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PLASMOIDAL HIGH-FREQUENCY OSCILLATORY DISCHARGES IN "NON-CONDUCTING" VACUA

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Abstract

Plasmoidal discharges. A new type of vacuum tube discharge is described, excited by comparatively low voltage high-frequency oscillations (1.7 meters up to 30 meters wave-length) in which remarkable luminous balls, spindles and pear-shaped bodies are formed. These have been reported in earlier papers in Nature and the Phil. Mag. A study of the conditions under which these bodies are formed and their behavior in magnetic fields has lead to the conclusion that surface charges play a part in their formation. They have been shown to be built of excited molecules, as their spectra are molecular band spectra (O_2 or CO) and since Langmuir has seen in their formation the possibility of plasma oscillations, such as he observed in the mercury arc; they have been named "plasmoids" provisionally.

Red phosphorescence of the glass wall. This occurs in all of the tubes containing oxygen at very low pressure. It appears to be due to low velocity secondary electrons in combination with excited oxygen. Its behavior in magnetic fields has been studied, and it appears when a plasmoid is deflected against the wall by a magnet. The red phosphorescence does not appear until after the high frequency discharge has operated on the glass for some minutes, becoming finally a bright ruby red. The same glass surface phosphoresces green under the impact of high velocity electrons given off from the inner surface of the glass when the external cathode is excited by higher voltages. It may happen that superposed streaks of red and green phosphorescence may occur simultaneously and they can be separated by a magnetic field.

Clean-up effects. Remarkable clean-up effects have been observed, it being possible to have a tube sealed off from the pump which can be made to show either a pure Balmer spectrum of atomic hydrogen (purple discharge) or the green discharge of molecular oxygen. The pressure changes occurring in the sealed off tubes as the type of spectrum changes have been followed with a vibrating quartz fiber manometer.

Spectroscopic investigation. The spectra of the plasmoids, their dark sheaths, and the less luminous gas in which they are imbedded have been investigated by projecting their images on the slit of a spectroscope. The band spectrum of molecular oxygen is seen in the whole tube, but is concentrated in the plasmoids and diluted in their dark sheaths; atomic lines appear as well, the local concentration being different for singly and doubly ionized oxygen.

General nature of discharge. There are two types of discharge, one at very low potentials, suggesting the Townsend discharge (unmodified by space or surface charges) and a more brilliant one which comes in suddenly as the potential is gradually raised. Plasmoids, however, appear to form with both types, though their shape and distribution in the tube changes as we pass from one type to the other. External electrodes are used in all cases.

IN THE Philosophical Magazine for October, 1929, I gave a short account of some phenomena exhibited by very highly exhausted tubes, excited through external electrodes by comparatively low voltages, at a frequency corresponding to a four meter wave. References were made in this paper to earlier work by Kirchner, who first drew attention to the circumstance that, what is usually called a non-conducting vacuum, is excited to bright luminosity by these very high frequencies at comparatively low potentials. During the past autumn I have made a more careful study of these discharges with an oscillator having a wave-length of 1.75 meters built by A. L. Loomis at his laboratory in Tuxedo, New York, and later on in my own laboratory with other oscillators and sources of high potential. The investigation concerned the general nature of the discharges, their behavior in magnetic fields, and the spectra emitted by them, as well as the very remarkable "clean-up" effects shown.

In the earlier paper reference was made to the curious luminous bodies, balls, spindles and pear shaped forms, which usually appeared in the tubes, and it was shown that these luminous masses were formed of singly ionized molecules, either of oxygen, showing the band spectrum, or CO showing the so called "Comet-tail" spectrum, now known to be due to singly ionized CO molecules. Kirchner's original theory to explain the production of a luminous discharge with a potential of only a few hundred volts in a vacuum impervious to the potential of a large induction coil, was that, at these high frequencies, the electrons made "to and fro" excursions ("pendelt") under the rapidly alternating electric force, increasing enormously their chance of ionizing the rarefied gas by collisions.

While I feel convinced that an oscillatory motion of the electron takes place in the discharges, it appears probable that the matter is more complicated than imagined by Kirchner, for the discharges occur equally well when the position of the electrodes and the dimensions of the tube are such as to make these long to and fro excursions impossible.

It seems highly probable that the comparatively heavy ions remain practically at rest, and the circumstance that the luminous bodies are shown by the spectroscope to be built-up of ionized molecules, while the less luminous regions show atomic line spectra, made it appear probable that a careful study of the movements of these bodies under magnetic and electric forces would throw some light on the nature of the discharge.

It is very probable that surface charges on the glass play a large part, for as I showed in an earlier communication, the deflection of the electrons by a magnetic field, as indicated by the movements of the ruby red phorescence patches on the inner wall indicated electrons moving away from the electrodes in their vicinity, and towards the electrodes at the opposite ends of the tube, the electrodes being near the middle. The end of the tube acted as if it had become a secondary cathode. Surface charges are also indicated by the curious circumstance that if the tubes fail to respond to the oscillator, they usually light up immediately if brushed once with a bunsen flame, or even if a lighted match is brought close to them. We thus have a vacuum tube which can be lighted with a match! I have frequently observed the discharge initiated by striking a match at some distance from the tube the effect being due probably to a modification of the surrounding field. In the earlier work sufficient care was not taken to insure a clean inner surface of the tubes, and the presence of CO masked the clean cut effects obtained in the present vork.

We will now consider briefly the phenomena exhibited by one of the tubes during the process of exhaustion and subsequently. A tube of soft glass 2 cm in diameter and 30 cm long is blown round at one end, drawn down at the other for sealing, and exhausted with a Holweck molecular pump. The wires from the oscillator are wound once around the tube, forming ring electrodes. The character of the discharge is profoundly modified by very slight changes in the position of the electrodes as will appear presently. The tube was very carefully cleaned with a boiling solution of KOH followed by chromic acid before sealing it to the pump. When the discharge is first started the spectroscope shows a mixture of nitrogen and hydrogen, the former disappearing as soon as the tube is heated, the water-vapor liberated from the glass driving out the nitrogen. At first the color of the discharge is pink, and the spectroscope shows the secondary spectrum of hydrogen as well as the Balmer lines, but after ten or fifteen minutes of operation, the tube being strongly heated from time to time the color changes to the "fiery purple" characteristic of atomic hydrogen.

At this state it may happen, if the electrodes are properly placed, that the discharge shows periodic changes of intensity, along the tube, as shown in Fig. 1a.

The intensity change is not very marked in the case of hydrogen, but, as we shall see presently with only oxygen in the tube, we may have the condition shown in the lower figures, the spindle shaped luminous bodies giving an appearance suggestive of stationary waves. We may heat and pump continuously for an hour or two, no visible change taking place, the color remaining intense purple, and only the Balmar lines showing in the spectroscope. That we have a nearly pure atomic hydrogen (purple discharge) in a tube at very low pressure with well baked walls, is undoubtedly due to the fact that the very high frequency discharge keeps the hydrogen thoroughly dissociated into atoms. A low frequency discharge under these conditions is nearly white, with the secondary spectrum strong, due to the catalyzing action of the walls as shown in an earlier paper. If now the tube is sealed off from the pump and the discharge continued, a most remarkable change occurs in a few seconds. The color changes to pink and the spectroscope or a direct vision prism shows that the oxygen bands in the red-green part of the spectrum are developing rapidly and the Balmer lines fading away. In two or three minutes the last trace of hydrogen vanishes, and the color of the discharge is now bright green. It is important to note that the transition from pure hydrogen to pure oxygen occurs only after the tube has been sealed from the pump, which means that a slight rise of pressure is necessary. An explanation of this very remarkable behavior will be given presently. If the tube is joined to the pump by a fine capillary, the oxygen may develop before the sealing off process, for the pressure in the tube will be higher in this case than with a wider connecting tube. The green luminous bodies are now strongly developed and their position and shape alters with every change in the position of the wire ring electrodes, a change in position of one of them of only a millimeter, giving a complete redistribution as shown in Fig. 1, b and c.

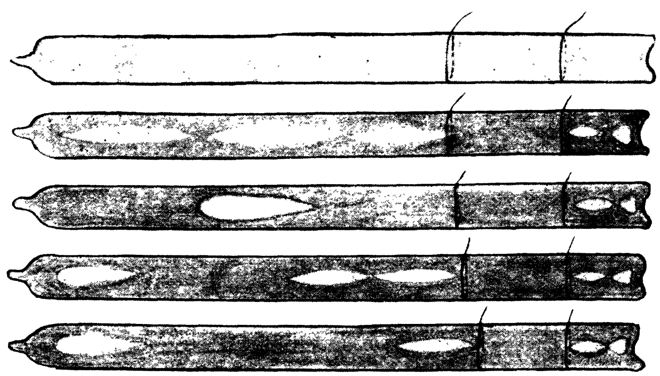

Fig. 1. Appearance of plasmoidal discharges under various conditions.

The tube shown in Fig. 1, b-c was flattened at one end and sucked in, producing a dome shaped bottom, like a wine bottle. This was done to see whether the form of the luminous body would be affected by the contour of the inner surface. A flattening of the green spindle was observed, as shown in the figure. An attempt was made to determine the effect of a change of length of the tube, with fixed electrodes by means of a sliding partition, (a short glass tube closed at one end which fitted snugly within the discharge tube) but a discharge formed on each side of it. A tube was then made with a glass partition fused within it, at the center, each half being exhausted separately. With ring electrodes near one end ,*both* compartments were excited to equal luminosity, i.e the glass partition served as an electrode quite as well as the wire rings. The excitation of the second compartment was not due to a stray field, as it appeared only when the wire electrodes encircled the other end of the tube.

The glass near the electrodes phosphoresces with a ruby red color, which is very intense, if the tube has been well baked and thoroughly exhausted. If the baking has been less complete the phosphorescence may not appear.

In this case the green discharge is usually brighter, but the spindles and balls are less pronounced.

Red Phosphorescence of Glass Wall

The red phosphorescence of the glass walls of electrically excited vacuum tubes appears to have been first noticed and studied by Lilienfeld whose papers will be found in the Verh. der Deutsch. Phys. Ges. for 1906–1907. It was observed independently by the author some years later in the long tubes used for extending the Balmer series of hydrogen when oxygen was admitted to them. Gehrke and Reichenbeim attributed it also to oxygen, while Lilienfeld considered it due to slow cathode rays, associated with some other undetermined factor, and from certain observations on the magnetic deflection, considered the hypothesis of positive electrons.

In my own study of the subject with tubes excited in a very different manner from that employed by Lilienfeld and, at the time, in ignorance of Lilienfeld's observations, I arrived at first at quite similar conclusions, and frequently remarked that things would be much simpler of explanation if we could admit the existence of positive electrons! Further study however showed that these were not required, and I believe that progress has been made towards the solution of the mysterious red phosphorescence, though there are still points that require further investigation.

In the first place it has been found that high speed electrons, from a single exterior electrode showered with high potential sparks produce a green fluorescence of the glass in tubes containing oxygen at low pressure, the red phosphorescence being produced by electrons of probably lower velocity, when the electrode is attached to one pole of the high frequency oscillator, operating at comparatively low voltage. In this case no green phosphorescence is observed, but in the former case red phosphorescence in general appears in regions of the tube bombarded by secondary cathode rays of presumably lower electron velocity. I feel convinced also that the presence of excited oxygen molecules in contact with the glass walls is also necessary as will appear presently. This may be the unknown factor mentioned by Lilienfeld.

The glass, moreover, must be acted upon by the discharge for some seconds or minutes before the red phosphorescence appears. In one case a streak of green phosphorescence appeared when the discharge was first started, the color changing to red after a few seconds of operation. If the tube was then rotated on its long axis, so as to bring an "untreated" portion of the glass into the electron stream, the green color appeared again, changing presently to red as before.

If a bright discharge is produced at one end of the tube with a single ring electrode until the glass phosphoresces with a red color, and the ring is moved to the other end of the tube, we have no phosphorescence there, although the discharge is of the same character as before. It is evidently associated with a chemical alteration of the glass.

Character of Discharge and "Clean-up" Effects

The duration of the exhaustion, the amount of baking of tube while on the pump, and the operation of the discharge during the pumping, profoundly influence the subsequent behavior of the tube. With a tube of soft glass joined to the pump by a wide capillary (2 mm) the pumping was continued for 3 hours, during which time it was heated with a bunsen flame about twenty times. The discharge was operating most of the time, the color being intense purple (pure atomic hydrogen). When sealed from the pump, the spectrum changed to one of pure oxygen with about ten minutes of operation. After standing over night the discharge, when first started, was again fiery purple, only the Balmer lines showing, which presently faded away and were replaced by oxygen bands and lines, the color changing to green. This process was repeated over and over again, the transition from oxygen to hydrogen, being accomplished in many cases in a minute or two by heating the tube. We thus have a tube with which we can demonstrate either the spectrum of atomic hydrogen or molecular oxygen at will! With continued repetition of the experiment it was found more and more difficult to obtain the hydrogen stage, and the tube finally reached a condition in which only oxygen bands were shown, and the character of the discharge indicated a higher pressure. Heating the tube caused a momentary trace of the hydrogen lines with the oxygen bands but they faded in a few seconds.

I believe that this behavior may be explained as follows. While the tube is on the pump the oxygen and hydrogen formed by the dissociation of water-vapor coming from the glass, are continuously removed allowing fresh water-vapor to come out of the walls. The spectrum is therefore the line spectrum of hydrogen, which always appears with a discharge in water-vapor at low pressures. A few oxygen lines of relatively feeble intensity appear as well.

If now the tube is sealed off from the pump the pressure rises until a point is reached at which no more water-vapor escapes from the glass, and the hydrogen, formed by the discharge is driven into the glass by the discharge, leaving pure oxygen in the tube. This results in a lowering of the pressure, so that more water-vapor can escape from the wall, if the tube is allowed a rest of a day or two, or heated slightly and we again get the hydrogen lines, until all of the freshly formed hydrogen has been driven back into the glass. Repeating the process over and over again gradually raises the pressure of the oxygen in the tube, water-vapor escapes in smaller quantities and it becomes increasingly difficult to get the hydrogen spectrum as has been mentioned. The alternative explanation of the slow return to the hydrogen state would be to assume that it is the hydrogen and not water-vapor that comes out of the glass. If this were so, the gradual rise of pressure with repetition of the experiment would not occur. A different sequence of events was observed in tubes very thoroughly baked out in an electric furnace.

A tube of Pyrex glass, baked during the pumping operation, at a dull red heat for over an hour in an electric furnace behaved quite differently. This tube was not excited electrically during the exhaustion. When first subjected to the potential of the oscillator there was only a very pale violet discharge, almost invisible. Red phosphorescence of the glass developed in a few minutes and presently a pale green ball (oxygen) appeared between the electrodes. Heating the tube caused the discharge to become brighter, and balls and spindles of green luminosity appeared but the hydrogen spectrum never appeared.

Study of Pressure Changes in "Sealed Off" Tubes with Quartz Fiber Manometer

It was obvious that a careful study of the pressure changes within the tube during these transitions was most important, and a number of tubes were prepared with quartz fiber manometers, (as used by Haber and Langmuir) by which the changes of pressure within the tube as a result of heating, electrical excitation, and repose could be followed.

These manometers are very easy to prepare, no graded seal being necessary. We have only to draw a fiber 8 or 10 cm long by hand (diameter about that of a very fine hair) drop it into the tube which has a round bottom like a test tube, heat the bottom to the fusing point and then quickly invert the tube, holding it vertical. The fiber will swing to the axis of the tube and remain firmly fixed to the glass. If it is off center, hold the tube horizontally and gently heat the glass at the point of attachment with a small flame until the fiber has sagged to the proper position. The fiber is illuminated by a lamp placed at the side and viewed through a low power microscope with micrometer eye-piece. By gently tapping the tube the fiber is thrown into vibration, and the time for the decrement to half amplitude taken with a stop-watch.

With a tube of soft soda-glass sealed off from the pump, after a one-hour pumping with the discharge operating continuously and repeated heatings (up to the appearance of the D lines of sodium) the color was fiery purple and the spectrum that of atomic hydrogen. This indicates water vapor at low pressure in the tube. The vibrating quartz fiber sank to a half amplitude value in 12 seconds. When on the pump the time for half amplitude decrement was 30 seconds. This showed that the pressure had risen after, or during the sealing off process.

The tube was now subjected to the high frequency discharge until the hydrogen spectrum was replaced by that of pure oxygen. The time for half amplitude decrement, which in future we will call H.A.D. was now found to be 30 secs, the same value as when on the pump. After operating for half an hour the time for H.A.D. had decreased to 15 seconds; showing that the oxygen pressure was increasing. The tube was now gently heated with a flame. Purple discharge of hydrogen and time of H.A.D. 7 seconds. Ran discharge until only pure oxygen spectrum. Time of H.A.D. 15 seconds, as before heating.

The inference from these observations is that, under the conditions of these particular experiments in which prolonged heat treatment was not given to the tube, water-vapor, liberated by heating the tube is completely "cleaned-up" by the discharge, while oxygen formed by the action of the discharge upon the glass or upon water vapor contained within the glass does not "clean-up" but accumulates in the tube with continued operation. This is not the case with a tube subjected to long heat treatment.

With a Pyrex tube the following results were obtained. At the start the spectrum showed both hydrogen lines and oxygen bands. Time of H.A.D 25 seconds. Heated until discharge white (Balmer lines and band spectra of hydrogen). Time of H.A.D. 4 seconds. We now have a relatively high pressure of water-vapor in the tube. Operating for 1 minute, time of H.A.D. 15 seconds. Operating for 5 minutes, time of H.A.D. 25 seconds. Oxygen spectra only. This indicates that *most* of the oxygen and all of the hydrogen of the original water-vapor present is driven into the glass by the discharge.

With a Pyrex tube baked in a furnace at a dull red heat, with the Holweck pump operating, for over an hour, the time of H.A.D. of the fiber was four minutes and 30 seconds! Discharge at first pale violet, with faint pink fluorescence of the glass. Red fluorescence developed in five minutes with faint green glow of oxygen in the tube. The time of H.A.D. was now 45 seconds. The elimination of water-vapor was evidently fairly complete in this case. Three days later the time of H.A.D. before starting the discharge, was found to have increased to 65 seconds. With the discharge operating the time was 90 seconds, and after running for half an hour it was back to 65 seconds. After 2 1/2 hours of operation by the discharge the time increased to 5 min. 40 secs., indicating a pressure as low as, or lower than when the tube came off the pump. After the lapse of several weeks, the oxygen discharge was strong (green plasmoids) and the time of H.A.D. was eight seconds, which changed to 45 seconds after a one minute operation on the five meter oscillator.

These results show that in a well-baked out tube the oxygen "cleans-up" but that it appears again after the tube has stood for some time, or been subjected to heat. The liberation of oxygen by heat and its rapid "clean-up" by the discharge can be repeated over and over again. Nitrogen and neon, introduced into the tube were rapidly cleaned-up.

General Nature of the Discharge

Langmuir, from his study of the oscillations which occur spontaneously in a mercury vacuum arc excited by a low voltage direct current, developed a theory based on the hypothesis that a cloud of ions served as a medium in which electrons could oscillate to and fro with a frequency dependent on the density of the ions (i.e. the number in unit volume). A region filled in this way with ions and electrons he called a "plasma," and he suggested to me that very probably the pheonomena shown by my tubes were closely related to those which he had observed with the mercury arc. The circumstance that the spectroscope shows that the luminous balls, spindles and pear shaped bodies are made up of singly ionized molecules, identifies them with Langmuir's plasma, (at least this is a plausible hypothesis to make), and on this account I propose, for the present at least, to call them *plasmoids*.

Before taking up in detail the subject of the type of discharge in which the plasmoids are formed, it will be well to consider some effects observed in the same tubes when operated by high potentials of lower frequency, as with hammer interrupter, or intermittent in which the character of the discharge is quite different. Some of the phenomena manifested can be considered to advantage in any effort to formulate a theory of the "plasmoidal" discharges.

Discharge by "Leak-Tester"

This apparatus, sold for therapeutic purposes, and used in physical laboratories for hunting for leaks in vacuum systems, generates a rapidly alternating intermittent potential sufficient to produce a shower of sparks an inch or more in length from its single terminal to any earthed conductor. Excitation of the highly exhausted tubes by this apparatus results in phenomena quite different from those observed with the high-frequency sets.

If the single electrode is applied to the under wall of the tube near one end a patch of green fluorescence is observed above it, and two strips of *red*

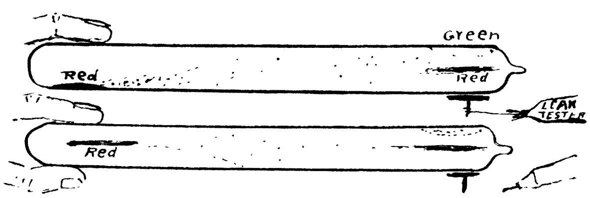

Fig. 2. Red and green phosphorescence patches. Low frequency excitation.

phosphorescence appear along the sides of the tube half way between the electrode and the green patch as shown in Fig. 2. Figs. 2, 3, 5, 7, 12, 13 and 14 are reproduced as "negative" i.e. bright parts of the discharge are black.

If the finger is touched to the upper wall at the opposite end of the tube, a patch of red phosphorescence appears below it on opposite wall. If the thumb is then applied to the wall over the red patch, two red streaks appear on the sides of the tube, half way between the thumb and finger, and if a third finger is applied over one of these it disappears at once and the remaining red streak in the opposite side becomes much brighter. These effects indicate that the red phosphorescence is caused by a discharge of some type, which initially filled the tube uniformly, but which is driven away from those parts of the wall which are "grounded" by an exterior electrode (the finger) and forced against the opposite wall. The depressed "discharge" appears as a faint green glow.

As a substitute for the two fingers and the thumb I wound a "grounded" strip of aluminum around three quarters of the circumference of the tube. The bright red streak appeared along the center of the gap and extended along the wall down the tube towards the electrode. Fig. 3, a.

If a wire, *W* held between the fingers, was brought up towards the red streak from below, the streak was deflected upwards spiraling around to the back of the tube Fig. 3b, while it was deflected downwards if the wire point was brought down from above. If the wire was touched to the outer wall exactly over the center of the red streak, it "forked" into a *Y*, the two branches curving around the wall and uniting at the back. Fig. 3c, very much as would a thin jet of water squirted along the inner wall, and divided into two jets by a small obstacle. The wire had little or no effect if brought up to the red streak in the region of the gap in the aluminum cylinder.

The red streak was also deflected by a magnetic field, upwards or downwards according to the direction of the field. Care was taken to ensure that this deflection was due to the field and not to the mere approach of the metallic mass. The direction of the deflection indicated electrons moving along the inner wall from left to right, i. e. *towards* the electrode.

The deflection by the magnetic field occurred only for that portion of the red streak beyond (to the right of the cylinder). The portion lying between the opposed edges of the 3/4 cylinder appeared to be held firmly fixed in posi-

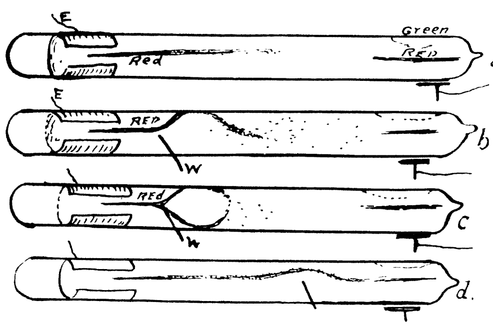

Fig. 3. Deflection of red streak of phosphorescence by grounded wire.

tion by electric forces, while the portion outside was free to move under the influence of the force applied by the magnetic field.

It is worthy of comment, in connection with the forking of the streak into a *Y*, when the point of a wire is placed over it, that the repulsive force due to the wire apparently exerts no influence on the electron (?) stream producing the red phosphorescence streak until it reaches the point immediately under the wire, and that the stream is not driven away from the glass wall towards the axis but merely divided laterally into two streams, which spiral around the tube wall in opposite directions, meeting on the opposite side.

The stream thus appears to have a tendency to stick to the wall, once it has been brought into contact with it by the electric forces set up by the grounded cylinder of aluminum.

In another tube in which the pressure was higher (?) the red streak was bent into an arc by the approach of the wire, i.e., the deflection occurred only in the neighborhood of the wire, as shown in Fig. 3, d. It seems possible that, in this case electron streams from opposite ends of the tube were uniting at the point near the wire. In this case the streak extended nearly down to the leak-tester and was more sensitive to the approach of an earthed conductor. It was also possible to drive it off the wall entirely, by the approach of an earthed conductor directly above it. A very important observation was made with another tube fitted with the three quarter cylinder of aluminum, and excited at the other end with the leak tester.

The streak of phosphorescence of yellowish color extending out from the gap in the cylinder towards the electrode, appeared to be a mixture of both types, green and red superposed, the latter more easily deflected by the wire or magnet. As the wire was brought up, the red streak was pushed aside, leaving a green streak almost undisturbed, and the same thing could be accomplished with a magnet. When the two streaks were thus separated the original yellow color vanished, being decomposed into its constituents pure red and green. This seems to indicate that we have high velocity electrons giving the green streak, and low velocity electrons, in conjunction with oxygen, giving the red streak. The green streak was visible only in the immediate vicinity of the aluminum cylinder, while the red one extended down the tube nearly to the electrode. If the wire were approached to the tube immediately above the red streak near its end (i.e., at a considerable distance from the gap in the cylinder) it could be made to disappear from the wall and reappear on the opposite wall, the electron stream having been pushed across the axis of the tube. If however the wire was brought up at a point nearer the cylinder the deflected electron stream clung to the wall, curving around the inner wall as a spiral, as has been shown previously (Fig. 2, b).

Excitation by 30 Meter Oscillator

The excitation in this case was brought about by simply holding the tube partly within the large coil of copper ribband carrying the oscillatory current. Two large green plasmoids were formed, one at each end, with sharply defined rounded ends facing the ends of the tube and fading away gradually towards the center which were repelled by bringing up the finger to the wall. The tube contained only oxygen at fairly low pressure, but there was no red phosphorescence. On pushing the tube entirely within the coil the discharge vanished, showing that it had been excited by the electric field outside of the coil and not by electro-magnetic induction.

The same tube excited by the "leak-tester" showed only green phosphorescence of the glass with no trace of red. The tube was then excited by the two meter oscillator, and red phosphorescence developed in two or three minutes, accompanied by formation of green plasmoids. This result was due to a partial clean-up of the oxygen i.e., the vacuum was improved.

On exciting again with the leak-tester a red phosphoresence mixed with green in an irregular manner was obtained.

Introduced once more into the coil of the 30 meter oscillator, the projecting end being held with two fingers and the thumb, a single plasmoid formed, tapering to a point on the side towards the finger, and rounded on the end towards the coil. A streak of red phosphorescence formed on the glass extending from the region between, but not covered by the fingers, to a point opposite the tapered end of the plasmoid. If now the end of a wire held in the fingers was brought up to the wall on the side opposite to that on which the red streak had formed, and near the pointed end of the plasmoid, the latter turned up and joined the red streak, i.e., it was repelled by the wire.

It seemed probable to me that the red streak produced by grasping the tube with the fingers was produced in each case at those moments at which the opposite end of the tube was anode. In the case of the excitation by the leak-tester it will be remembered that red phosphorescence streaks were produced at each end of the tube Fig. 2, a and Fig. 3, a.

If the above hypothesis is correct, the red streaks should not appear simultaneously but in alternation. Examination of an ordinary Geissler tube excited by the leak tester in a waggled mirror showed that its polarity alternated in unison with the vibrations of its small "hammer-break," but the light of the red streaks was not bright enough for a conclusive test in this way, the single images seen in the mirror being rather feeble. A stroboscopic method was therefore adopted, by which the tube could be observed at rest and continuously.

Stroboscopic Examination of Discharge

The tube was excited by connecting a single ring of wire, wound around one end of the tube with one pole of a 20,000 volt (60 cycle) transformer. The other end was furnished with an earthed three-quarter cylinder of aluminum foil, as before.

Red phosphorescence appeared close to the ring, and as a red streak in the gap of the cylinder. The tube was viewed through a slot in a card-board disk mounted on the shaft of a synchronous motor operated on the same 60 cycle circuit as the transformer. Only one red patch could be seen at a time, the one visible depending upon the position of the eye as it was moved around the circumference of the disk. This experiment appears to prove that in all of the experiments, in which, with a single electrode at one end of the tube, we have electrons moving from the other end towards the electrode, the motion occurrs only at the moments at which the electrode is anode. This applies also I believe to the high frequency experiments, in which plasmoids are formed, and should be taken into account in framing a theory of the formation of the plasmoids. Experiments were also made to ascertain how low a frequency would produce a visible discharge.

If the tube were placed between the poles of a small Holtz machine, no luminosity whatever appeared within the tube, though the potential was high enough to cause sparks to jump around the wall. This same tube, on the five meter oscillator with a potential sufficient to give a spark of only half a millimeter or less, showed a brilliant green plasmodial discharge. A small rotating commutator was now made by pasting tin-foil strips along the edge of a disk of ebonite mounted on the shaft of a small motor. By means of this the steady potential of the Holtz machine could be converted into an alternating potential. Luminosity appeared within the tube with alternations as low as six per second and reached a maximum at about fifty per second. The discharge vanished as the speed of the commutator increased, for reasons which are not quite clear. Possibly the conductivity became so good that the machine could not build up potential.

The Plasmoids

The study of the plasmoids has been conducted along two quite different lines. (a) Their formation and the changes which they undergo when the form and position of the external electrodes are altered, and their behavior in magnetic fields have been very carefully investigated, with oscillators of different frequencies and with the gas at different pressures. (b) Spectroscopic data have been obtained in regard to the radiations emitted by the plasmoid, by its relatively dark sheath and by the more or less uniformly luminous gas in which it is embedded. It seemed probable that a determination of the distribution in space of singly and doubly ionized atoms and the singly ionized molecules, would be of help in ascertaining the physical processes involved in the plasmoid formation.

There appear to be two distinct types of discharge, one in which the luminosity of the gas is low and the other in which it is high. Plasmoids are formed in both cases, but the transition from one type to the other is abrupt.

This suggests perhaps a transition from a "Townsend discharge," to a glow discharge, space charges and charges on the wall being absent in the former, and the potential drop merely the normal drop from anode to cathode while the "glow discharge" results when ionization becomes more pronounced, and space charges are present.

The transition from one type to the other was well shown in the case of a very highly exhausted tube containing oxygen as the residual gas. It was furnished with two ring electrodes formed of single turns of fine wire wound tightly around the tube.

With the lowest potential capable of exciting a luminous discharge, a pale green disk shaped like a double convex lens appeared midway between the ring electrodes as shown in Fig. 4, a. As the potential increased the disk expanded to the form shown in Fig. 4, b, while a further increase of potential caused the sudden appearance in its place of a much brighter green plasmoid in the form of a prolate spheriod, Fig. 4, c. My first attempt to explain the formation of the plasmoids with their sharply defined smooth surfaces, was along the lines usually followed in accounting for the stratifications in gas discharges, namely that the plasmoid surface represented an ionization caused by electrons which had acquired the requisite velocity after leaving the cathode. This works out well for cases a and b of Fig. 4, for the equipotential surfaces of the ring electrodes are about as shown in Fig. 5 which is a cross section through the rings. At low potentials (as in Fig. 4, a) ionization does not result until the electrons have reached equipotential surfaces 1, and the lenticular luminosity appears in the region between them. At a slightly higher potential the electrons have acquired the requisite velocity when surface 2 is reached, and the region between these surfaces is luminous as in Fig. 4, b. The sudden production of the spheroidal plasmoid at a slightly higher potential may result in part from the formation of negative

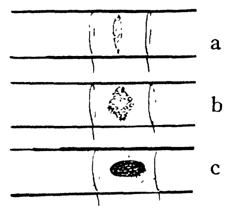

Fig. 4. Change in shape of the plasmoid with increasing potential.

charges on the tube wall between the electrodes, but the complete explanation in this case probably requires the introduction of other factors, such for example as the plasma oscillations imagined by Langmuir.

It appears possible that if we could apply a stroboscopic method to these very high frequency discharges we might find that the brilliancy at opposite

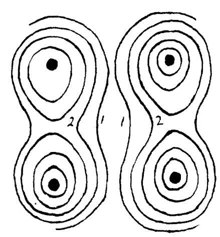

Fig. 5. Equipotential surfaces of ring electrodes.

ends of the plasmoid oscillated in unison with the discharge, i. e. the rounded ends facing the ring electrodes became luminous in alternation. My reason for considering this possible was the circumstance that in the case of a short tube excited by introduction into the helix of the thirty meter oscillator two plasmoids were formed as shown by Fig. 6. That these occur in alternation

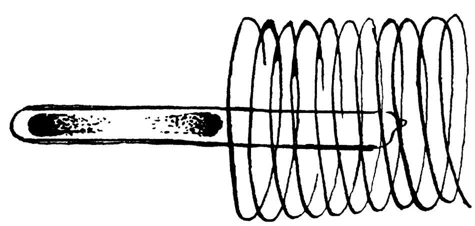

Fig. 6. Plasmoides formed with 30 meter oscillator.

and not simultaneously is indicated by the behavior of the discharge at low frequency as examined with the stroboscope. If now the conditions were such as to bring these plasmoids closer together we should have the single spheroidal plasmoid referred to above. The tube in which the lenticular and spheroidal plasmoids formed was excited with the 1.75 meter oscillator by means of two disk electrodes applied on opposite sides of the tube as shown in Fig. 7.

These give a field of simple type, which is easy to calculate, with a potential sufficient to give a spark about half a millimeter long. With a potential giving a spark perhaps half a millimeter in length a brilliant green plasmoid shaped like a double convex lens appeared midway between the electrodes and parallel to them. Fig. 7, a. The plasmoid was surrounded by a dark sheath and two dark arches covered the electrodes as shown in the figure. As the potential was lowered by reducing the filament current, the lenticular disk contracted, remaining very bright however, but suddenly was replaced

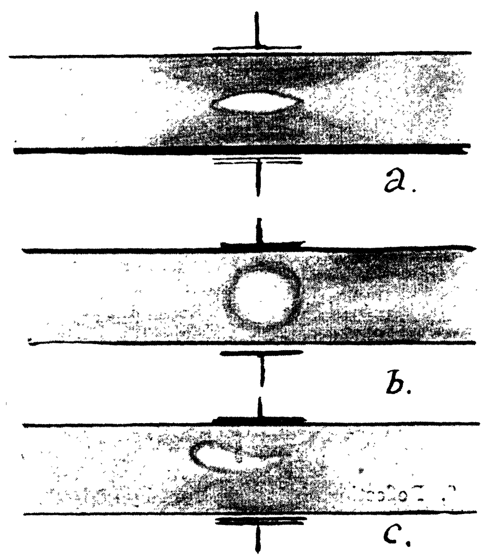

Fig. 7. Change in shape of plasmoids with decreasing potential and magnetic deflection of plasmoid (c).

by a sphere of low luminosity surrounded by a wide dark sheath. Fig. 7, b. If the pole of a small bar magnet was brought up to the wall, in the condition "a" the plasmoid was squeezed to one side and deflected upwards as shown in Fig. 7, c. The magnetic field was such as to deflect downward moving electrons to the left and upward moving ones to the right. The formation of the sphere and disk I am unable to explain.

The development of plasmoids at periodic intervals along the tube, as shown in Fig. 1, I was at first inclined to ascribe to a zig-zag reflection of the electrons from surface charges built up on the inner walls by electron impact. It seemed, however, highly improbable that such sharp localization could be produced in this way, or that a movement of one ring electrode through a distance of only one or two millimeters could cause such a change in the paths of electrons down the tube as to cause a complete redistribution of the plasmoids in space. Langmuir's theory that the plasmoids are oscillators having a definite frequency of vibration seems to be a much more promising line of attack.

Nevertheless, certain observations have been made which apparently show that a reflection in the manner imagined actually takes place. In a tube at very low pressure, containing only oxygen and excited by a single disk electrode placed close to the outer wall, the following phenomena were observed as the capacity of the condenser in the oscillatory circuit was increased from zero. It must be remembered that with the variable capacity set at zero, the circuit is practically interrupted and the potential is very low if oscillations are present at all. As the capacity is increased a patch of ruby red phosphorescence appears on the upper wall of the tube immediately over the disk, with an area considerably larger than that of the disk, and a second red patch on the lower wall of the same diameter as the disk, as shown in Fig. 8, a.

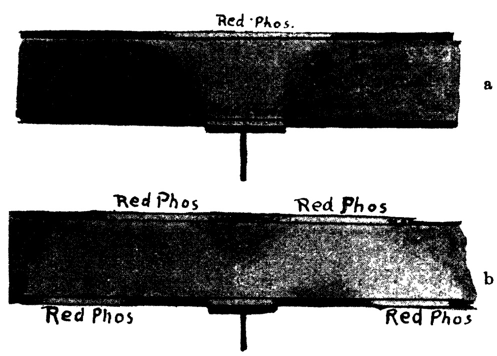

Fig. 8. Reflection of slow electrons by surface charge.

The only way in which I can account for the circumstance that the lower red patch exactly covers the region immediately above the disk electrode is to assume that some of the electrons moving along the lines of force, when the disk is negative fail to reach the upper surface before the field reverses and hence travel backwards along the reversed lines of force to their starting point.

The paths of the electrons through the gas is marked by a faint green luminosity. If the capacity is made slightly greater, which increases the potential, the upper red patch divides at the middle and spreads out, the glass ceasing to phosphoresce immediately above the electrode, and two new red patches appear in the lower wall as shown in Fig. 8, b.

The cause of the division of the electron stream over the electrode results perhaps from the formation of a negative surface charge immediately above the electrode, while the two lower red patches of phosphorescence, appear to be due to the downward deflection of the oblique streams of electrons by negative surface charges at the upper red spots. A slight further increment of capacity results in the sudden birth of two plasmoids to the right and left of the descending streams. The reversal of the electron stream alluded to above was also indicated in a vertical tube so highly exhausted that practically nothing but red phosphorescence was observed, (with a disk-electrode at the bottom). In the upper two thirds of the tube and at the bottom upward moving electrons were found, while a strong downward stream was indicated by the magnetic concentration of red phosphorescence about one third of the way up. This stream appeared to me to be due to the pulling back of the tail end of the upward electronic blast, when the disk became anode. This case will be alluded to again presently.

If the oxygen is at a slightly higher pressure and we gradually increase the capacity in the oscillating circuit, we get a quite different sequence of events, and can watch the birth of a plasmoid. With a moderate capacity the discharge has the appearance indicated by Fig. 9, a.

Its color is yellow-green of much greater intensity than in the previous case and there is a dark arch over the electrode. The upper wall shows a feeble red phosphorescence, indicating that some of the electrons succeed in reaching it. There are also indications of a segmentation at *A*, which is

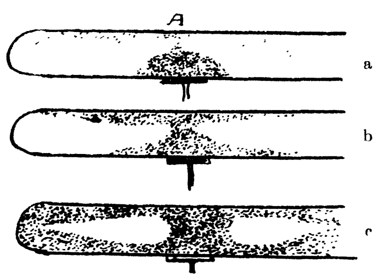

Fig. 9. Birth of a plasmoid.

destined to become the breaking point of the discharge when the plasmoid forms. If now a magnet pole is brought up from the side (of polarity such as would cause upward moving electrons to be deflected to the left) the portion *A* is squeezed to the left and a large and perfectly formed plasmoid develops Fig. 9, b and c.

With an oscillator of five meters wave-length, and a single disk electrode applied to the flat end of the tube the plasmoid development as the capacity of the condenser was increased is illustrated in Fig. 10.

The total capacity of the condenser was about 300 cm and the scale was graduated to equal divisions from 0 to 100. The capacity of the condenser is given below each figure. With the two smallest capacities, the discharge is of the first type and of a very feeble green color, the plasmoid having the shape of a spear-head.

Increasing the capacity to 11 causes a sudden increase in luminosity and two plasmoids form of the shape indicated. With capacity 16 the upper rounded end of the large plasmoid streams up to a point, and at capacity 20 a break to the brighter type of discharge occurs and two sharply defined plasmoids appear at opposite ends of the tube. Two rings of red phosphorescence appear immediately above and below the lower plasmoid, due probably to reflection of the electrons from charges on the tube wall, or possibly to the upward electron stream from the disk cathode and the downward stream which occurs when the disk becomes anode, a condition mentioned a moment ago. If a magnet pole is brought up to the lower plasmoid, both plasmoids contract and disappear at the same moment, but if the magnet is brought up to the upper one it contracts and vanishes but the lower one remains unaffected.

I think it highly probable, in view of the stroboscopic experiments previously described, that the two plasmoids appear in alternation as the field reverses, the upper plasmoid appearing as a result of a negative charge on

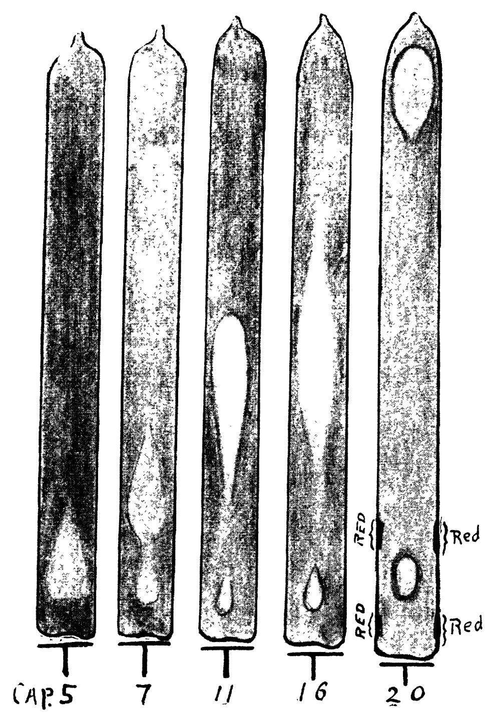

Fig. 10. Plasmoid formation with increasing potential.

the wall of the tube above it, at the moment when the electrode becomes anode. The application of the field at the lower end prevents the electrons, in part at least, from reaching the upper end of the tube, and this probably is responsible for the contraction and disappearance of the upper plasmoid.

The effects of a magnetic field on the plasmoidal discharge is very complicated, due, probably to the circumstance that we have electron streams moving in opposite directions but with different velocities at the same point in the tube. These streams do not of course occur at the same instant but in alternation as the polarity of the oscillator reverses, and they will be deflected in opposite directions by the field. This two-fold deflection is often observed at the center of the tube.

The magnetic field, in some cases, causes the plasmoids to shrink and disappear, in others it causes the birth of plasmoids where none existed previously. It has been found extremely difficult to systematize the multitude of different effects observed, or draw any very definite conclusions from them, and only a few selected examples will be given. The others will be kept on record, as they will be of value in testing any theory of plasmoid formation that may be developed subsequently. It will be best to begin with what appears to be the simplest case, a tube containing oxygen at such low pressure that scarcely any trace of plasmoid formation occurs. The pale green discharge filling the tube quite uniformly, when excited by a single disk electrode at the base and the five meter oscillator. A small U-shaped magnet was used, much larger than shown in the figure in such a position that the lines of force were perpendicular to the paper in Fig. 11. The intens-

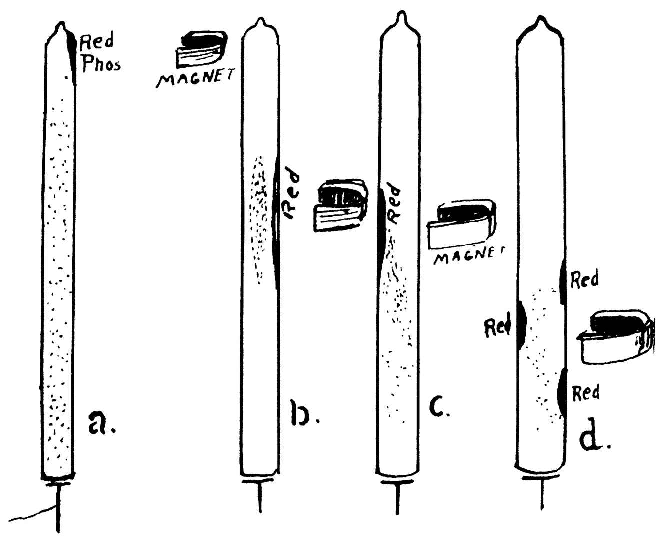

Fig. 11. Magnetic deflection of discharge.

ity of the luminosity fell off gradually towards the top of the tube where it was practically zero. The top of the tube showed a faint red phosphorescence, which was deflected to one side when the magnet was 20 cm from the tube, the direction of the deflection indicating upward moving electrons. On moving the magnet down the tube it was necessary to bring it up closer to cause red phosphorescence on the wall. This indicated that the upward moving electrons had a higher velocity half way down the tube than at the top, due perhaps to a reversal of the field direction during their flight from the disk cathode towards the top of the tube. A small plasmoid formed along the axis of the tube in this stage Fig. 11, b. On bringing the magnet closer to the tube a bright red patch formed on the opposite wall below the magnet, indicating electrons moving down, the plasmoid disappeared and the luminous discharge was pressed against the wall terminating at the spot of red phosphorescence. Fig. 12, c. The inference appears to be that we have at this point, electrons moving down with a velocity a little greater than that of the electrons moving up, the streams occurring in alternation of course.

On moving the magnet down the tube, two red patches formed on the right hand wall, and one on the left half way between them, Fig. 11, d, and the discharge appeared to zig-zag across the tube as shown. This case is more complicated, and I cannot account for it by considering simply two electron streams moving in alternation in opposite directions with different velocities.

Appearances suggest the formation of surface charges and reflection of the electron streams as in a former case (Fig. 8, b.). Some of the effects described above might be explained by assuming upward moving electrons along the inner wall, the downward stream being at the center, but this seems improbable. We will next consider the case of a tube with oxygen and CO at low pressure in which a white plasmoid formed at the top of the tube with its head pointing downwards as shown in Fig. 12, a.

If the pole of the bar magnet was brought up from behind towards the tail of the plasmoid, it disappeared when viewed from the front but was still visible when viewed from the side, due to its having been spread out

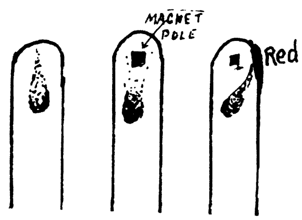

Fig. 12. Magnetic deflection of plasmoid.

into a fan. This would indicate electrons moving both up and down. No phosphorescence of the glass was observed. On bringing the magnet closer a new sharply defined tail formed, and the head of the plasmoid was pulled up; at the same time the tail bent to the right, finally touching the glass forming a patch of red phosphorescence on a closer approach of the magnet. Downward moving electrons were indicated in this case.

With the magnet still closer to the tube a faint red patch appeared on the left hand wall, below the magnet, due to upward moving electrons.

If the magnet was approached immediately below the plasmoid, or even below the bulbous expansion of the tube, the plasmoid contracted and vanished, without suffering displacement.

When the magnet was brought up to the plasmoid shown in Fig. 10, Cap. 11, the upper end was deflected to the right and the lower end to the left red spots forming on the wall, indicating electrons streaming out from the center of the plasmoid through its upper and lower surface. In this case the discharge was of the first type (Townsend?).

In other cases the magnet indicated electron streams flowing into the opposite ends of the plasmoid. Elongated plasmoids were constricted or broken into two, by the magnetic field the broken ends being deflected in opposite directions against the wall forming red spots, the indication in this case being electron streams flowing out of the broken ends.

It has not been found possible to systematize these observations, doubtless due to the fact that the field, by deflecting electrons, establishes a new condition in the tube (destruction or rupture of a plasmoid and a redistribution of surface charges) and the effects we observe are those produced by the field on this modified discharge. In general I have found that whenever a plasmoid is pushed against the wall by a magnet red phosphorescence is produced.

In the condition shown in Fig. 10, Cap. 20, if the magnet pole is brought up from behind the upper plasmoid, the plasmoid slowly collapses to a point and disappears, red phosphorescence appearing on the left hand wall indicating electrons moving down. The oxygen pressure was higher in this case than in one previously mentioned, in which an upward electron stream was found in the upper two thirds of the tube.

Spectroscopic Study of Plasmoidal Discharge

In this study an image of the discharge was focussed on the spectrograph slit, so that a point-to-point correspondence obtained. It was found that the spectrum of the faintly luminous discharge in which the plasmoids were immersed, (with pure oxygen only in the tube) showed the bands of the

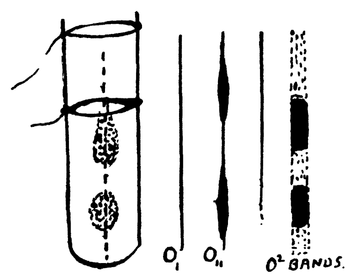

Fig. 13. Distribution of intensity in spectrum lines and bands.

oxygen molecule, and the atomic lines due to OII and OI. The discharge in the single case which we shall consider was produced with the 1.7 meter oscillator with two wire ring electrodes, the plasmoids having the form shown in Fig. 13. The slit covering the portion shown by the dotted line. In this diagram the local intensity of a line is roughly indicated by its width. The atomic line due to OI was of uniform intensity throughout its length, the OII lines showed a slightly greater intensity in the vicinity of the plasmoids, two lines (oxygen triplets) between the green and blue bands were of uniform intensity except at the bottom of the tube, where they were very faint, while the bands due to oxygen molecules were much more intense in the plasmoids, the intensity decreasing abruptly at the plasmoid surface. This shows that in the plasmoid we have a concentration of excited oxygen *molecules*, while the concentration in its dark sheath is less than in the luminous discharge in which it is embedded.

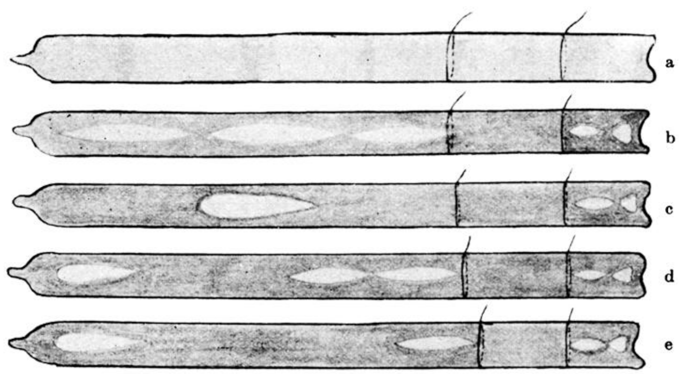

Fig. 1. Appearance of plasmoidal discharges under various conditions.

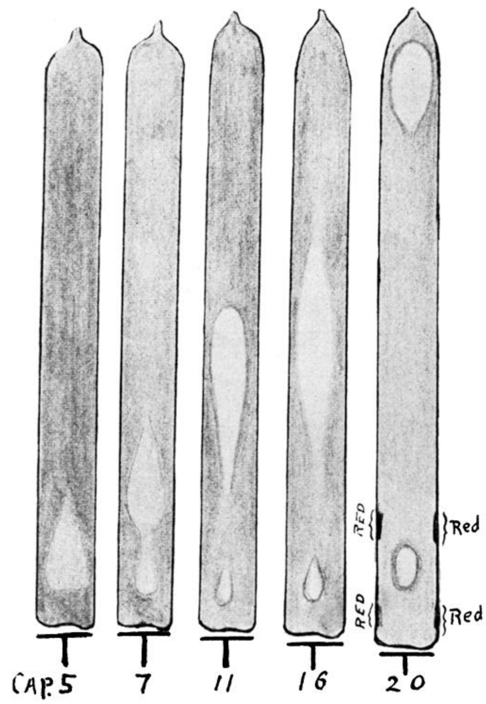

Fig. 10. Plasmoid formation with increasing potential.

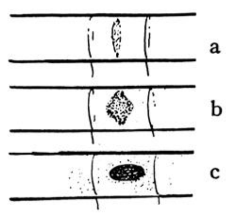

Fig. 4. Change in shape of the plasmoid with increasing potential.

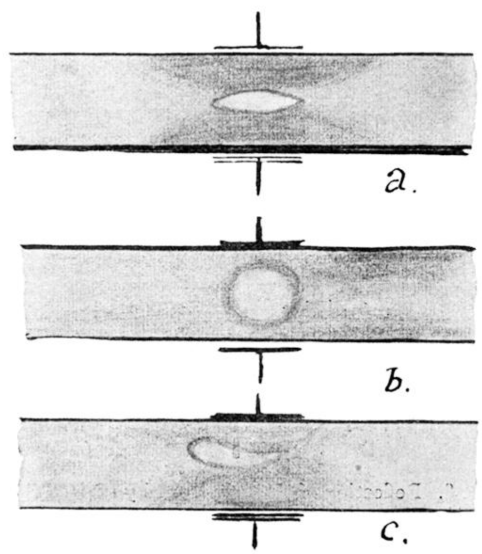

Fig. 7. Change in shape of plasmoids with decreasing potential and magnetic deflection of plasmoid (c).

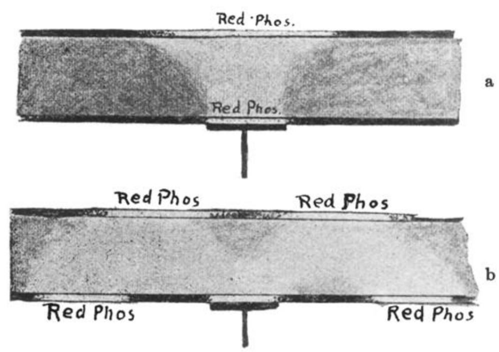

Fig. 8. Reflection of slow electrons by surface charge.