which precedes the discharge-relief-effect, *i.e.*, that in which the luminous column is repelled. This cannot be taken to be analogous to the repulsion in tubes which do not give both forms of relief-effect (which repulsion we have seen to be due to the formation of a CROOKES' space within the glass), for it is very much greater in amount, and moreover, when the air-spark interval is increased, it disappears, giving place to the discharge-effect which we have seen is the true analogue of the repulsion in tubes which do not give both forms. The interpretation of this repulsion has been felt by the authors of the present paper to be a matter of great difficulty, but they have come to the conclusion that it represents a discharge of the same type as the non-luminous discharges that pass through vacuum tubes under certain conditions of exhaustion and current. This identification must be considered to a great extent hypothetical, but the authors of the present paper believe that it will on examination be found to be free from objections, and to satisfy the conditions of the problem more completely than any other.

Thus we see that the four effects divide themselves into those caused by positive pulses and those caused by negative pulses,* and that the effects of these are respectively to form a positive and a negative terminal within the tube beneath the tinfoil.†

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* Now that the relief-effects can be divided with certainty into those which are produced by positive pulses to the outside of the tube and those which are produced by negative pulses, and these can be recognised by the nature of the appearances within the tube, the full force of the experiment described on pp. 178, 179, becomes felt. If the air-spark be in the positive the effect of joining the tinfoil to earth will be to produce negative pulses to the tube whether the positive or negative terminal be joined to earth, that is to say, whether the tinfoil be maintained at a potential higher or lower than any portion of the circuit in which the tube is situated. And, of course, a similar remark applies to the case where the air-spark is in the negative.

† These are the *primary* effects; but in each case there is, as we have seen, a secondary effect of a precisely opposite character, viz.: the formation of a negative and a positive terminal in the respective cases.

IX.—*On the nature of striæ, and the artificial production of striation in the luminous (sensitive) discharge.*

We have seen that positive and negative pulses on the outside of the tube, co-periodic with the discharges that pass through it, cause the interior of the tube within the tinfoil to assume the character of positive and negative terminals respectively. The negative terminals so formed possess all the characteristics usually appertaining to terminals of such shape, but otherwise they do not give us any suggestions specially valuable for our present inquiry. With the positive terminals, however, the case is far different, as we shall proceed to show, taking as an example the special effect when the air-spark is in the positive circuit.

We have seen that the positive discharge due to a ring of tinfoil forms a hollow cone with a sharply-defined luminous outer surface. This cone, if the nearest negative terminal is the negative terminal of the tube, passes into a column of diffused luminosity similar in all respects to the ordinary luminous column which starts from the positive terminal of a tube. But if there is another similar ring of tinfoil also connected with the positive terminal between the former ring and the negative terminal, the luminous column that starts from ring No. 1 is stopped by ring No. 2, and from this latter ring there starts a second hollow luminous cone which stretches away in its turn towards the negative terminal in a diffused luminous column as before described. If these rings be placed at the proper distance from one another, and the size and exhaustion of the tube be suitable, the short luminous column between the rings will dwindle down to a hollow cone with blunt rounded head, this head being greatly superior in brightness to any other part of the cone and stretching to a point close up to or even a little within the next ring, so that it is in the middle of the space enclosed by the hazy blue inside surface of the hollow cone that starts from that ring. And by using additional rings this can be made to repeat itself until the whole luminous column is segmented into these hollow luminous cones or shells with bright rounded heads.

The theory which the authors of this paper desire to put forward is, that each of these luminous cones or shells is a perfect stria both in function and structure. The resemblance in appearance is most striking. In the luminous shells which we have just described there is the same convex bright outline pointing towards the negative terminal, and the same hazy blue ill-defined hollow surface turned towards the shell immediately behind or on the side towards the positive terminal of the tube, and there are the same dark intervals dividing consecutive shells as divide consecutive striæ. In fact, this segmented discharge presents to us all the familiar phenomena of striated discharges in which the striæ have rounded or conical forms. Moreover, the conical is not the only type of striæ which can be successfully produced in this manner. It is equally possible to form flat or annular striæ by proper adjustments of the air-spark interval, as explained in page 192. And as these are precisely the forms which natural striæ tend to assume when they deviate from the conical type, it may be fairly stated that all the forms of natural striæ can be artificially reproduced: a fact which is strongly in favour of the identity of the two phenomena.

But it is not only in structure that these luminous shells resemble striæ. There is also an identity of function. We know that when the positive pulses arrive at the glass they drive off similar positive pulses from the interior of the tube, and thus form the luminous shells. And knowing, therefore, that each luminous shell signifies a positive discharge, and also that no electricity passes through the glass, it is absolutely certain that a like amount of negative electricity must be collected at the surface of the glass within the tube, and must ultimately satisfy an equal amount of the original positive discharge—*i.e.*, of that which comes to it from the positive terminal, or from the shell immediately on the positive side of the one we are considering, as the case may be. We have then a negative discharge from the side of the tube, or from the gas immediately within it, satisfying a positive discharge advancing towards it along the tube; and we find that it causes the luminosity of this discharge to stop short and terminate in a bright, clearly-defined rounded head, which is separated by a dark space from the seat of the negative discharge. This, then, is the function of the shell: the bright part is to serve as the place of departure of the positive electricity that is about to pass across the dark space (or the place of arrival of the negative electricity after so doing), and the hazy interior of the cone is to form the place of its arrival (or the place of departure of the negative electricity); and, so far as we know, this is the sole function of these elements of the shell. Now let us take the case of the striated discharge. Here, also, we know that the positive electricity in the current must leave the bright head of the stria, and, after passing the dark space, arrive at the hazy inside of the next, and the negative electricity must take a reverse course. There is an absolute identity in the functions of the corresponding parts of the two structures, the only difference being that we know, from independent extrinsic evidence, that the electricity in the artificially segmented discharge does not flow continuously, but in intermittent discharges. This independent testimony is absent in the case of the ordinary striated discharge. We shall refer to this point again at the conclusion of this paper, but at present we shall assume what we have already stated to be so highly probable, viz.: that all vacuum discharges are in reality intermittent. Any who do not wish to admit this must take the reasonings of this section as applicable only to those striated discharges which are known to be intermittent.

Returning, then, to the case of the artificially produced conical shells, the *modus operandi* of the discharge is as follows:—When the pulse of positive electricity arrives at the terminal and causes the discharge into the tube, a positive discharge equal [*] to

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[*] It may seem an unwarranted assumption to assume that each of these artificially produced discharges is equal to the whole original discharge, but the appearances (with suitable adjustments) seem to warrant it, and as the reasoning is simplified, and the validity of the theory is not affected by this assumption, we shall, through the rest of this section, suppose such to be the case.

that which passes into the tube moves synchronously from the interior of the tube at each ring of tinfoil, forms the bright shell or stria, and passes on to the next shell or stria; thus supplying the place of the positive pulse that the ring of tinfoil there has just sent on. The last shell passes its discharge to the negative terminal, and the first shell receives a discharge from the positive terminal. In this way a discharge passes through the tube identical in quantity and character to that which passes into it from the positive terminal.

If, then, we are right in supposing that the series of artificially produced hollow shells are analogous in their structures and functions 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 by 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 processes 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 to the stone which the boy in front of him has left.

The truth of the foregoing theory is confirmed by the fact that it is not only by means of the positive special effect that we obtain formations analogous to striæ, but we can also obtain them by means of the other special and relief-effects when the electrical actions are of such a kind as would lead us to expect them according to the theory here put forward. Take, for example, the positive relief-effect. When the pulses passing through the tube are positive and a finger is placed on the tube, the positive relief-effect so caused consists, under certain relations of quantity and tension in the discharge (and notably when the discharge is due to the action of a small coil, as described on page 210, the negative terminal of the tube being put to earth), of a faint haze beneath the finger, and a large dark space extending right across the tube, and stretching for some distance from the spot on which the finger rests along the tube towards the positive end (Plate 18, fig. 16).* The termination of the positive luminous column at the place where it abuts on this dark space, is bright with a sharply-defined rounded outline, like the bright head of a stria, excepting that instead of pointing centrally along the tube it is slightly thrown upwards so as to point to the spot where the finger is placed. Here, again, we have a case in which

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* If the positive terminal be put to earth, the striæ will be immediately beneath the fingers as in Plate 18, fig. 16A, as should be the case.

there is a positive discharge, which gets satisfaction from a source of negative electricity, or, as we may term it, a negative terminal, situated within the tube at the surface of the glass, and we find precisely the same formation present itself. The luminous positive column is separated from the negative terminal by a dark space, and its head becomes bright, rounded, and definite in outline, and assumes all the characteristics of the bright head of a stria. And the experiment may be made still more striking and instructive by placing a second finger a little on the negative side of the first. The luminosity which previously commenced close to the first finger and stretched away towards the negative end of the tube, becomes divided exactly as in the previous case, and the portion intercepted between the fingers resembles in all respects a stria, except that the hazy blue negative surface is imperfectly developed, being really replaced by the haze under the first finger, which is the place at which the interchange of discharges takes place. The length of the body of this stria can be varied at will by increasing or decreasing the distance between the fingers so as to leave a more or less prolonged positive column behind the bright head, but the real structure is in nowise altered thereby.

The unit of a striated vacuum discharge is therefore composed of the body of a stria terminating in its bright surface, the dark space in front of it, and the hazy interior surface of the stria on the further side of that dark space. In this unit* we have a positive terminal, with a positive luminous column starting from it, a space across which the discharge passes non-luminously, and a negative terminal; so that in each unit we have represented all the elements of a complete discharge. And in the opinion of the authors of this paper, all striated vacuum discharges are composed of reduplications of this unit, and any phenomena connected with the negative terminal which seem to contradict this view, and to point to a special structure of the discharge near the negative terminal unlike anything that exists in other portions of the discharge, are merely modifications due to the local circumstances of the terminal in a manner now to be explained. We allude, of course, to the phenomena known as the *negative dark space*, the *negative glow*, and CROOKES' *space;* and we now proceed to examine these phenomena, taking first the negative glow, as the one presenting the greatest difficulty on the foregoing theory.

It is well known that the bright surfaces of striæ are usually convex. But this is not always the case. If a striated discharge be produced in a tube which has a bulb in the middle of its length, of diameter considerably greater than that of the tube, it will be found that the striæ in the bulb towards the side nearest the negative are concave on their bright surface, especially in that part of the bulb that rapidly narrows

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* It must be borne in mind that the analogue of the positive terminal in this unit is a surface within the body of the striæ, at which the separation of the electricities takes place; and that the body of the striæ is to be regarded as a short positive column terminating in the bright luminous head or conical surface of the striæ. In artificially produced striæ this column can, as we have seen, be made of any length; and even in the natural striæ its length varies within very wide limits.

towards the orifice of the tube (Plate 18, fig. 17).* And this phenomenon is not due to the shape of the sides of the glass; for it may be produced in a tube of uniform section. If we join to earth a ring of tinfoil placed round a large tube in which striæ are formed by the use of a coil working with a high-speed break, and thus constrict the striæ in the immediate neighbourhood of the ring, it will be found that those on the positive side of the ring have the same peculiarity as we have above noticed. Their bright surfaces are concave, but as you pass from the constricted portion each is of less curvature than the one before it.

We see, then, that we can greatly modify the bright outline of a stria by modifying the size and shape of the next stria, *i.e.*, of the negative terminal of this unit. If we make this small, then the bright surface of the next stria will curve round it and be concave; if, on the other hand, it is large, and still more if it be hollow and partially envelop the next stria, the bright surface of the latter will be very convex. Now if we replace this negative terminal (whose hazy, gaseous structure is readily capable of being moulded by and probably owes its form and structure to the discharge itself) by a fixed metallic body, we must expect great modifications in the appearance of the other members of the unit. It is not to be wondered at that the dark space, and the bright surface which forms the other boundary of this dark space, should follow the outlines of the new negative terminal, and that if it consist of a small metallic body projecting into the tube, the general appearance should be as if the bright surface enveloped it, remaining always separated from it by a dark space. This is exactly the appearance of the negative glow, and the above is, we believe, a complete explanation of its formation and function. This negative glow and the haze behind it, which terminates in what is known as the negative dark space, is, according to this theory, a *stria turned inside out* by the influence of the shape and character of the negative terminal (Plate 18, fig. 18).†

We have only to reflect on the very remarkable way in which the negative glow shows the shape of the negative terminal, to see that there is nothing improbable in assuming that such a deformation has taken place. If the negative terminal be spherical, the negative glow forms a spherical envelope round it; if it be merely a

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* An exactly similar phenomenon is shown in the familiar experiment of the electric egg, where the striæ which surround the negative terminal are concave on their bright surfaces.

† It will doubtless occur to those familiar with striated discharges, that there are considerable differences in the behaviour of striæ and the negative glow when subjected to the action of a magnet. It must, however, be remembered that the positions of the striæ are dependent on one another, since each receives the discharge from the one behind it. But in the case of the negative glow the lines of electric discharge whose termination it marks are fixed to the negative terminal at one end, and thus the glow can only be displaced so far as the deformation of these lines will permit. In fact, the negative glow is like *a stria at anchor*. There is just the same difference between the behaviour of the two as between the effect of waves on floating seaweed and seaweed that is growing on rocks. In this respect the artificial striæ of which we have been speaking resemble the negative glow, with the exception that they have a fixed positive terminal instead of a fixed negative terminal.

straight wire, the negative glow forms itself into a cylindrical envelope around it with a rounded or hemispherical head. If the negative terminal be in the shape of a ring the negative glow envelops it, remaining at a constant distance from the surface of the terminal and thus taking the shape of an anchor ring,* or else (especially if the ring be a small one) no portion of it lies within the circuit of the ring, but it envelops the ring as a whole, the bright surface of the glow having a boss or protuberance opposite to the centre of the ring. If the negative terminal be large and flat, it will be found that the negative glow does not substantially differ in appearance from a flat stria; and by making the negative terminal in the shape of a hollow cone, which is the natural shape of the negative terminal of what we have considered to be the physical unit of a striated discharge, there is little doubt that its resemblance to an ordinary stria would be rendered still more striking.†

If we are right in our conclusion as to the nature of the negative glow, it follows almost necessarily that the *negative dark space* and CROOKES' *space* are merely the representatives of the dark space which occurs as we have seen in every unit of a striated discharge. The former belongs to the unit of which the stria at the head of the positive column is the positive terminal, and the negative haze is the negative terminal, and the latter belongs to the unit of which the negative glow is the positive terminal, and which has for its negative terminal that of the tube itself. No doubt there is one great difficulty in this interpretation, viz.: the contrast in the lengths of the dark spaces in these two units, both when compared with one another and with the dark spaces in the other units throughout the tube. But if we remember the different circumstances of the discharge in the cases of these terminal segments when compared with those that prevail in the other segments of the discharge, we shall see no reason to give great weight to these unexplained difficulties as telling against the truth of the theory. In the first place we are dealing, in the case of CROOKES' space, with the passage of electricity from metal to gas or gas to metal, instead of simply the passage of electricity from one portion of gas to another. And further, we have the far more important circumstance that both in CROOKES' space and the negative dark space we have a case of a discharge in which the negative terminal of the unit is of a shape and disposition wholly unlike that of the negative terminal of any other of the

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* These last remarks will explain a difficulty which would otherwise be felt, as to why it is only in particular cases that we get any analogues of striæ from those special or relief effects which cause negative discharges within the tube. Like all other fixed negative terminals, the glass insists on having its dark space round it in all directions. This dark space is bounded by a glow which, as we have seen, is the analogue of the bright surface of a stria. But its arrangement is such that all we can expect is a stria turned inside out, as at an ordinary negative terminal; or more particularly, at a negative terminal in the form of a flat ring placed close to the interior surface of the tube. And this is precisely what we do obtain.

† Other remarkable instances of the modification of the form of the negative glow, and of the extent to which it may be made to assume the appearance of an ordinary stria under suitable local conditions, will be found in the Postscript to this paper.

segments of the discharge; and hence it is not to be wondered at that we should find that the distance across which the non-luminous discharge takes place in these segments is not identical with that which prevails in the other segments, all of which resemble each other so closely in these respects. And though we would not adduce any considerations as to what is more or less probable, unsupported by experiment, yet we are, we think, justified in saying that it is just in such respects that we should expect to find the details of a unit of striated discharge modified by changes in its terminal arrangements.

It will be seen that the authors of this paper regard each segment as constituting a separate discharge. One phenomenon observed by them, of a different kind to those of which we have been chiefly speaking, appears strongly to confirm this. 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.

It is natural to inquire what, in this theory, is the physical structure of striæ. Are they merely luminous appearances (*i.e.*, loci of maximum luminosity), or are they aggregations of matter having a material structure? This is a question which it is beyond the scope of this paper to discuss, but the most probable view, in the opinion of the authors, is that they should be regarded as septa of complete electric porosity, having a material structure. One of the most important facts favouring this conclusion is that when striæ are formed by a coil working with a high-speed break, the striæ produced by the two currents (the make and the break) adhere persistently together in pairs as though the alternate currents found ready to hand striæ that only needed a little deformation to make them available for their purposes (Plate 17, fig. 15). There are other facts tending to support this conclusion, but a complete examination of the question would carry us beyond the limits of the present paper.

A great difficulty in the way of this, and indeed of all attempted solutions of the stratification of vacuum discharges, arises from the difficulty of imagining any physical cause which could form material aggregations in the form of striæ out of the diffused and mutually repellant particles of the rarefied gas. The following theory is thrown out as a suggestion of a possible mode of accounting for their formation. It is known that the blue haze that surrounds the negative halo or glow is magnetic, and follows the lines of magnetic force just as would be the case were it a mass of magnetized steel filings. Now on the present theory this haze is identical in function, and therefore in structure, with the blue haze at the back of ordinary striæ, and it is a luminosity formed at the places where the non-luminous electric streams arrive at the surface of the stria, or where, as perhaps it should be stated, the positive currents that arrive meet the negative electricity set free by the pulse of positive electricity that has just been expelled from the stria. Now if we suppose that these discharges are effected by or accompanied by convection of free electricity on particles of gas, it does not seem impossible that a positively charged particle might pass so near a negatively charged particle that they would rotate rapidly round one another, under the influence of the mutual attraction of the free electricity with which they are respectively charged, thus forming an analogue to a circular current, which would behave like a magnetic particle just as the electrically laden particles in CROOKES' lines behave like flexible currents. In this way we should have matter capable of mutual attraction, it being assumed that there is on the average some directing force or factor which prevents the directions of the poles of the magnetic matter being completely indifferent. That in some way there must be manufactured out of the gas a substance capable of mutual attraction, which when formed into the glow has a surface tension, is quite evident from Mr. CROOKES' experiments with the radiometer, in which he found that the particles driven off the vanes (when used as a negative terminal) did not produce rotation so long as the glow did not intersect the side of the glass vessel. This is explicable only by supposing that the glow and the vane formed a physically continuous surface kept together by mutual forces.

It may be objected to this theory that the circular currents produced by the two elements of a revolving pair would be in opposite directions, and that they would consequently represent two magnets having opposite polarity, which would neutralize one another. But there is no reason to think that the two currents would be always exactly equal; and any inequality in the currents would produce a preponderance of magnetic polarity, and the preceding remarks would apply.

It is no objection to this theory that the bright portion of the glow does not appear magnetic. Its position is fixed by its being the locus of the extremities of the CROOKES' lines that proceed from the fixed negative terminal, and it can only be affected by the displacement or deformation of these lines, as is found to be the case.

X.—*The passage of the discharge through the tube occupies a time which is sufficiently small in comparison with the interval between the discharges to prevent any interference between successive electrical pulses.*

We shall now revert to the phenomena of the sensitive discharge, and show that all the effects of which we have spoken are due to actions whose durations are comprised within the time that a single pulse takes in passing through the tube, so that these effects are not in any way due to the action of one electrical pulse on a consecutive one. In other words, the whole of the effects take place in each individual pulse, and the repetition in successive pulses only serves to make them appear to the eye as continuous phenomena.

The most valuable direct evidence of the velocity of the discharge through the tube and the independence of each discharge is obtained from the examination of the discharge by a revolving mirror. For this purpose a revolving four-sided prism, whose sides consisted of glass platinised on the upper surface, and which was rotated by hand at a rate of from 400 to 800 revolutions per minute, was made use of. It was found that this instrument was capable of showing the intermittence of the current when in a sensitive state however small the air-spark, showing that the superior limits of the rapidity of the pulsations when produced by the aid of an air-spark is by no means a very high one. The difficulty in increasing the rapidity of the pulsations arose from the tendency of the heated poles of the air-spark to produce an arc between them if they are kept too close to one another.* The revolving mirror was used in the ordinary way by placing a narrow slit upon the tube so that the image of the discharge was a bright line about one-eighth to one-sixteenth of an inch wide. On making the mirror revolve rapidly the appearance in the mirror consisted of parallel bands alternately bright and black; the black bands becoming broader the greater the rapidity with which the mirror revolved and the less the frequency of the discharges.

On trying the above experiments it was found that the discharge could always be resolved into such black and bright bands. There was no broadening out of the bands discernible, showing, so far as such means of observation were capable of demonstrating it, that the discharges were instantaneous. When the air-spark was reversed, *i.e.*, thrown from the positive into the negative, a change occurred in the appearance of the bands; but it was difficult to define the essential characteristics of such change. They seemed to consist in a slight variation of the circumstances of the discharge caused by what may be termed a want of electrical symmetry in some portion of the circuit rather than to any change in the nature of the discharge due to any fundamental contrast in the properties of the two electricities. The definition seemed to be sharper when the air-spark was in the negative than when it was in the positive.

The negative end of the tube was first observed, the slit used being sufficiently long to allow the negative pole, the negative dark space, and the negative end of the positive column to appear in the field at the same time. On the mirror being set to revolve, the black and bright bands appeared generally to extend in straight lines through the whole field right across the negative dark space, although they grew faint and sometimes even invisible in the region of the negative dark space.

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* The air-spark in these experiments passed between two small platinum spheres. Perhaps a variation of the form of the poles might give air-sparks whose periodicity would be much more rapid. This tendency to form an arc was most strongly marked when the air-interval was in the negative part of the circuit.

When the air-spark was lengthened, not only did the black bands get broader, but, associated with the intensely bright bands, there seemed to be one or more other bright bands, much fainter in character, and apparently narrower. Whether they were in fact narrower it is difficult to decide, as their greater faintness would perhaps give them the appearance of being so; but if it is the fact that they were narrower, it is possible that this points to the main bright lines being broader than the image of the slit, which would show that the principal discharge occupies some little time; on the other hand, the apparent width of the bright bands may be due to irradiation. The subsidiary discharges may perhaps arise from the existence of return currents, such as are evidenced by the appearance of negative discharge at the positive pole, when an air-spark of considerable size is introduced, and also by the double effects which tubes so constantly show when we try to produce the relief or non-relief-effects.

A metal ring was now put round the tube about the middle of its length, and the slit was so placed that the ring passed across it about its centre. This ring was then joined successively to the air-spark and non-air-spark terminals, and to earth, and the slit examined in each case. There was not in any instance found to be any crookedness in the bright lines, although when the air-spark was in the positive the slit sometimes included the bright termination of the positive column and a section of the hollow luminous cone which surrounds it. These observations show that there is no want of simultaneity between the discharges caused by the relief or the non-relief-effect and the ordinary discharge in the tube; and as we know that the pulse which causes the former passes along the outside of the tube with the velocity of electrical currents in a conductor, this experiment would seem to demonstrate the existence of a velocity in the discharge within the tube of a similarly high order.

In order further to test the possibility of single pulses giving rise to the effects of which we have been speaking, the following experiment (to which reference has already been made) was tried. The terminals of a tube were connected with the outside and the inside of a small Leyden jar. The poles of the secondary circuit of a coil were placed so that the discharge from the coil charged the jar by leaping over intervals of considerable size (about a quarter of an inch for the negative pole and three-quarters of an inch for the positive pole), so that the make-current was excluded. When the coil was worked there appeared a brilliant discharge caused by the jar periodically discharging itself through the tube. A slit was placed on the tube and the luminous column was examined by the revolving mirror, and it was found that the discharge was quite instantaneous, and that usually it was not followed by the next at any regular interval, but that occasionally it was multiple. The discharge was then tested for both relief and non-relief-effects, and notwithstanding the very large quantity that passed at each discharge, it gave them very markedly. The contact breaker was then worked by hand so as only to give single flashes. These were tested for sensitiveness and were found to be perfectly sensitive. Thus it appears from experiment that the whole of the relief and non-relief-effects are completed within each single pulsation, and that the effect of the rapid repetition of the discharges is merely to give the appearance of permanence to effects which in reality appear and disappear during each separate discharge.

XI.—*The discharge is effected under ordinary circumstances by the passage through the tube from the air-spark terminal of free electricity of the same name as the electricity at that terminal.*

The knowledge derived from our previous experiments of the difference between the effects of positive and negative pulses arriving at the outside of the tube, enables us to ascertain the nature of the electrical disturbances within the tube, for as we have seen there is a complete dissimilarity between the appearances produced within the tube by the two kinds of pulses. Now, if we take a tube containing an ordinary sensitive discharge in which the sensitiveness is produced by an air-spark and connect tinfoil placed upon it to earth, we get the same type of effect wherever we place the tinfoil. Thus, if the air-spark be in the positive portion of the external circuit, the effect of joining to earth a piece of tinfoil placed upon any part of the tube will be what we may term a negative effect, showing that throughout the tube the primary and main effect is a sudden irruption of positive electricity across the section of the tube beneath the tinfoil.* This is the case even though the tinfoil be placed very close to the negative end of the tube. Thus throughout the whole length of the tube the charge of positive electricity passes without awakening a response from the other terminal, or if there be any response it must be a very faint one so as not in any way to make doubtful the very great preponderance of the original charge. If the negative be the air-spark terminal the same result is observed, with the exception that the charge passing through the tube is of negative electricity.

It must be observed that in saying this we do not commit ourselves to the two-fluid theory of electricity, or to any equivalent theory. It may be that instead of a charge of negative electricity being thus sent through the tube the thing that is propagated is a state of deficiency of positive electricity. Nor do we necessarily adopt any special theory of the propagation. It may be that the electricity is carried on material particles of gas; it may be that it is passed from one particle to another without or in addition to the actual motion of the particles charged with it at any moment; or it may be propagated without the assistance of the material particles of the gas. Which

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* These remarks are strictly only applicable to cases in which the discharge in the tube would, without the interposition of the air-spark, be non-sensitive. Those tubes which of themselves render discharges sensitive must be regarded as tubes, one or both terminals of which act as though there were an air-interval essentially connected with them, so that when using such tubes with an external air-spark we are often in the position of using a tube with an air-spark in both the positive and negative external circuits. The phenomena in such cases are of course somewhat complicated, as special effects (though different in character) are obtained by connecting the tinfoil to either terminal, but otherwise they present no theoretical difficulty, and will not be further noticed in this paper.

of these represents the actual means by which the electricity is propagated through the tube must be decided by other evidence. All that is claimed as following from these experiments is that the charge passes (disruptively) from the air-spark terminal in the shape of what we know as free electricity, and in such shape passes through the tube until it arrives at the other terminal and becomes neutralized by the opposite electricity that is awaiting it there. And this is shown conclusively by the identity of the relief-effect throughout the whole of the tube.*

The cogency of these arguments will become more evident if we consider certain results obtained with an arrangement which rendered the conditions of the two terminals of the tube electrically symmetrical instead of permitting them to be in so radically different electric conditions as is the case where an air-spark is used.

If we take a coil giving rapid discharges of small quantity, we shall obtain a sensitive discharge. If the tube be symmetrical in figure, and the terminals as nearly alike as possible, then, on examination, we shall find that the sensitiveness is very slight in the centre of the tube and that it increases towards the ends. This is in marked contrast to the ordinary sensitive discharge hitherto described, which shows a sensitiveness gradually decreasing through the whole length of the tube as we pass from the air-spark terminal; and, moreover, the character of the relief-effects differs in the two portions of the tube. In the portion towards the positive terminal the effects are similar to those presented by a tube having an air-spark in the positive, while in the portion towards the negative terminal the effects are similar to those in a tube having an air-spark in the negative. The part of the tube near the centre, which shows little or no sign of sensitiveness, will be called the *neutral zone*.

Nor is this the only peculiarity presented by this form of sensitive discharge. If we place a piece of tinfoil on the tube near to one of the terminals and connect it with the nearer terminal we get a marked effect, wholly different from the to-earth or relief-effect. If, on the other hand, we connect it with the more distant terminal we get an effect which, though stronger and more marked in character, is decidedly of the type of the to-earth-effect. These peculiarities are in no way caused by the double current, as they are well marked when the break-current alone passes.

These phenomena are easily explained by the supposition that owing to the

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* These conclusions, coupled with the experiments with the Leyden jar described in the last section, have a curious bearing on the question of the rival theories of electricity. So far as the authors of the present paper are aware, no attempt has ever been made to determine the sign of the electricity in the disruptive discharge. Hitherto if a Leyden jar charged with positive electricity was allowed to discharge itself into a neighbouring conductor, it was uncertain whether positive electricity passed from the jar to the conductor or negative electricity passed from the conductor to the jar, or whether both operations took place. The present experiments indicate a possible method of ascertaining in which of these ways the discharge actually takes place—at all events, when the disruptive discharge takes place in the modified form of a discharge through a vacuum tube. It would, however, be premature to assume that any such considerations as these would decide the vexed questions involved in the present electric theories until the matter has been much more thoroughly examined into than has as yet been the case.

symmetry of the electric condition of the terminals the arrangement is equivalent to an air-spark at both ends, and that the positive and negative pulses are approximately equal in quantity, and rush simultaneously along the tube so as to meet about the centre. The parts near the centre will thus be continually in a state of no electric tension, and hence there can be no relief-effect and no sensitiveness. The pulse at either terminal is of the opposite sign to the pulse at the other terminal, and hence to the pulses that strive to leave the tinfoil upon the tube near that terminal. Hence the connexion of a piece of tinfoil with the more distant terminal will naturally produce the relief-effect, though in a stronger and more decided form. And, moreover, the relief-effects in the two portions of the tube are of opposite characters, showing conclusively that the corresponding electrical pulses within the tube are of opposite signs.

A slight variation of the experiment tends to confirm this view. If we join one of the terminals to earth, so that these discharges cannot produce electrical tension or elevation of potential there, we find at once that the neutral zone disappears, that the luminous discharge presents all the characteristics of an ordinary sensitive discharge with the air-spark at the terminal opposite to that which is to earth, and that the sensitiveness decreases in the usual manner throughout the whole length of the tube as we proceed from the air-spark terminal towards the other end of the tube. And if instead of connecting the terminal to earth we connect it to a condenser of small capacity whose other surface is to earth, so as to diminish, without completely suppressing, the variations of tension, we find an effect of an intermediate character produced. The neutral zone is displaced towards the terminal which is connected with the condenser, and the sensitiveness is found to decrease as we pass from either terminal towards the neutral zone.

A striking confirmation of the correctness of the interpretation here given of these phenomena is obtained by placing a broad piece of tinfoil round the tube midway between its extremities, and putting a telephone in circuit between the tinfoil and the earth. When discharges from a small coil (such as above described) are sent through the tube, the sound heard within the telephone will be faint; but it instantly springs into loudness upon either terminal of the tube being touched with the finger. The reason is obvious. By touching one of the terminals, the discharge becomes one in which the same kind of electricity passes throughout the tube; and the wants of the tinfoil are all of one kind, and are therefore additive. But when both discharges enter the tube, the wants of opposite ends of the tinfoil are of different signs, and it is only the balance which has to come through the telephone circuit.

Still more striking effects in illustration of the subject were obtained by the use of a larger coil with a tube moderately exhausted, and a break working at a somewhat rapid rate. The luminous discharge presented the ordinary characteristics of a coil-discharge as we have just described them. When a ring of tinfoil, somewhat less than an inch in breadth, was placed round the tube not far from one end and connected electrically with the more distant terminal, the portion of the tube between this terminal and the tinfoil became totally dark, and the whole discharge was confined to the portion between the tinfoil and the nearer terminal. And this discharge presented most remarkable features. The hollow luminous cone of the positive non-relief-effect stretched from the interior of the tube within the tinfoil towards the nearer terminal, and also the blue luminosity within the tinfoil which we associate with the positive relief-effect made its appearance. On placing a similar ring of tinfoil in the same position relatively to the opposite terminal, and connecting it with the terminal most distant from it, an exactly similar discharge took place at that end of the tube, and the middle portion of the tube remained dark.

The interpretation of these very striking phenomena follows readily from the theory we have enunciated. Indeed, the action in this case is so plain that it is easy to arrive at the interpretation of the phenomena without any reference to the theory of sensitive discharges; and the importance of these experiments for our purposes is chiefly due to the support they give to the explanations we have put forward of the hollow luminous discharge in the positive non-relief state, and the other characteristic phenomena of sensitive discharges. A positive pulse coming from the secondary circuit rushes at once to the terminal and to the tinfoil ring. At the same instant a negative impulse rushes to the terminal nearest to the tinfoil ring and leaps into the tube. The impulse to the ring has already produced an inductive discharge into the tube of positive electricity, and this meets and satisfies the negative pulse from the terminal, leaving negative electricity predominating near the tinfoil, and this holds for a brief instant the positive charge in the tinfoil. That brief instant suffices for the next pulse from the coil (which will necessarily be of the opposite character) to come up and satisfy the positive charge, and thus set free the negative within the tube, which in its turn satisfies the positive pulse that now comes from the terminal, and then the cycle recommences.

As it has reference to the phenomena of sensitive discharges described in the earlier part of this paper, it is worth remarking that if we do not properly adjust the breadth of the tinfoil, or if the tube be not of a suitable character, we fail to get a complete absence of discharge in the intermediate portion of the tube, but we find that superposed upon the discharges as we have described them there is a somewhat feeble discharge going through the whole tube. This is precisely what we so often obtain in the case of the relief and non-relief-effects in tubes; the phenomena are there with all their characteristics, but blurred or masked by the superposition, as it were, of a further discharge which does not show the usual phenomena. It is reasonable to suppose that the cause is the same, viz.: that the external actions are not of the suitable strength, or the internal conditions are not such as to permit the effect upon the discharge to exist in all its completeness.

We see, then, that observation of the relief-effects enables us to determine the terminal from which the discharge proceeds, and the distance it goes without provoking a response from the other terminal. And this method shows us that in the ordinary case of the air-spark discharge it passes right through the tube before this response comes, if in fact it can be said to come at all. One of the most important consequences that necessarily follows from this is that the discharges at the two terminals of the tube are entirely independent, and are primarily determined each by the conditions at its own terminal and only in a secondary degree, if at all, by the conditions that exist at the opposite terminal. We shall hereafter recur to this point, and shall show still more conclusively the complete independence of the discharge at either terminal of a tube, but it will be well to call attention here to the very important consequences that flow from this principle. Since the discharges are not identically the same at both terminals, the tube must contain different free charges at different times.* It is therefore in no respect like a conductor, but is an independent electrical system, holding much the same position as the air-vessel in a forcing-pump. All the electricity that comes into it goes out again, but the truth of this can only be asserted when we consider the whole discharge from the beginning to the end, and it may not be even approximately true during a small finite time.

This independence of the discharges from the two terminals is a most important fact in the analysis of the mode of passage of electricity through rarefied gases. It dissipates the error of seeking analogies in metallic conduction; and shows that any appearance of obedience to regular laws as to change of potential as we proceed along the tube, resistance, &c., must arise from the fact that the effects measured are really average effects over a space of time enormously long compared with the duration of

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* In order to show this conclusively, a vacuum tube was enclosed in a metal canister (the wires passing to its terminals through tubes of insulating material inserted in small holes in the canister) and a telephone was placed in circuit between the canister and the earth. When a discharge with an air-spark in the external circuit was sent through the tube a sound was heard in the telephone similar to that made by the air-spark. By a fundamental proposition in electricity the free electricity on the surface of the canister (and which escaped through the telephone to the earth) was at any instant equal to the excess of one kind of electricity over the other in the space within the canister. Had the discharge been in the nature of conduction, as in a galvanic current, there would at no instant have been an excess of either kind of electricity, and therefore there would not have been any sound in the telephone. The existence of a sound testified to variations in the algebraical sum of the free electricity in the tube. To show that this was not due to anything depending on the wires leading to the tube, the same experiment was repeated with a tube in which the middle portion was connected with the two end-portions by very narrow passages. The middle portion was placed in the canister and the narrow parts passed through small holes made in its side, so that only a portion of the complete tube was within the canister. The same results were obtained with this arrangement.

By these experiments, together with those previously described, in which a telephone is placed in circuit between the earth and a piece of tinfoil upon the tube, we are able to obtain from the telephone direct evidence of the intermittence of the discharge at the time of its actual passage through the tube. This evidence fully confirms that previously obtained by the use of the revolving mirror. It is, however, of inferior value, for though it shows conclusively that there are rapid periodic alterations of intensity or character in the induction round the tube, it does not enable us to decide whether these are due to intermissions or only to fluctuations in the discharge.

individual discharges. These average effects may remain constant notwithstanding great variability during the individual discharges.

XII.—*On unipolar discharges.*

We have seen that, inasmuch as the discharge from the air-spark terminal produces its special effect without any indistinctness or confusion close up to the opposite terminal, it would appear that the discharges from the two terminals are so far independent that the discharge may take place from one and the free electricity pass right through the tube to the immediate vicinity of the other without evoking a specific response from the latter terminal. And if each such discharge does in any way call forth from the other terminal a specific response, it must be so slight that it does not affect materially the electrical condition of the interior of the tube, or the effect which that condition produces on conducting systems outside the tube. And we have also seen that this independence implies that the electricity leaves the terminal from which it starts in consequence of the electric tension within that terminal, and only in a very subordinate degree in consequence of the correlative action at the opposite terminal. Lest these should seem to be too hastily drawn conclusions we will proceed to describe a class of phenomena which furnish very important evidence of their truth.

If we take two exhausted tubes of the same general type, and connect one terminal of each with one terminal of a large HOLTZ machine, and connect their other terminals with the other terminal of the machine, interposing an air-spark (say in the positive circuit) so that the electricity has two alternative paths, the one through the one tube and the other through the other, the air-spark being common to both paths, a very remarkable phenomenon will be witnessed (Plate 19, fig. 19). If the air-spark be of a suitable magnitude it will be found that one of the tubes is wholly traversed by the discharge, but that the other is occupied only by a luminous column extending from the positive terminal into the tube for a considerable portion of its length, and gradually tapering to a point. If the air-spark do not exceed a certain limit, depending upon the "resistance" of both tubes, there will be no luminosity at the other end of the tube, and no discharge through it. No effect will be produced upon the luminous column, nor on any portion of the discharge, by breaking the connexion with the distant terminal, showing, what the appearance of the column itself sufficiently indicates, that the discharge is unipolar or incomplete. Slight indications of blue haze are sometimes seen at the tip of this tapering column, due probably to some negative electricity gathered from the neighbourhood, but not directly discharged from the opposite terminal. The discharge is, in fact, one which passes into the tube but not with sufficient force to pass through it, and which accordingly returns by the way by which it entered. The cause of this recall we shall examine hereafter; for our present purposes it suffices to point out the fact that here we have a discharge from one pole which is unable to approach near enough to the other pole to get relief there, and actually prefers to return by the way it came rather than to pass through the tube to the other terminal. Such discharges we shall term *unipolar discharges.*

This unipolar discharge is of course intermittent, and therefore sensitive. If we take a glass rod with a piece of tinfoil at the extremity electrically connected by a wire with the positive terminal of the tube, and hold it near to but a little beyond the end of the luminous column, we shall find the luminous column driven back; and by carefully advancing it towards the positive terminal we can often succeed in driving the luminous column wholly back and preventing any visible discharge taking place into the tube (Plate 19, fig. 20). The explanation of this is obvious. At the moment that the charging-up, which causes the discharge, takes place in the positive terminal, there is also a charging up in the tinfoil, and this by its inductive effect tends to prevent the advance of any free positive electricity. Thus, however rapid the pulsation, the force tending to oppose the discharge keeps exact time with it, and causes the heading back of the luminous column. If the tinfoil and wire be connected with earth, or otherwise made a relieving system, we find the usual to-earth-effects produced on this unipolar discharge.

A form of these experiments, which is in some respects even more striking, is obtained by taking a tube with an intermediate terminal and connecting the intermediate and one of the end terminals with the positive terminal of the machine, and the other terminal of the tube with the negative terminal of the machine. Interpose an air-spark in the positive circuit so that it forms part of the path to both of the terminals which were connected with the positive terminal of the machine. With an air-spark of proper dimensions it will be found that while the whole effective current passes from the positive intermediate terminal to the negative terminal, there is seen, besides, first a tongue-shaped luminous column extending from the positive end terminal towards the intermediate terminal; and secondly a similar tongue-shaped luminous column stretching out from the intermediate terminal to meet it (Plate 19, fig. 21). Or again, if we arrange two tubes as first described, and connect both terminals of the second tube with the positive terminal of the machine, we shall have two positive unipolar columns as before. These two do not join; and it is clear that here we have naturally the same effect as that obtained by the use of the tinfoil in the former case (Plate 19, fig. 22). Each of these discharges acts repulsively on the other, and they drive each other back. If we use the tinfoil, as in the former experiment, we can drive each in turn back towards, and sometimes into its terminal, and, within considerable limits, when one column is driven back, the other advances, and *vice versâ.*

This experiment with the intermediate terminal, shows very forcibly how the discharge from an air-spark terminal depends solely on the forces at work at the terminal itself, and has but little reference to the condition of the other terminal of the tube. We see here that the positive electricity from the intermediate terminal actually issues copiously in the direction in which lies not only no negative terminal, but actually a positive terminal, which ultimately succeeds in repelling its advance.

In corroboration of the statement that these tongue-shaped luminous columns are parts of two distinct incomplete discharges, we may add that the magnet shows that they represent discharges going in opposite directions, the positive electricity in each proceeding from the base of each column towards the apex.

Similar phenomena, save in respect of the shape of the luminous columns, are seen when the two terminals are joined to the negative terminal of the machine; but we shall not dwell here on the resemblances or differences between the two phenomena. The two kinds of unipolar discharge, however, are at once distinguishable from one another, and this may be made use of as a final proof of the correctness of the conclusions arrived at as to the nature of the electric displacements which cause the relief-effects. If a piece of tinfoil be placed on a tube through which a discharge passes, and this tinfoil be electrically connected with *one* terminal of a tube of suitable resistance, it will be found that when an air-spark is introduced into the discharge a unipolar discharge will appear in the tube whose terminal is connected with the tinfoil (Plate 20, fig. 24). If the air-spark be in the positive circuit, this will be found to be a positive unipolar discharge; if the air-spark be in the negative circuit it will be a negative unipolar discharge. This test is made still more certain and useful by taking the wire from the tinfoil to both terminals of the auxiliary tube. The result will then be a double unipolar effect, the nature of which is much more readily recognisable. This gives a very convenient test of the sign of the disruptive discharge at any part of the tube, and has been frequently employed with great advantage in cases where the complexity of the circumstances has made it difficult to ascertain it directly.

The following experiment is instructive in relation to unipolar discharges. If, with the arrangement described on page 214, we place upon a tube containing a positive unipolar discharge a ring of tinfoil not very far from the further end of the tube, and connect it with the positive terminal, the discharge is at once completed, and continues to pass throughout the tube (Plate 19, fig. 23). On examining it we find that from the interior of the tube within the ring of tinfoil proceeds the usual hollow conical discharge characteristic of the non-relief state with the air-spark in the positive, and this stretches in the usual way towards the negative terminal of the tube, and the luminosity that starts from the positive column comes up to and stops at the limit of the dark space within this cone in the usual manner. Thus we have by our tinfoil ring cut the tube into two, each of which shows its own separate discharge; and the tension which was insufficient to cause a discharge through the whole tube is equal to the task of supporting the two shorter discharges. And, just as in the corresponding case in the ordinary sensitive discharge, the pulsations in the tinfoil cause positive induction discharges which are strong enough to reach the negative terminal, and the relief of the tension in the tinfoil which ensues on the occurrence of the discharge into the tube from the positive terminal sets free negative electricity from beneath the tinfoil which satisfies the discharge from the positive terminal. Thus the interior of the tube within the ring of tinfoil acts alternately as a positive and negative terminal, forming part first of the discharge that occupies the further portion of the tube, and then of that which occupies the part of the tube nearer to the positive terminal.

We have already spoken of the results of connecting a small condenser with one of the terminals of the tube, when a coil discharge is used, so as to depress the electrical tension produced at that terminal, and shift the position of the neutral zone. It is very instructive to compare these effects with the analogous effects in the case of unipolar discharges. If we join the effective terminal of the tube containing the unipolar discharge to a small condenser composed of, say, two pieces of tinfoil about three square inches in area, with a plate of mica between them, we shall see the luminous tongue slightly shorten. If, now, we connect the other side of this condenser to earth we see a further shortening of the column, which will often almost disappear. If we connect the terminal with a larger condenser or a Leyden jar the discharge wholly disappears. Thus we see that the condenser or Leyden jar has, just as in the case of the coil discharges, the effect of muffling or toning down the intensity of the impulsive changes of electrical tension at the terminals and thereby lessening the violence of the discharges into the tube.

We conclude, then, from these experiments that the independence of the discharge from each terminal is so complete that we can at will cause the discharges from the two terminals to be equal in intensity but opposite in sign (as in the case of the coil) or of any required degree of inequality (as in the case of the coil with a small condenser). Or we can cause the discharge to be from one terminal only, the other terminal acting merely receptively (as in the case of the air-spark discharge); or we can cause the discharge to pass from one terminal only and return to it, the other terminal not taking any part in the discharge; or, finally, we can make the two terminals pour forth independent discharges of the same sign each of which passes back through the terminal from whence it came.

XIII.—*On the state of the tube during the occurrence of the discharge.*

We have already shown that each pulsation may be considered as a separate disturbance the effects of which have passed away before the next pulse comes. It now remains for us to ascertain what is the state of the tube during the continuance of the almost instantaneous pulse which may be considered as the unit of which the visible discharge is built up.

For the purpose of experimentally ascertaining this, it is obvious that if we employ any tests which are not themselves affected with the same periodicity as the discharge that is being examined, we shall get no results that speak with any degree of certainty of the state of the tube at the instant in question. Thus, if we listen with a telephone in circuit between the earth and a piece of tinfoil on the tube, we hear a sound identical in pitch with that of the air-spark, but this only tells us that there is a change of electric tension in the tinfoil at every pulse, and it cannot possibly tell us at what point in the period of the pulse the change occurs. To ascertain this we must use some tests which in themselves partake of the periodicity of the current itself.

The simplest experiment is that of taking two pieces of tinfoil, one near the air-spark end and one near the opposite end of the tube, and connecting them with a thin wire.

In an ordinary sensitive discharge, if we thus place a piece of tinfoil somewhat near to the air-spark terminal and connect it with a larger piece of tinfoil at a considerable distance along the tube, we shall find that we have complete relief-effect at the first-mentioned spot. And if we examine the effect at the larger piece of tinfoil we shall find indications of the non-relief-effect. If now we reverse the arrangement and place the larger piece near the air-spark terminal and the smaller piece at a considerable distance from it, we shall find that while we have feeble relief-effects at the larger piece we have strongly marked non-relief-effects at the other.*

Nor must it be thought that it is only the less definite types of relief and special effects that can be thus produced. If the pieces of tinfoil be made in the form of rings surrounding the tube, all the effects previously described can be produced in this manner. If, for instance, with a positive air-spark a broad ring of tinfoil near the positive end of the tube be connected to a narrower ring near the opposite terminal, we shall, with a proper adjustment of the air-spark, obtain the segmentation of the luminous column and the formation of the hollow cone, just as definitely as if we had joined the narrow ring to the positive terminal of the tube. A similar effect can be produced with a negative air-spark, provided the narrower ring is the one that is nearer to the air-spark terminal.

Now these effects can scarcely be reconciled with any theory which makes the discharge simultaneous throughout the tube. Suppose that it is so, then if we take A to be the smaller piece of tinfoil (which we shall suppose is the nearer to the air-spark terminal) and B to be the larger piece, it is obvious that the sudden change

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* We have seen that the negative special effect is identical with the positive relief-effect; and it might, therefore, be thought that, after all, the effects seen are nothing but the relief-effects belonging to a discharge from the terminal nearest to the tinfoil, somewhat as was the case when a coil is used. But it is easy to show that this is not the right view to take of the matter; for if, instead of connecting the tinfoil that is further from the air-spark with that which is nearer, we connect it with earth, so as to give to that part the full relief it desires, we find it to be an effect of an opposite character, showing that the former effect was truly a special effect.

Another conclusion of some importance may be drawn from these experiments. We see the relief-effect in A causes B to be so raised in potential as to give marked non-relief-effects. Hence the magnitude of the electric displacements which accompany relief-effects, though of course not so great as those accompanying non-relief-effects, which are the same as those of the discharges themselves, are yet comparable with them, and are quite capable of causing inductive discharges in the tube.

of tension at A is greater than that at B, since it compels B to give it relief. But however large B might be, such relief could never be greater than would amount to making the potential at A sink to that at B, which would by no means be tantamount to connecting A to earth, since the impulsive change at B will ordinarily be very considerable. Hence, as we get complete relief at A by joining it to B, it must be that B has not suffered any increase of potential at the moment that A seeks relief, and that thus it is not prevented from giving to A that relief which its size and distance from the spot where the free electricity is at the instant in question enable it to give—a relief which, as we have seen, is to all intents and purposes complete. But it does so at the expense of receiving a pulse of electricity from A of the same type as it would receive were it joined to the air-spark terminal, and we therefore get indications of non-relief-effect. We see then that the discharge is progressive, and that it proceeds from the air-spark terminal. For the electric disturbance at A makes its demand for relief on B, and finds B quite as capable of giving it as though no discharge had taken place, so that the discharge has not yet reached B.

Another very instructive form of these experiments is obtained by placing a long strip of tinfoil along the tube from end to end, taking care, of course, that it is not connected with the terminals (Plate 20, fig. 25). Suppose the air-spark is in the positive, then, if the tube be sufficiently sensitive, it will be found that near the positive terminal there is the discharge relief-effect. A little further on there is repulsion, which gradually diminishes and is finally replaced by attraction of the luminous column which, as we have seen, is an ordinary form of non-relief-effect.* The portion of the tinfoil near the air-spark terminal has derived relief from the remainder by reason of its being the first to experience the sudden change of tension, and the more distant parts receive in consequence pulses of electricity sufficient to cause the non-relief-effects. If the tinfoil be divided a little beyond the part of the tube occupied by the discharge relief-effect the positive end of the further portion will now present the discharge relief-effect; because instead of being a part of the relieving system to the portion of the strip of tinfoil between it and the positive terminal, it is now the part of the further piece of tinfoil which is the first to feel the call for relief, and consequently is the part that derives the full benefit of the relieving system formed by the piece of tinfoil of which it forms a part. And at the same time the negative end of the nearer piece of tinfoil (which previously showed relief-effects) will show non-relief-effects, inasmuch as it has to afford relief to the part nearest to the positive terminal and has no longer any more distant piece of tinfoil from which to draw supplies of positive electricity.

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* When the air-spark is in the negative the relief-effect usually assumes the appearance of an attraction of the luminosity to the inner surface of the tube. In reality it is due to the luminous positive discharges from the side of the tube, such discharges always appearing (as we have seen) to start from the actual surface of the glass. The same remarks apply to the non-relief-effect when the air-spark is in the positive.

This experiment, then, proves that the instantaneous increase of tension arrives at the tinfoil nearer the air-spark end, which we will call A, sooner than at the other, which we will call B. Now what is the state of the tube at B at the moment when the rise of tension occurs at A? We have shown that it is not affected by the rise of tension at A, but we have not otherwise ascertained its electrical state. This is ascertained in the following way. Fasten the piece of tinfoil B to a glass rod and let the wire that connects it be a fine wire running near to the tube during the whole of its course, so that the capacity of the system relieving A may depend almost exclusively on the capacity of B (Plate 20, fig. 26). Now if we move B as far as possible from the tube, keeping the wire straight, it will be found that *the capacity of B to relieve A is diminished.* In other words, by placing B on the tube we place it in a neighbourhood where there is a rising demand for the very electricity which is driven off from A. Suppose, for example, that the air-spark is in the positive. The electricity that leaves A is positive; and hence it follows that at the part of the tube upon which B rests there is a demand for positive, which amounts to saying that there is a rising negative potential there; or in other words the quantity of negative electricity within the tube at B must be increasing.

There would seem to be but one interpretation of this phenomenon. The negative terminal (in this case) is connected with its source of electricity during the whole of the interval between the pulses, and it must be pouring its electricity into the tube during all that time, thus raising gradually the quantity of negative electricity in the tube. When the pulse of positive comes it sweeps up all the negative that it encounters and rushes out at the opposite terminal probably leaving the tube in a positive state. Indeed, this is so marked that we often see indications of a reverse current so soon as we introduce an air-spark, showing that the positive pulse is so violent that it causes over-relief. When this pulse has passed, the non-air-spark terminal, or (as we may better term it) the connected terminal, commences to pour out its electricity, undoing the effect of the pulse on the tube and gradually filling it with negative electricity till the next pulse comes.

So much then for the condition of the tube in front of the electric pulse. We must next inquire what is the condition of the tube behind the pulse during the discharge. This is much more difficult, because we can no longer use the test above described, as we cannot tell whether the reaction which undoubtedly follows the relief-effect occurs during or after the passage of the pulse.

If, however, we put several pieces of tinfoil on the tube and connect the one nearest to the air-spark terminal to earth, placing a telephone in circuit, we shall find that the loudness of the tone is increased by connecting the other pieces of tinfoil with the first piece. This shows that their relief demands are additive, and as we know that the sign of the electricity in the relief-pulse is the same for all, and consequently that the pulse which constitutes the re-action must also necessarily be of the same sign for all, we see that the last piece must be in a condition demanding relief before the first has ceased to need it. In other words, the discharge is like a pair of lazy tongs and not like a bullet; and if we remember that we saw reasons for coming to the conclusion that the discharge was produced by action at the air-spark terminal and was almost independent of the condition of the other terminal, we see a sufficient reason why the discharge should be as we have found it to be. As each kind of electricity repels its like, there is every reason why the pulse should extend itself throughout the tube, and it is not easy to conceive any action that should make it pass through the tube in a compact mass like a bullet. This theory would also account for the observed fact that the relief-action is more violent near to the air-spark terminal than at a distance from it. With the special effect it is not so—indeed, the effect is feebler the nearer we are to the air-spark terminal—and this also is, as we have previously remarked, in full accordance with the above theory, inasmuch as it is natural that the effect of the external pulses should be less marked in proportion as the conflicting action within the tube is more powerful and commences more immediately after the special action commences.

To check the correctness of the conclusions arrived at in this section, it may be well to contrast the results above described with the analogous results obtained from a coil discharge where there is a neutral zone. According to theory, the nature of the relief required in such a case is different upon opposite sides of the neutral zone. Hence it should be possible to give complete relief to a part of the tube on one side of the neutral zone by connecting it with tinfoil placed on the tube at a suitable spot on the other side of the neutral zone. This is found to be the case, and further, it is found that the two corresponding spots approach and recede from the neutral zone together. Moreover, if a long slip of tinfoil be placed on the tube extending from end to end it is found that there are relief effects all along it, though of course they are of opposite types on opposite sides of the neutral zone, and that a very slight change is caused by connecting the strip of tinfoil to earth, showing that the demands of the two portions of the tube are well nigh complementary. And further, although the experiment is difficult to try in such a way as to leave no doubt as to the result, it has been several times observed that the effect of connecting a piece of tinfoil (which is connected to earth through a telephone) near one terminal of a tube containing such a discharge with a piece near the other is to lessen the sound instead of increasing it, thus showing that the electrical wants of the two pieces are opposite in character; and in further confirmation of this we may refer to the experiment described on page 212, which in a more marked and obvious way exemplifies the fact that the electrical wants of pieces of tinfoil on opposite sides of the neutral zone are of opposite signs.

Concluding remarks.

Having thus examined the sensitive state of vacuum discharges, and ascertained the special cause to which their sensitiveness is due, and also the way in which that cause directly operates in producing the effects observed, we are brought face to face with the question, How far are our conclusions relative to these discharges applicable to the case of ordinary or uninterrupted vacuum discharges? or in other words, How far they are independent of the peculiarity of the interruptedness of the discharge? In considering this most important question, it must be conceded that all due weight must be given to the consideration that our investigations have been carried on by means of experiments which would, one and all, have failed had they been applied to ordinary vacuum discharges; so that any conclusions sought to be drawn from them relative to such ordinary discharges must be received with great caution. But this would not justify us in neglecting the remarkable resemblances that exist between the two classes of discharges, or in refusing to examine the information which our knowledge of the constitution of the one gives us of the probable constitution of the other.

As we have previously remarked, it may be stated generally that there is no phenomenon presented by ordinary vacuum discharges which may not be shown by sensitive or interrupted discharges; and conversely there is no phenomenon presented by the latter (except such as directly depend on and are due to its sensitive and interrupted character) which is not also shown by the former. In illustration of this we will select two important features, viz.: striation and the terminal peculiarities. And first as to striation: Every one of the manifold shapes presented by the striæ of the one can be found among striæ produced by the other; and, moreover, the very same element which predisposes to the presence or absence of striation (viz.: the greater or less quantity of electricity discharged) in the one case predisposes also in the other. No doubt the sensitive discharge, in the conditions under which it has been here studied, is much less often striated than is the non-sensitive, but as the character of such a discharge is essentially variable and unsteady, it is not at all surprising that effects which are known to depend on complete steadiness of the discharge should be those least frequently met with. And that we are right in assigning these as reasons for the tendency in interrupted discharges to be non-striated is rendered more probable by the fact that, when we compel the discharges to operate with great regularity and within the prescribed limits of quantity and of time, as for example in the case of the high-speed break or of artificially produced striation, we at once find it easy to produce the steady effects commonly observable in ordinary discharges.

Next as to the terminal peculiarities.* These are, it will be admitted, common to both classes of discharges. But inasmuch as we have seen that the relief and non-relief-effects are substantially identical with terminal peculiarities, we can now go further, and say that they are shown wherever there is an instantaneous electric discharge from the space close to the surface of any fixed body. The consideration,

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* If the theory of the authors of this paper be correct, these terminal peculiarities are in reality cases of striation where the circumstances of the discharge are such as to maintain perforce the requisite steadiness and uniformity of conditions. But for the present purposes it is better to consider them separately.

therefore, of either of these important features alike leads us to the conclusion that the essentials of the discharge of electricity through rarefied gases are the same whether the discharge be interrupted, uninterrupted, or wholly discontinuous, and perhaps alternate, as in the case last mentioned.

Now the simplest, and indeed the only obvious explanation of this result is, that the character which was found to be fundamental in sensitive discharges, viz.: disruptiveness, is common to both kinds of discharge; and that the difference between the two kinds is to be sought in the scale on which that character is displayed.* In both discharges each terminal pours forth its electricity to satisfy its own needs, and only in a very secondary degree to satisfy the needs of the opposite terminal. The one terminal does not feel the electric state of the other directly, as would be the case were they metallically connected, but pours forth its electricity in the shape of free electricity, and leaves it to wander at its own will in that shape. If these matters could be demonstrated conclusively—in other words, if it could be shown that all disruptive discharges are discontinuous, and that the appearance of continuity is, in the case of the ordinary discharge, solely due to the extreme rapidity with which consecutive pulses follow each other, and the correlative fact that each individual pulse is of extreme minuteness, a great step would be gained in our knowledge of the nature of electric discharges; and though this is not to be hoped for at present, we trust that the results recorded in this paper add considerably to the evidence in favour of them, and we shall now proceed to indicate the considerations which have led us to this conclusion.

In the first place it is undeniable that all the phenomena of vacuum discharges, and especially the terminal phenomena, *may* be presented by discontinuous discharges, each individual member of which is wholly independent of those before or after it, so that we may say that they may be produced by single instantaneous discharges. And if the circumstances be such as to produce considerable regularity in the successive discharges, we shall have all the characteristic phenomena of the steady uninterrupted discharge presented by them. Hence the idea of continuity of discharge is not necessary to account for these effects. Nay, further, we can show that a continuous displacement of electricity from the surface of a body will fail to produce these effects when a more rapid displacement (of an equal amount) will produce them. In the experiment given on page 170 it is found that, if the wire to the outside of the tube comes from the *positive* terminal of the machine, the appearance within the tube is of a *negative* terminal and *vice versâ*. Now, as the action must necessarily be alternate within the tube, there must be as great a discharge of positive electricity during the one part of the process as there is of negative during the other. The only difference is that the one occupies only the time required for a spark to pass between the

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* To this we must add the restriction that, in the case of the ordinary discharge, the discontinuous pulses in which the electricity leaves the terminals must be very minute, a condition which is almost a corollary from the greater rapidity of intermittence in that discharge.

terminals, and the other occupies the vastly longer period that elapses between two consecutive sparks.*

The probability that both kinds of discharge are really pulsatory is increased by the consideration that the striæ are *formed* by the discharge. This increases the difficulty of supposing that a strictly continuous current could imitate effects which we have seen to be caused by discharges known to be instantaneous and disconnected. If the evidence given in the paper as to the form of the discharge from one stria to another (see page 205) be considered sufficient, these remarks have still greater weight, for it is scarcely conceivable that a strictly continuous current should take so strange a course. The passage from stria to stria must then be taken as disruptive and discontinuous, and if this be granted, then, as striæ are only particular cases of terminals, it follows almost as a matter of course that all discharges in rarefied air are equally so. And this consideration becomes of greater weight when we consider the intimate relation of striæ and their component parts to what we have termed the *physical unit* of a striated discharge. Such a discharge is, as we have seen, made up of repetitions of a unit consisting of the bright surface of a stria, the dark space between it and the next stria and the hazy interior of the latter. Such a structure then must either be necessary for the passage of the discharge or its natural consequence. Take the hollow cone discharge produced by the positive non-relief-effect. Here we compel a positive discharge to leave the interior surface of the glass under such circumstances that an equal amount of negative electricity is left behind to satisfy the original positive discharge. This it effects by causing the positive column to stop suddenly at a considerable interval from the place of the discharge, and to terminate in a sharply-defined bright head, which is in all respects identical with the outer surface of a stria, while on its part the negative discharge forms the hazy interior of the hollow cone. Thus the discharge requires and compels the formation of a unit of the structure above described. It seems in the highest degree improbable that structures formed and maintained to satisfy the needs of disruptive discharges (which have to leap from the one part and alight on the other of the differently constituted terminal portions of the structure) should also be formed and maintained by discharges which, in virtue of their continuous character, must be supposed to flow with the same evenness as in a metallic current, and to remain obedient to the law that the same amount of electricity flows across every section of the circuit in the same infinitesimal portion of time.

But if we admit that the ordinary discharge is discontinuous, the rapidity of the intermittence must be very great. For if this were not the case the individual pulsations would be of considerable magnitude, and would cause sufficient rise and fall of electric tension outside the tube to give to us the phenomena of the sensitive state. But if they are thus rapid there is no difficulty in the non-sensitiveness of the

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* This is selected as the most striking instance. But most of the phenomena of the relief and non-relief-effects would probably be found on examination to afford instances of it.

discharge. There may be many discharges from each terminal into the tube in the space of time that it takes the discharge to pass through the tube, and the alterations of tension at any point outside the glass may be infinitesimal, so as to be wholly unequal to producing any relief-effect within.

It may be objected that this theory supposes something like a discontinuity in the range of rapidity of pulsations in electrical discharge. Either they are of the comparatively slow period that gives the sensitive state, or of the indefinitely more rapid period that gives the non-sensitive state. This difficulty is, however, only parallel to the difficulty with which we are met when we see an air-spark interval enlarged to beyond the striking distance, when the discharge across it at once becomes silent, and the current that passes is found, when conducted through the tube, to have all the characteristics of a continuous discharge. No one can believe that the discharge across the interval has suddenly become continuous—the real nature of the change must be that the intermittent pulses (whether carried by convection on particles of air or not) have become so numerous that the average of the discharge, when taken over an extremely short space of time, is constant. And the appositeness of the comparison is shown by the fact that the discharge through the tube is non-sensitive.*

We have seen that the discharges in the sensitive discharge are sudden and of sufficient quantity to affect to a considerable extent the electric tension in the space around. This suddenness is an essential. And it is to this that we must attribute the indifference of the discharge to the potential of the body affecting it and the dependence of the effects on the change of electric state alone. If an electrified body be surrounded by air, it must of course form an electric field around it, which will or will not alter with time according as the air can or can not get at the body and convey away its free electricity. But when this electric field has been formed, it is affected just as easily by a new electric force brought suddenly into the field as though the original body were not there. The change is to all intents and purposes the same. We do not know what material changes accompany the formation of such an electric field, but for the sake of argument assume that there is a certain driving off of gaseous particles until equilibrium is attained. Then the new force suddenly brought in will send away a like stream of particles whether or not the field on which it operates has already been subjected to a similar operation.

The true analogue to these effects is to be found in the consideration of impulsive and continuous forces in dynamics. It is a well-known principle that in calculating the effect of impulsive forces all continuous forces, whether they be of the nature of pressures, strains, external attractions, or otherwise, may be neglected. And the same is true of the changes of electric tension with which we are dealing in

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* In this case, as in the other, there is probably no discontinuous change in the character of the discharge. No doubt much of the discharge is carried in the silent form as we approach striking distance, and the apparent discontinuity is due to the fact that the increase in the proportion so carried is very sudden as we get near that point.

the sensitive discharges. They are so sudden and yet of such considerable magnitude that in considering the change they effect we may proceed as though no other electrical forces were at work. Thus, if we take the case of the positive unipolar discharge, a conductor connected with the acting terminal will, if approached towards the head of the column, drive it back, because when the sudden rush of electricity comes to the terminal, and from it into the tube, there is an equally sudden rush of the same kind to the conductor. Each causes an impulsive change in the electric tension around it; and as these are of a character to nullify one another within the tube the column is shortened. But a Leyden jar charged with the same kind of electricity to a much higher potential than the source of the discharge will not drive back the column. All that it does is to set up a permanent electric field which offers no resistance whatever to the sudden impulsive electrical changes that occur in the terminal and in the space within the tube.

The authors of this paper have abstained purposely from dwelling upon any questions involving theories of the nature of electricity or the difference between positive and negative electricity, or upon other differences which have come to light during the present investigation. But it is important to observe that the difference in behaviour of the two kinds of electricity is not confined to cases in which these electricities leave the terminals proper of the tube, but is equally present when they come from quasi-terminals (as in the case of the relief and non-relief-effects), or even when they form their own terminals out of gaseous materials, as in the case of striæ.

POSTSCRIPT.

(June 28, 1879.)

A.—*On the variations of form of the negative glow.*

It is obviously a matter of great importance to the theory of striæ put forward in this paper, that the negative glow should be shown to be merely a stria modified by the local conditions that exist at the negative terminal of the tube. We have therefore thought it desirable to record one or two cases of special forms assumed by the negative glow under special circumstances, which have been met with by us since the date at which this paper was originally presented to the Royal Society, and which appear to us to show very clearly that the negative glow is only a modified stria.

The first case was observed by one of the authors of this paper in a tube belonging to Mr. WARREN DE LA RUE, which was being experimented upon in his laboratory with a current of several thousand cells of his well-known battery. The negative terminal was in the form of a rather large ring, but the exhaust of the tube was so good, and consequently the breadth of the CROOKES' space was so considerable, that the negative glow did not assume the form of an anchor ring, but of a surface of revolution, the section of which through its axis was bean-shaped, as represented in Plate 18, fig. 27. The glow as a whole had the ordinary whitish appearance, but the blunt protuberance or boss, opposite to the centre of the ring (marked R in the figure), where we should naturally assume any action that might be going on in the glow to be most intense, was deeper in tone and was precisely like a stria in appearance, both as regarded colour and shape, save that it was at its edges continuous with the negative glow. And when a certain change was made in the current by an alteration of some of the circumstances of the external circuit, a small conical stria appeared *within* the negative glow, just in front of the boss above spoken of, and quite separated from it, the two resembling in all respects (save in their position relative to the negative glow) two small striæ separated by the usual dark space, the dimensions of the latter being, like those of the two striæ, very small.

Again, Plate 18, fig. 28, represents the variations of the negative glow, and its transition into a complete striated form, under the influence of a perforated disk terminal. In this it will be seen that the so-called negative glow not only follows the general contour of the disk, but that it projects through the aperture. This part of the discharge assumes the character of a positive column in a constricted tube, and exhibits the well-known bead-like striæ.

It has been already suggested in the text of this paper, that the long dark space intervening between the negative glow (or stria, as it is here regarded) and the head of the striated column is due to the local action of the terminal itself. An experiment, shown in Plate 20, fig. 29, corroborates this view. Beside the end terminals which were used for the discharge, the tube was furnished with an intermediate ring terminal, which remained disconnected, except so far as leakage through it from the air. The column of striæ did not usually extend from the positive end so far as the ring. But when the column was drawn out by the influence of a magnet, and made fully to reach the ring, the column of striæ was immediately thrown back, so as to form a comparatively long dark space between the stria so anchored on the ring and the column behind. This sudden throwing back was repeated every time a stria was brought on to the ring by the magnet, and was doubtless due to the fact that the ring was acting as a (weak) negative pole through leakage from the air.

B.—*On the double character of the coil discharge.*

We have given experimental proof in Section XI. of this paper, that when we take a discharge of small quantity from a coil of symmetrical make, the electricity passes into the tube simultaneously at both terminals, and that the two discharges meet and form a neutral zone near the middle of the tube. Since the paper was originally written, the authors have met with cases in which the distinction between the nature of the discharges from the two terminals and the position of their place of meeting are of themselves visible to the eye without needing to be demonstrated by the tests we have described in the paper.

The tube in which this was first observed was one of considerable length, but only of moderate diameter and moderately good exhaust. The appearance of the discharge is shown in Plate 20, fig. 30. The break current alone passed. The luminous column starting from the positive terminal was much smaller in diameter than the interior of the tube, and consequently left a dark space between it and the sides of the tube. The portion in the half of the tube nearer to the negative terminal, on the contrary, appeared wholly to fill up the tube. On touching the positive terminal the discharge filled the tube throughout; on touching the negative terminal the discharge of smaller section extended throughout the whole length of the tube, and when a small condenser was used, as described on page 211, the portion of the length occupied by each could be varied at will. It should be added that the narrow and broad discharges showed, by the nature of their relief-effects, that they were respectively caused by positive and negative electricity, and the part of the tube where they were seen to join was found in all cases to be the neutral zone. It also should be added that either column could be shortened by producing relief-effects near its root as though such a proceeding delayed the discharge, just as the small condenser would do.

The cause of the difference in the two discharges is not difficult to explain. Both the discharges get some portion of relief from the inner surface of the glass even when the finger is not placed thereon, and this in the case of the positive discharge naturally results in the formation of a dark space at the surface of the glass, while in the case of the negative discharge it leads to the formation of positive luminosity close up to the surface of the glass.

A similar difference in appearance in the two discharges has since been observed in other tubes, and it is probably not an uncommon phenomenon. It is doubtless analogous to what is very frequently seen in the case of a discharge with a positive air-spark, in which it is found that the luminous column is very slender and does not nearly fill the tube while the air-spark is small.

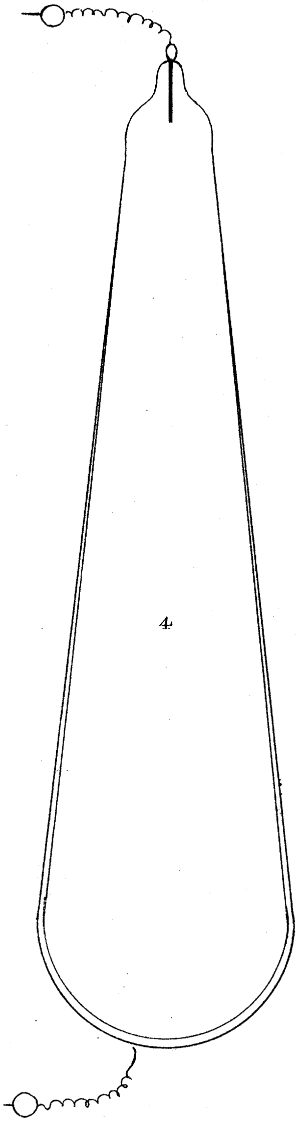
C.—*On the interference of intermittent discharges.*

In making certain experiments with intermittent discharges, it happened that a discharge was sent through two tubes placed in series, but lying parallel to one another, and at no great distance apart. It was observed that the discharge in the one tube strongly affected that in the other, and from this the authors were led to examine more closely the question of the interference of discharges which do not take place in the same tube.

For this purpose intermittent discharges were sent through two parallel tubes in series, the current passing sometimes in the same, and sometimes in contrary directions through the two tubes. The two discharges were found to be greatly affected by one another, as could be clearly shown by putting the one tube at a greater or less distance from the other. On examining the nature of these effects, they seemed to follow the same law as would have prevailed had the tubes formed one long one which could be doubled up or bent so as to make the one portion of it parallel to the other portion. This law is that the discharge in the portion of the tube nearer the air-spark tends to produce special effects on the further portion, and itself to manifest relief-effects. One remarkable result of this law deserves mention. When the air-spark is in the positive the special effect is of course accompanied by positive luminous discharge from the inside of the glass. Accordingly, the tube through which the discharge passed last had positive luminous discharge throughout its whole length, on the side where the other tube lay, and thus the whole luminosity in that tube appeared to be attracted towards the other discharge. This was of course the case whether the discharge passed in the same or contrary directions through the tubes, so that the remarkable phenomenon was presented of a luminous discharge (which we know behaves like a current) appearing to attract violently a discharge going in the opposite direction. After the explanation given above, it will be understood that the phenomenon was not really a case of two currents going in opposite directions attracting one another, but was a case of the luminous effects of the interference of the two co-periodic discharges through the medium of the impulsive static induction of the pulses of which they were constituted.

When a discharge is intermittent it can be made to pass through several tubes which are so connected as to offer alternative paths to the discharge. When this was done it was found that these discharges affected each other either by apparent attraction or repulsion of the luminosity which accompanied them. The authors have not had time to go further into the subject so as to ascertain precisely the law in such cases, but they have no doubt that on examination the effects could be accounted for by similar considerations to those which were found to hold in the previous case.

An extremely interesting experiment showing how intermittent discharges can in this way be made to interfere when they are synchronous, but not otherwise, was made by using two equal small coils to produce the discharges in two parallel tubes. When the contact breakers were made to work in unison any effect which the discharges produced upon one another was steady, as would have been the case had their co-periodicity been due to their forming part of one discharge as in the previous cases. But when they were a little out of unison, so that audible beats were given in addition to the two notes produced by the contact breakers, it was found that the luminosities in the tubes flickered (*i.e.*, were attracted or repelled) synchronously with each such beat. The reason is obvious. It was only just at the time that the contact breakers were moving approximately synchronously that the two intermittent discharges were sufficiently synchronous to interfere with one another.



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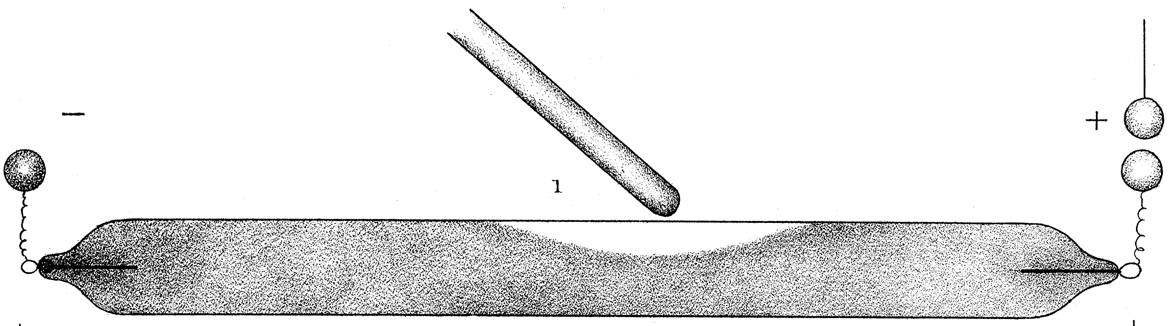

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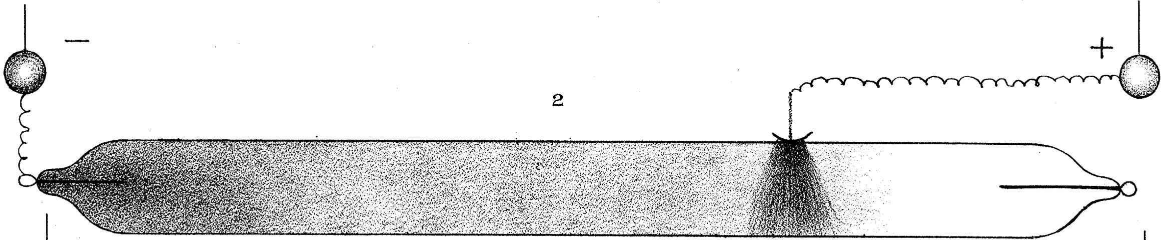

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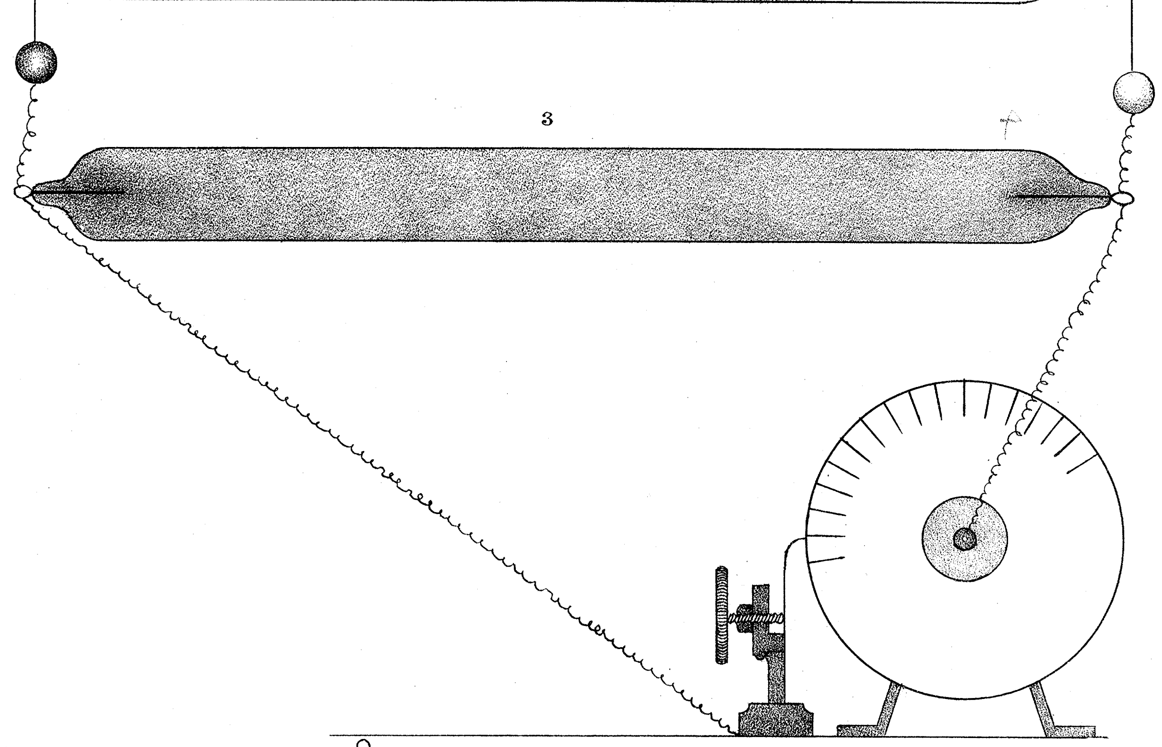

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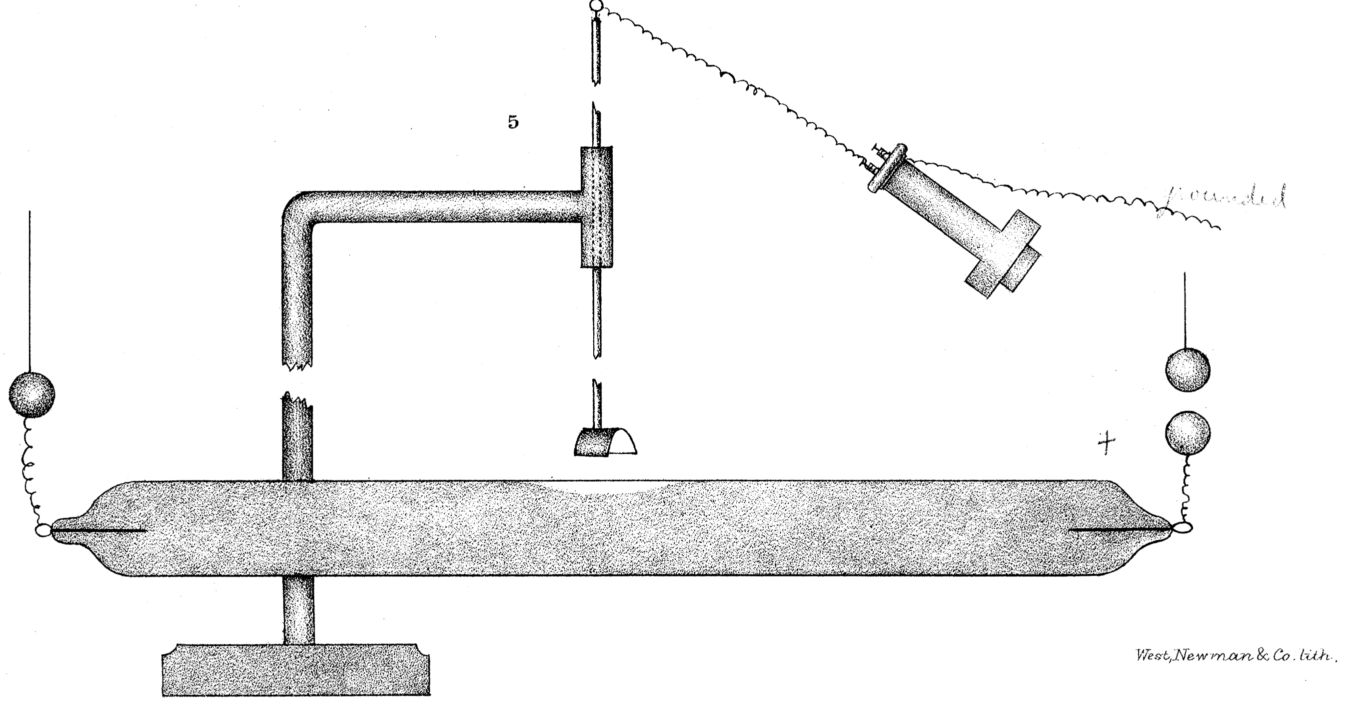

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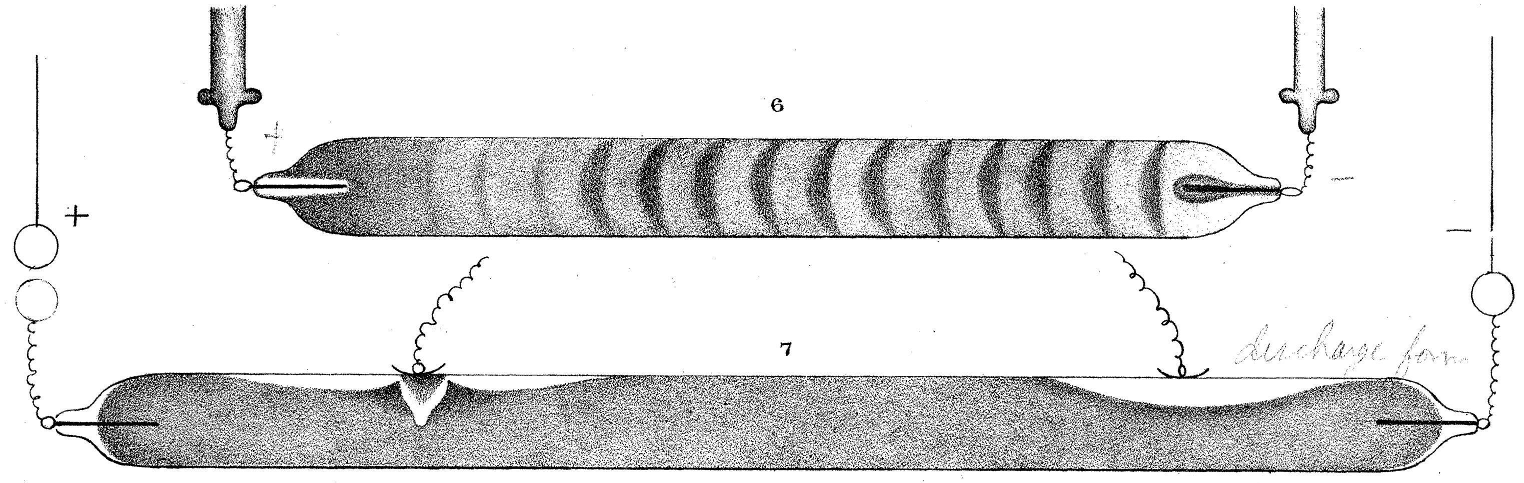

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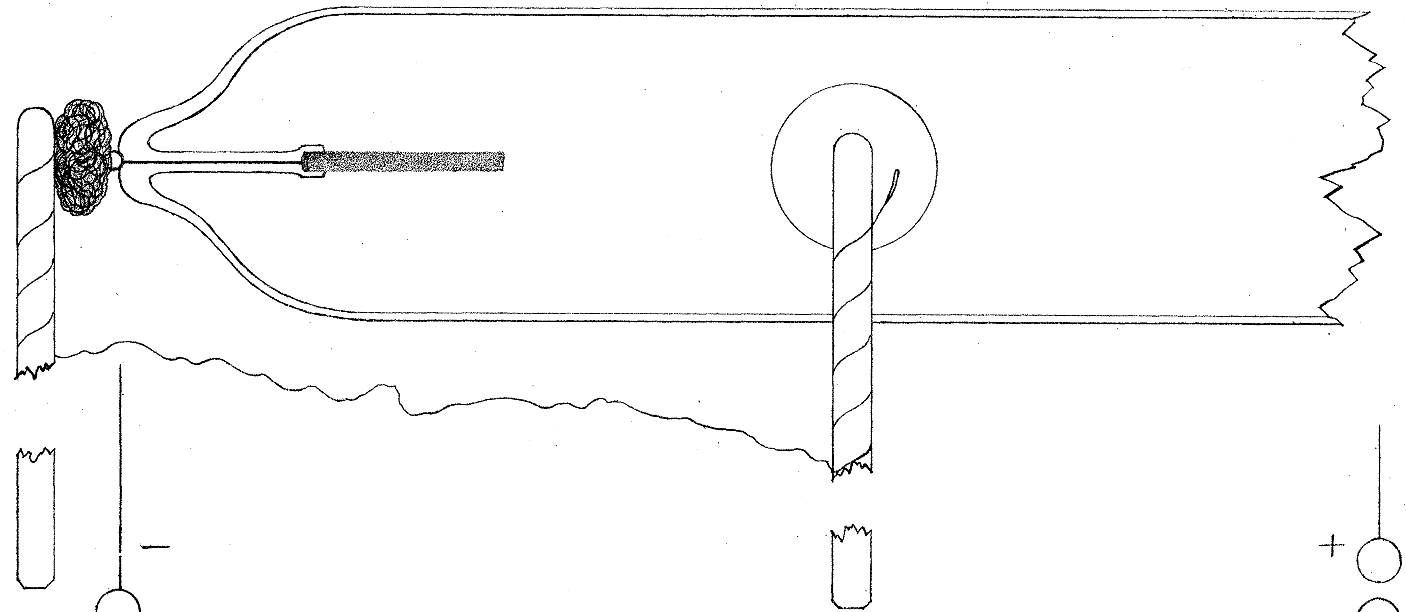
discharge form



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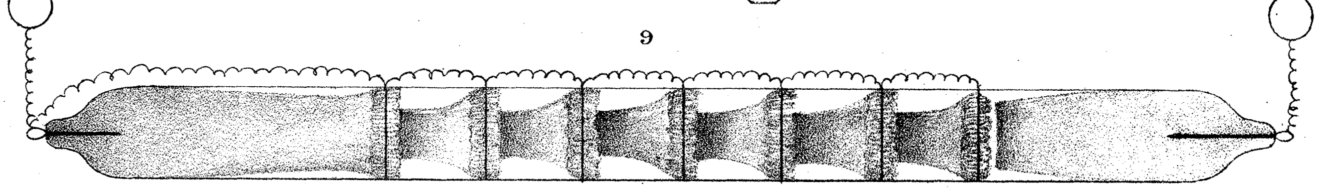

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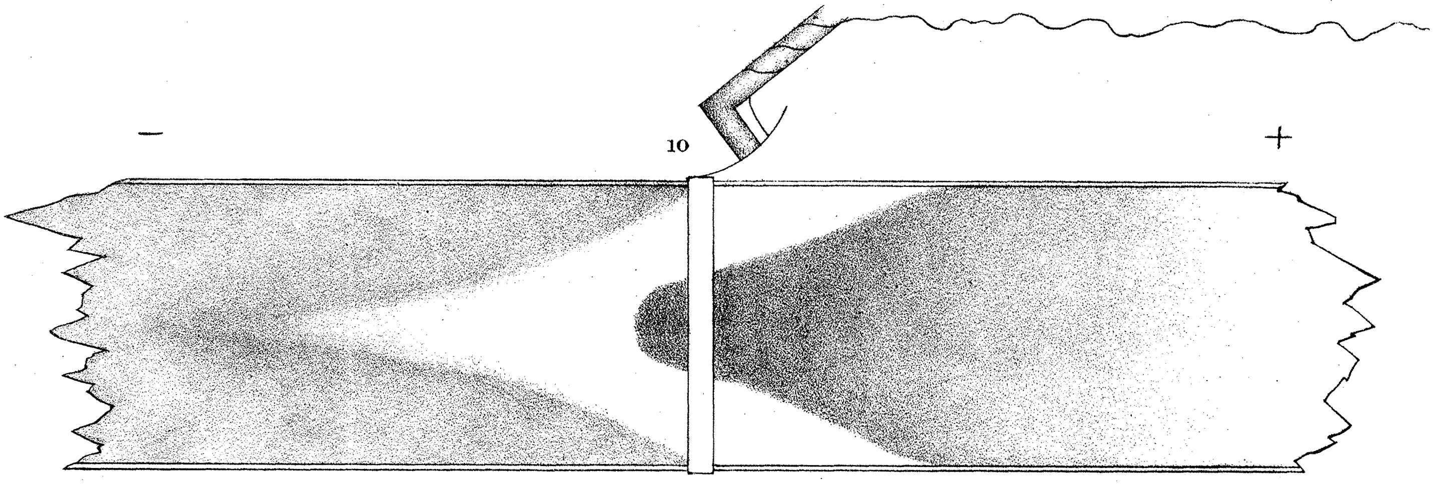

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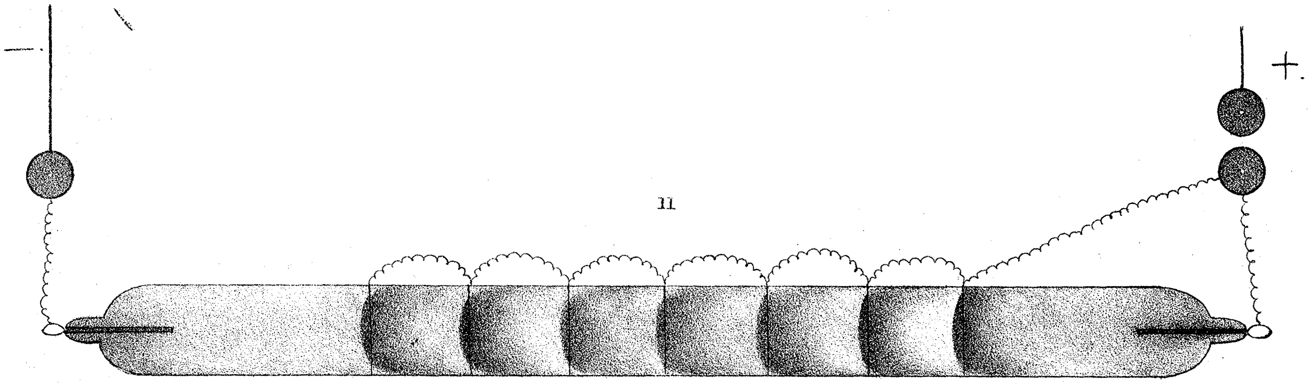

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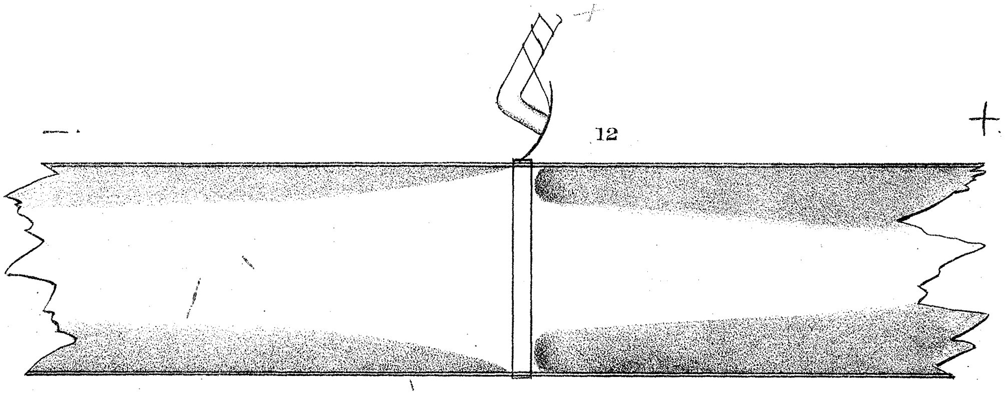

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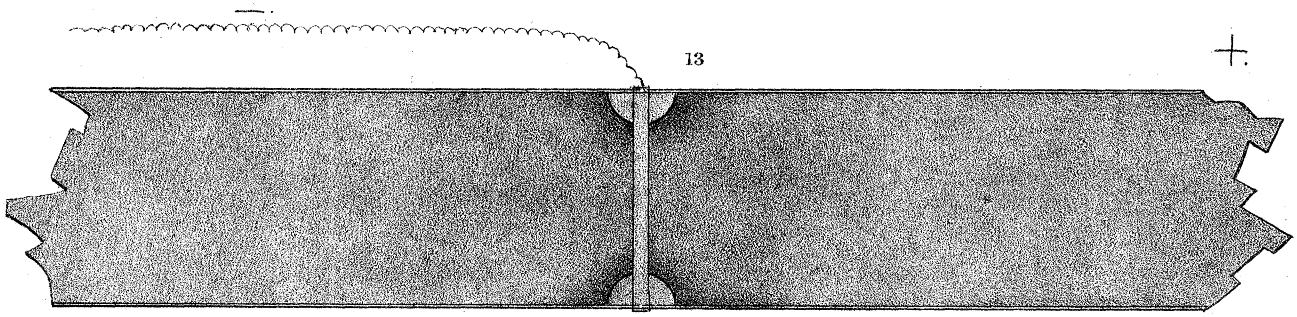

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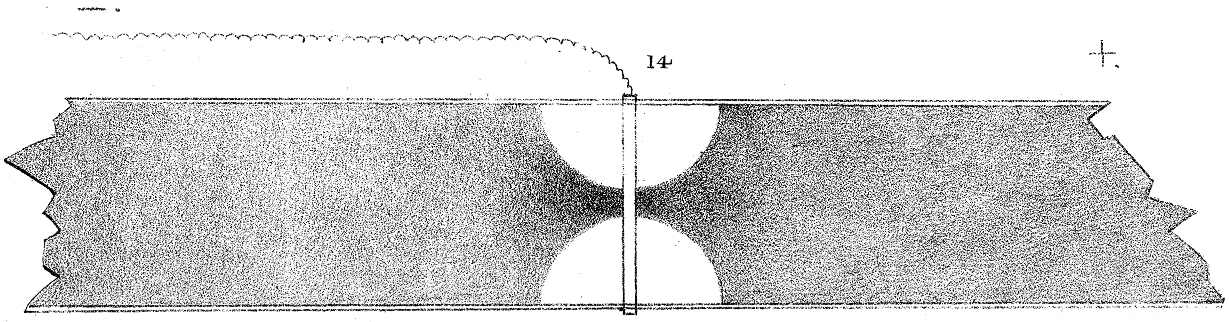

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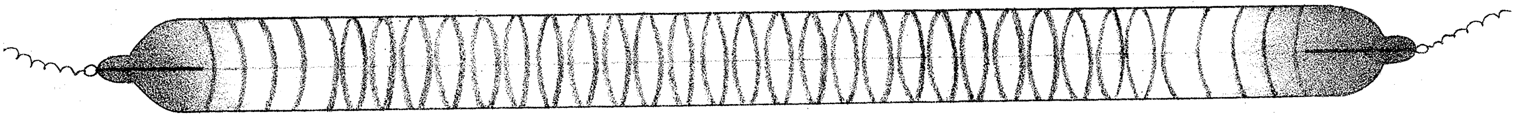

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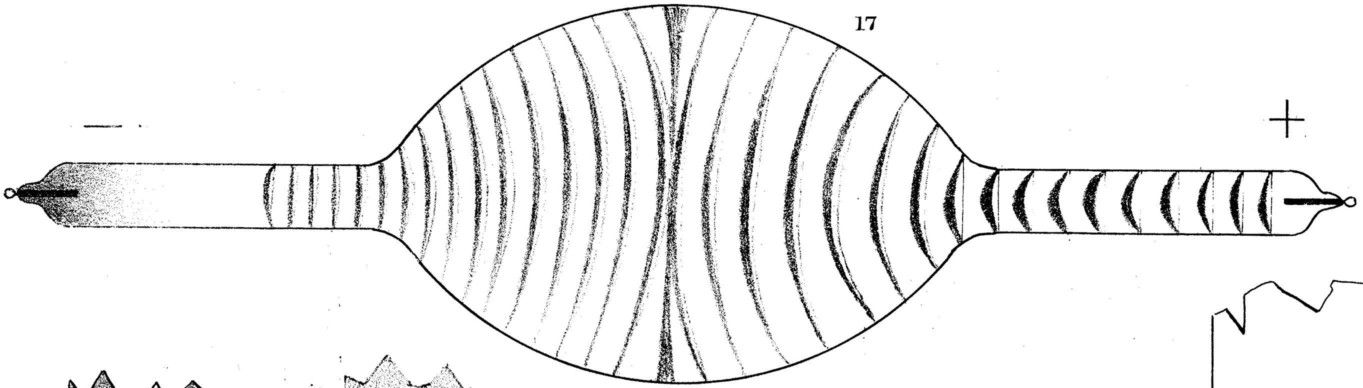

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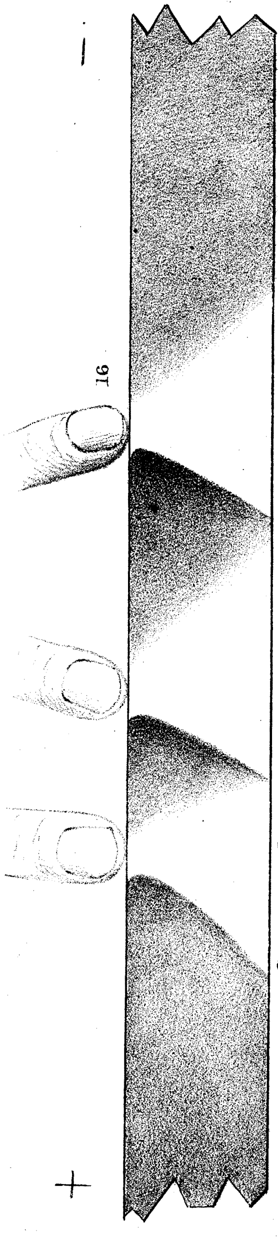

Striæ with small coil — negative terminal to Earth.

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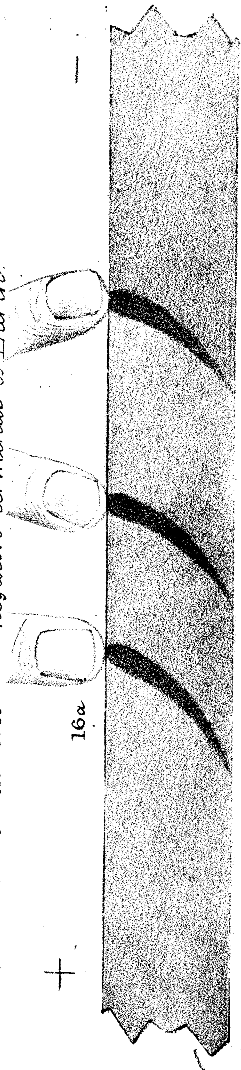

Striæ with small coil — positive terminal to Earth.

Reversed!

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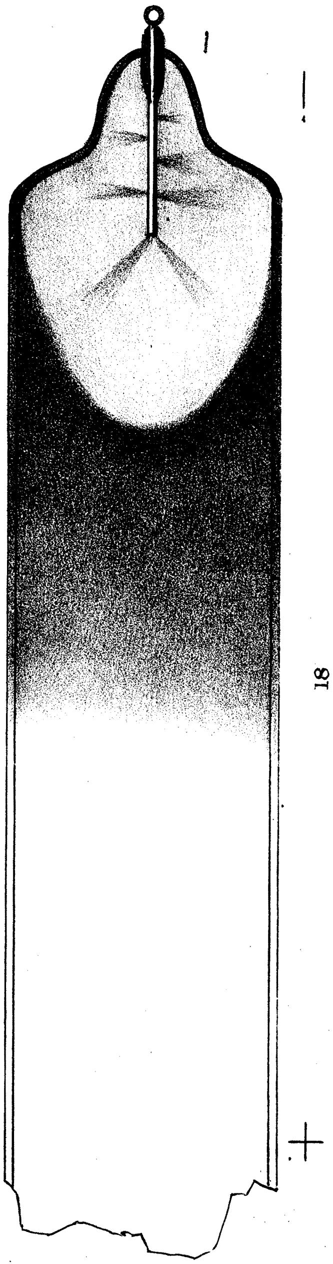

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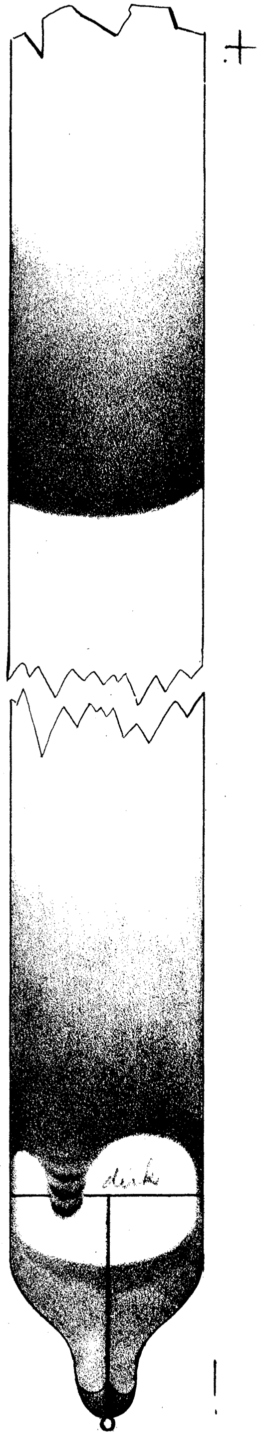

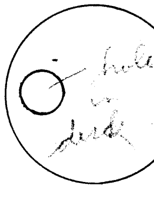

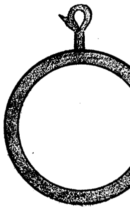

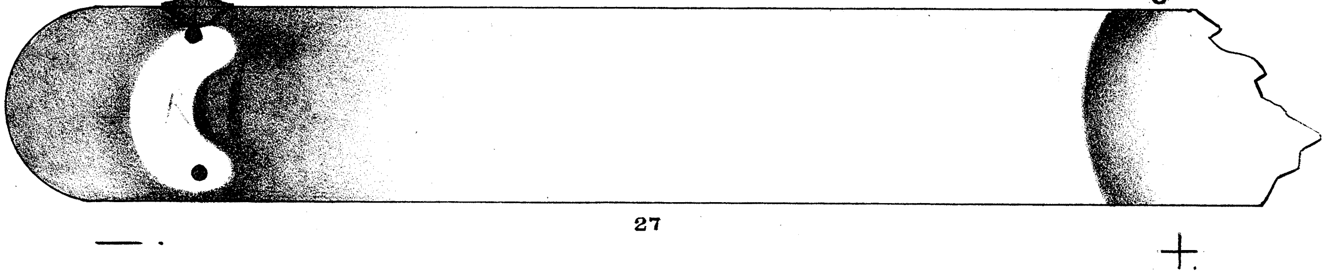

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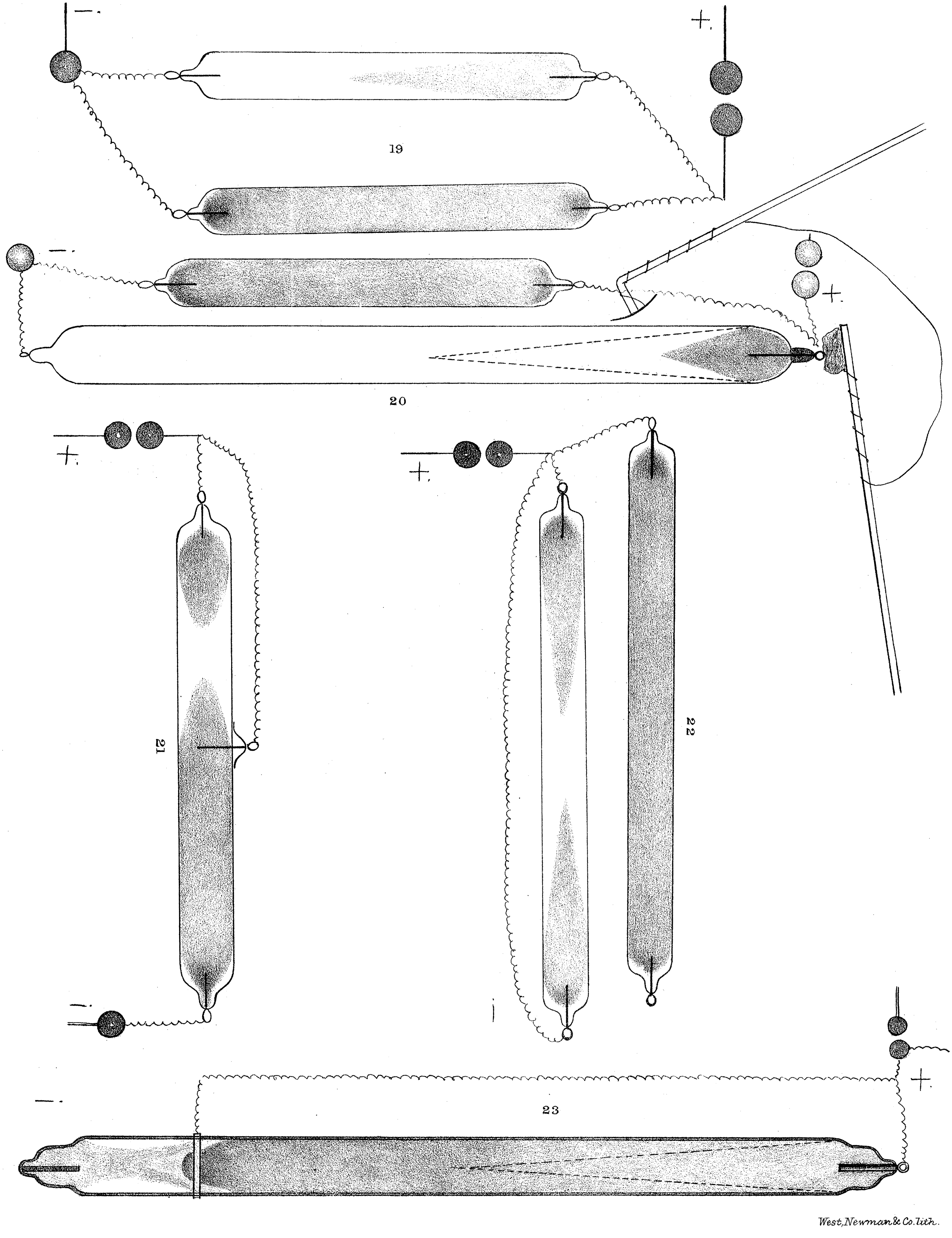
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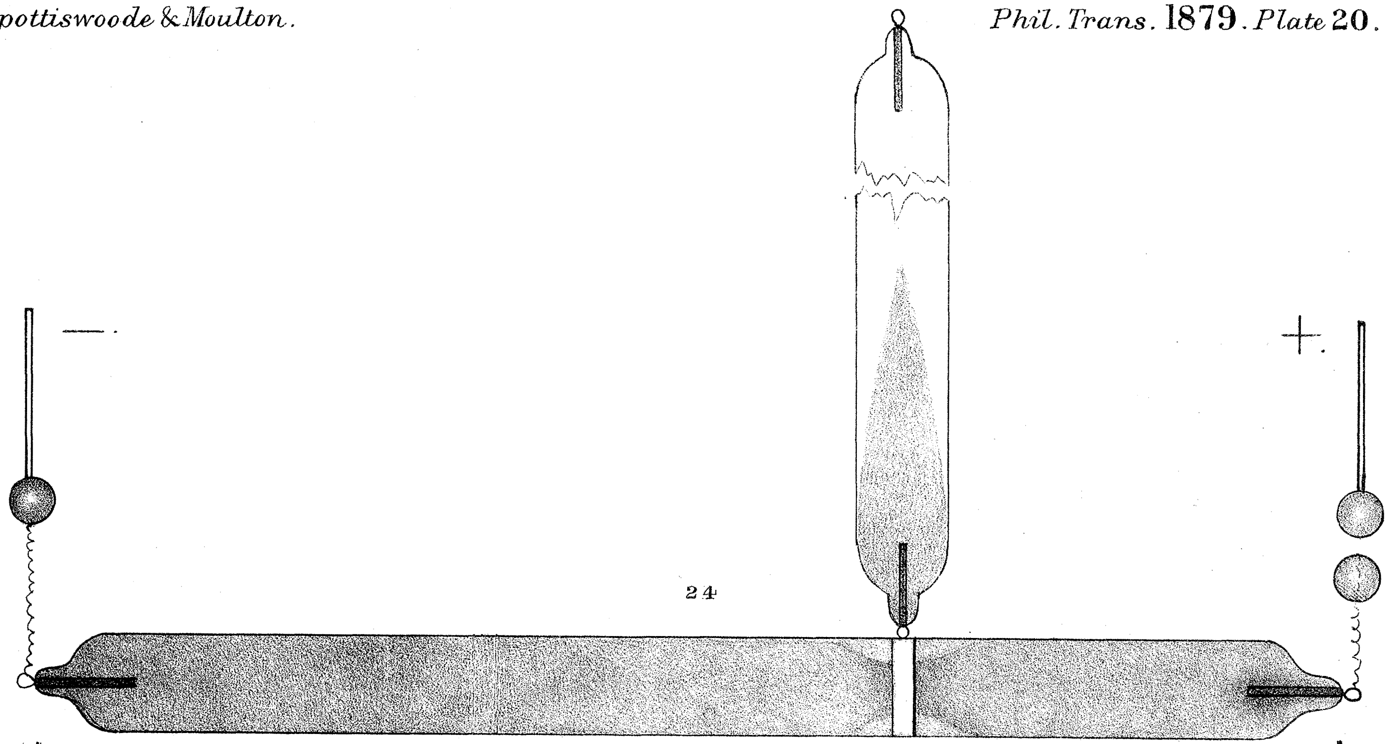

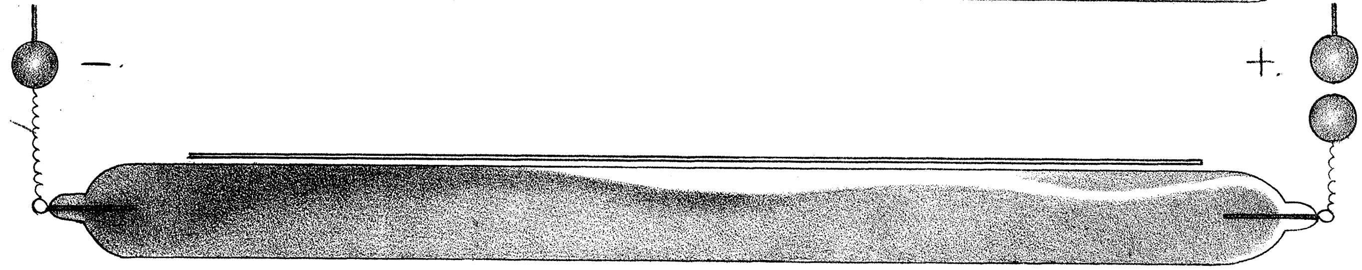

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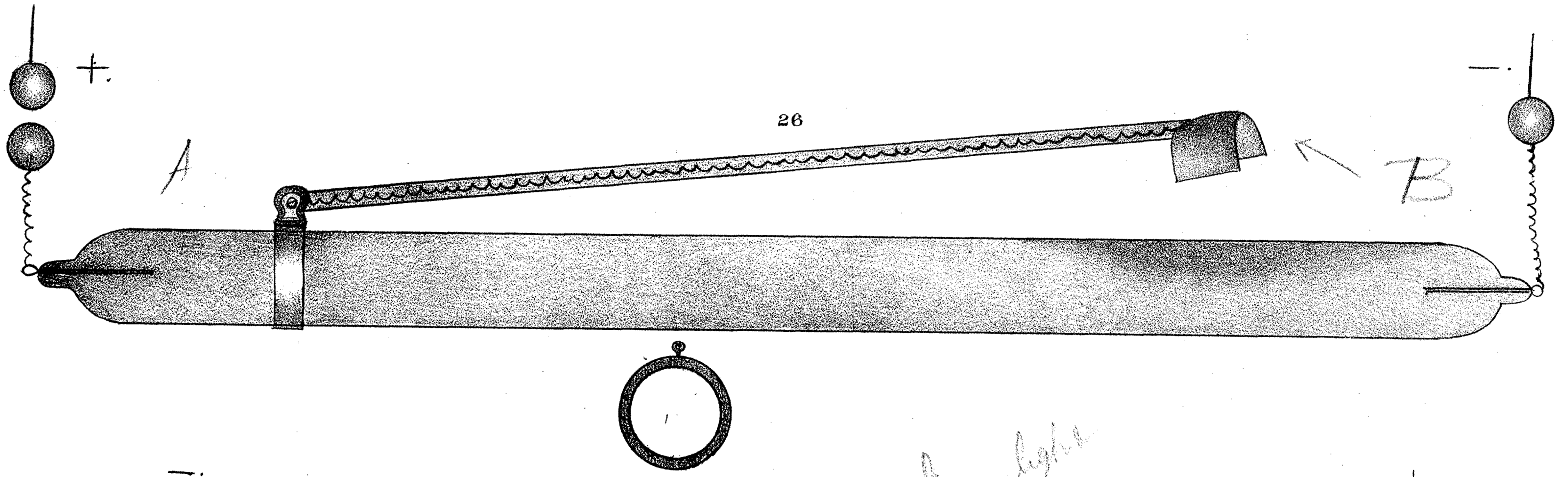

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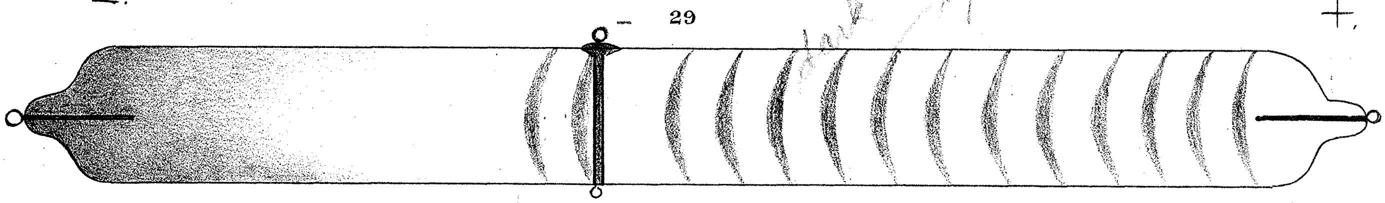

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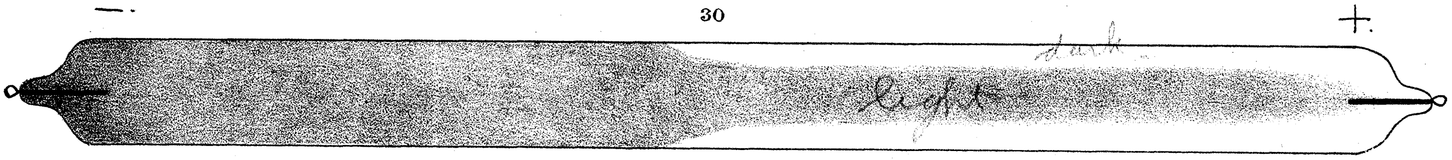

West, Newman & Co. lith.