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Oscillatory Phenomena in Direct Current Glow Discharges*†

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In glow discharges having a positive column with a constant emf and a series resistance, oscillations usually are observed in tube voltage, current, and light intensity. While current and voltage oscillations represent a modulation of only a few percent, the intensity decreases to zero between maxima in the positive column, but there is an appreciable steady component near the cathode. The intensity maxima move as positive striations toward the cathode, or as negative striations with a much higher speed toward the anode. Where positive and negative striations meet they stop for times up to 100 μsec.

The oscillations are often very stable and repeat themselves without change for hours. Often several modes exist and the discharge moves back and forth between them and appears unstable.

The data presented in this paper were obtained chiefly from argon discharges although similar phenomena occur in most other gases over a great range of pressure and current. A discussion of the mechanism producing the phenomena is given.

I. INTRODUCTION

IN the direct current glow discharge through gases at low pressures, the simplest conditions which can prevail are usually taken to be those in which the positive column is homogeneous, and the current is constant. It is well known that such conditions are not always met, and considerable study has been made of oscillations of several types which have been detected in "direct current" discharges. These include the high frequency oscillations of electrons in the space charge plasmas, the moving striations in rare gas and mercury vapor glows and arcs, and low frequency electrical oscillations which have been associated with these striations in a few cases. However, the information concerning these oscillations in the literature is rather fragmentary, and they have remained among the least well understood phases of the subject of electrical discharges in gases.

This is true even in the case of the moving striations in the positive columns of rare gas and mercury vapor glow discharges which were discovered by Abria[1] in 1843. A summary of the information which has been obtained since then can be found in any of the standard treatises on gas discharges[2–4] or in the review of Druyvestyn and Penning.[5] The study of the striations themselves has been made chiefly by means of rotating mirrors or by rotating cameras,[6] although Pupp,[7] who has made a rather extensive study of these phenomena, used also a photo-cell in conjunction with a cathode-ray tube to obtain a record of the fluctuations of light intensity caused by the striations. Electrical oscillations accompanying the moving striations were the subject of investigations by Appleton and West and by Fox.[8]

Owing to the difficulty of obtaining very precise or detailed information from the instruments available for all this work, it was not possible to set forth a satisfactory explanation for the moving striations.[9] As a result they have never really acquired a stature beyond that of a mere curiosity, a manifestation perhaps of a somewhat abnormal situation.

It should also be remarked that almost the same might be said for another example of inhomogeneity in the positive column—the case of the standing striations which appear for certain ranges of pressure and current in discharges through diatomic gases. There are many more experimental data for these striations than for the moving striations.[10] But again a theoretical explanation is lacking. In particular, no relationship has even been discovered between moving striations and those of the stationary type.

Recently, during a survey in this laboratory of short period phenomena in a large number of gas discharges of various types, it became apparent that oscillations are much more common in gas discharges than seemed to have been realized.[11] In fact, so seldom were they absent that it seems quite likely that any theory of discharges which neglects them is defective in some essential way. Therefore, a program to study these oscillations as thoroughly as possible under controlled

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† Revised manuscript received July 31, 1950.

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[2] A. v. Engel and M. Steenbeck, *Elektrische Gasentladungen* (Julius Springer, Berlin, 1933).

[3] L. B. Loeb, *Fundamental Process of Electrical Discharge in Gases* (John Wiley and Sons, Inc., New York, 1939).

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[5] M. J. Druyvestyn and F. M. Penning, Revs. Modern Phys. **12**, 87 (1940).

[6] F. W. Aston and T. Kikuchi, Proc. Roy. Soc. **98**, 50 (1921). T. Kikuchi, Proc. Roy. Soc. **99**, 257 (1921). R. Whiddington, Nature **116**, 506 (1925); **126**, 467 (1929). B. v. Manen, Physica **1**, 968 (1934). A. H. v. Gorcum, Physica **2**, 535 (1935).

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[8] E. Appleton and A. West, Phil. Mag. **45**, 879 (1923). G. W. Fox, Phys. Rev. **35**, 1066 (1930); **37**, 815 (1932).

[9] See for example the remarks of Druyvestyn and Penning, reference 5, page 169, or of Loeb, reference 3, page 573.

[10] Druyvestyn and Penning, reference 5, p. 166.

[11] Dieke, Loh and Crosswhite, J. Opt. Soc. Am. **36**, 185 (1946). H. Y. Loh and G. H. Dieke, J. Opt. Soc. Am. **37**, 837 (1947).

conditions seemed desirable and promising. The application of photo-tubes and the oscillograph to the problem offered a promise of gaining more complete information about these oscillations than any technique previously used.

The following paper is a report of results obtained in this study for a number of dc glow discharges. In the earlier survey referred to, ac had been used as a matter of convenience and because during the ac cycle insight can be had into various transitory and break-down phenomena which are not readily observed with dc. But it is, of course, desirable to study the discharge under the simplest and most easily evaluated conditions. These surely obtain when the discharge is through a low pressure gas enclosed in a glass tube and driven by constant batteries. Then, if ever, one should expect a steady time independent discharge.

II. EXPERIMENTAL TECHNIQUE

The experimental arrangement is shown in Fig. 1. The glow discharge is maintained by a bank of batteries *B* or by a regulated rectifier power-supply in series with a variable resistance *R*. The discharge tube *T* is mounted horizontally. Riding beside it on a rack and pinion is the electron multiplier tube *P* (type 931-A or 1P28) in its housing. Light from a narrow region of the glow is admitted to the sensitive surface of the photo-tube through a narrow slit. Various methods for selecting light from the discharge tube have been used. Sometimes a second slit, almost touching the discharge tube, is placed about 2 cm in front of the slit on the photo-tube housing. A lens or mirror has also been used to focus an image of the discharge on the photo-tube slit. All of these schemes give practically the same results. Output currents from the photo-tube circuit flow through a resistance *Y* at the input terminals of an oscillograph. Thus the pattern on the cathode-ray tube screen gives the light output near a selected point in the glow discharge as a function of time.

The discharge voltage can be studied as a function of the time merely by bringing leads directly from the electrodes to the oscillograph (i.e., opening K_1 and closing K_2. In a similar manner the current at any point in the circuit can be studied in terms of the voltage variation across a properly chosen series resistance.

Figure 2 shows the results observed in a typical case (discharge in Hg vapor in the presence of 4 mm argon). Oscillations in the light intensity and the tube voltage were observed for all values of the current used (from a few tenths of a milliampere to about 60 ma). Often the fluctuations had the disordered appearance of Figs. 2A and 2B. Under such conditions the positive column seemed to contain striations which jumped about with great disorder and rapidity. But often the fluctuations are quite definitely periodic (Figs. 2C and D). The positive column appears then quite steady and homogeneous to the eye.

There is a very essential difference between the oscillations in the tube voltage and in the light intensity. The voltage fluctuations represent a modulation of a few percent (e.g., in the example of Fig. 2 the amplitude of the oscillations is 5 volts when the tube voltage is about 200 volts). The intensity fluctuations on the other hand represent a 100 percent modulation; i.e., the intensity is zero or very nearly so in the minima. In the ordinary oscillograph traces such as those of Fig. 2 this difference is not apparent as the amplifier in the oscillograph suppresses the dc component. The zero line can be brought out by applying the signal directly to the deflection plates or through a dc amplifier. The same result can be also achieved by interposing an electronic switch between signal and oscillograph (see e.g., Figs. 4, 5, 6).

III. OSCILLATIONS AND MOVING STRIATIONS

That the oscillations mentioned above are closely related to moving striations is apparent from the fact that voltage and intensity oscillations always have the same frequency and always become erratic and regular in the same way. This shows that the two types of oscillations are different manifestations of the same phenomenon.

The voltage fluctuations can thus be used to trigger the driven sweep of the oscillograph (e.g. DuMont type 248 A) which means that the sweep will always begin at the same instant of the cycle. The phase of the intensity oscillations are then observed to depend on the point in the tube from which the light comes. In Fig. 2F the point of observation is 0.34 cm closer to the cathode than in Fig. 2E. The pattern is clearly retarded by the time distance between two successive markers; i.e., 100 μsec. This indicates that the intensity wave travels from the anode to the cathode with a speed of about 34 m/sec and these traveling waves are called

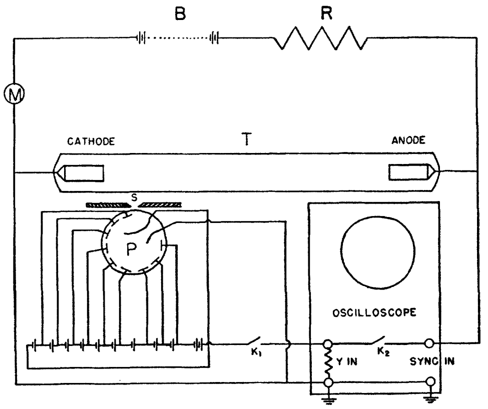

FIG. 1. Diagram of the discharge tube and photo-multiplier tube circuits.

B: Bank of twenty-five or more dry batteries, 45 volts each.
R: Variable resistance, maximum value 42,000 ohms.
M: Milliammeter.
T: Discharge tube.
P: Electron-multiplier phototube.
K_1, K_2: Switches.

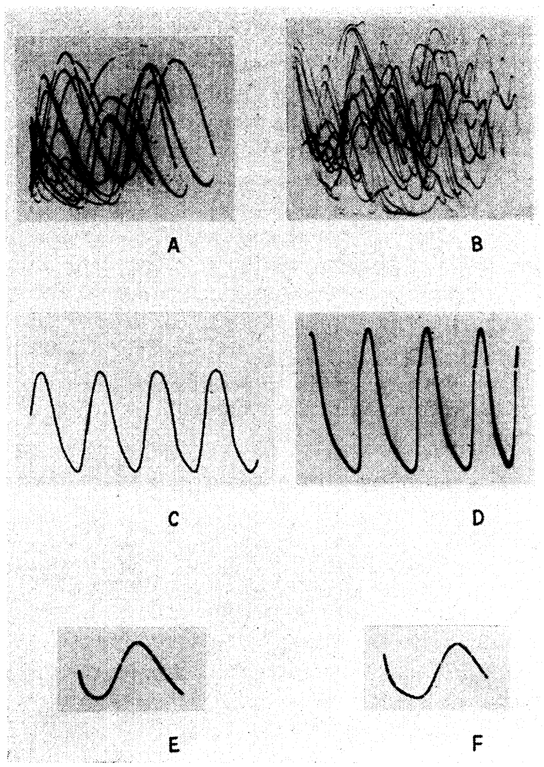

FIG. 2. Voltage and light intensity oscillations in a dc mercury vapor-argon glow discharge. The argon pressure was 4 mm. The sweep-length is 1000 μs with markers every 100 μs for *A*, *B*, *E*, and *F*.

A: Light intensity 4.83 cm from anode; current, 6.00 ma.
B: Voltage oscillation; magnitude 7 volts for same conditions as *A*.
C: Light intensity 11.60 cm from anode; current 6.00 ma.
D: Voltage; amplitude of sharp rise 5.72 v for same conditions as *C*.
In *C* and *D* the sweep-length is about 3500μs.
E: Light intensity 5.70 cm from anode; current, 5.12 ma.
F: Light intensity 6.04 cm from anode; same conditions as *E*.

The frequency in *E* and *F* is 1333 sec^{-1}.

moving striations. The frequency of the oscillations at a fixed point in the example of Fig. 2E–F was 1300 sec^{-1} which means that the wavelength, i.e., the distance between successive maxima is $(\lambda\nu=v)$ 2.55 cm.

The method of study used chiefly for this paper is to observe the intensity pattern at one point in the discharge, then to observe the same thing at a neighboring point and to repeat this until the whole length of the tube has been covered. It is essential, of course, that the discharge conditions remain constant during the whole procedure. Fortunately this can be monitored with relative ease as the character of the oscillations is very sensitive to small changes in the discharge conditions. After the data have been obtained for one set of conditions the discharge parameters like current and pressure can be changed and the discharge analyzed in the same manner for the new conditions.

It seems desirable to study the moving striations and their associated electrical phenomena under as simple conditions as possible. These probably prevail in a monatomic gas and for this reason the glow discharge in argon will be discussed in some detail. We had available four cylindrical tubes[12] of equal dimensions filled with argon at pressures of 2.1 mm, 4.4 mm, 12 mm, and 30 mm respectively. They were made of Pyrex, 15 mm in diameter. The electrodes were small zirconium cylinders of square cross sections with 5 mm sides. The distance between the electrodes was about 42 cm.

We shall take as a typical example the argon discharge at 12 mm pressure which shows most of the interesting phenomena. After this, attention will be called to the differences observed at the other argon pressures. Phenomena observed in other gases like Hg, He, Ne, Kr, Xe, H_2, and air will only briefly be mentioned although examples from such discharges will be used occasionally to illustrate some point.

IV. OSCILLATIONS IN ARGON AT 12 MM PRESSURE

Figure 3 shows the ordinary dc characteristic of the discharge, i.e. the tube voltage against discharge current, both measured with an ordinary dc instrument. The character of the oscillations (stability, frequency, velocity of propagation, etc.) was observed as function of the current over the range 10–200 ma.

Figure 3 gives also the observed frequency of the oscillations. It is immediately apparent that the various values do not lie on one continuous curve. When the current is increased the oscillations may become unstable and with further current increase, or sometimes even after a suitable waiting period at the same current, the oscillations become stable again but with a markedly different frequency. We have thus several *modes* of oscillations. Six such modes are indicated in Fig. 3. For some values of the current several modes can exist. Which one is in evidence at a given time depends on the previous treatment of the tube, e.g. whether a particular value of the current was reached by increasing or decreasing the current. Sometimes the tube moves back and forth between two different modes and a confused picture arises as in Fig. 2A and B. After some time the tube usually will settle on a definite mode. For other current values stable oscillations apparently do not exist under any conditions. Regions in Fig. 3 where no frequencies are indicated are such regions of instability. There are values of current and pressure (not, however, in the range of Fig. 3) where the discharge is entirely free from oscillations (see Figs. 4G and 4H).

Figure 4 shows that the intensity pattern may be quite different for different modes. Figures 4A and 4B represent mode III, 4C mode VI, and 4D mode VII. The wave form of the intensity pattern may also change considerably when different parts of the tube are com-

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[12] We are indebted for these tubes to the late Dr. A. C. Rentschler of the Westinghouse Research Laboratories at Bloomfield, New Jersey. Owing to his cooperation a great deal of delay was avoided at a time when facilities for constructing such tubes were not yet available in our own laboratory.

pared. It is usually more or less the same all through the positive column but changes very greatly in character in the parts near the cathode. A study of this behavior reveals valuable clues to the nature of the mechanism which produces the moving striations.

V. ANALYSIS OF THE MOVING STRIATIONS

The low current modes, particularly modes I and III of Fig. 3, in argon at 12 mm reveal some of the characteristic properties of the striations.

There were faint but definite stationary striations visible in the part near the cathode at the low currents whenever the oscillations were stable. The separation d_s of the stationary striations was related to the distance λ between the moving striations by

$$\lambda = nd_s,$$

where n was an integer, usually one or two. The moving striations cross the standing striations. They are broad and move relatively slowly in the bright parts and are much sharper and move faster in the minima of the standing striations. Tables I and II give some of the properties of these striations. Let us look at mode I at a current of 19.20 ma through the tube. The appearance of the discharge is as follows. The distances are measured from the cathode.

Cathode glow	0.22 cm
Cathode dark space	0.70
Negative glow	1.60
Faraday dark space	2.05
Positive column	2.42

Figures 5 and 6 show the appearance of the oscillations at various distances from the cathode. The variation of the curves with position is quite striking as is the complexity of the pattern.

We shall call each of the maxima visible on these traces a "striation." From the time scale on each trace the moment can be determined at which this particular striation reaches the spot of observation. From an inspection of the figures it is obvious that there are several striations of different character passing the spot of observation during each cycle. By comparing a whole set of pictures taken at different parts of the tube it is possible to trace the movement of each striation through the tube. A particular striation will not only move along the tube but may change its amplitude and shape as it moves along.

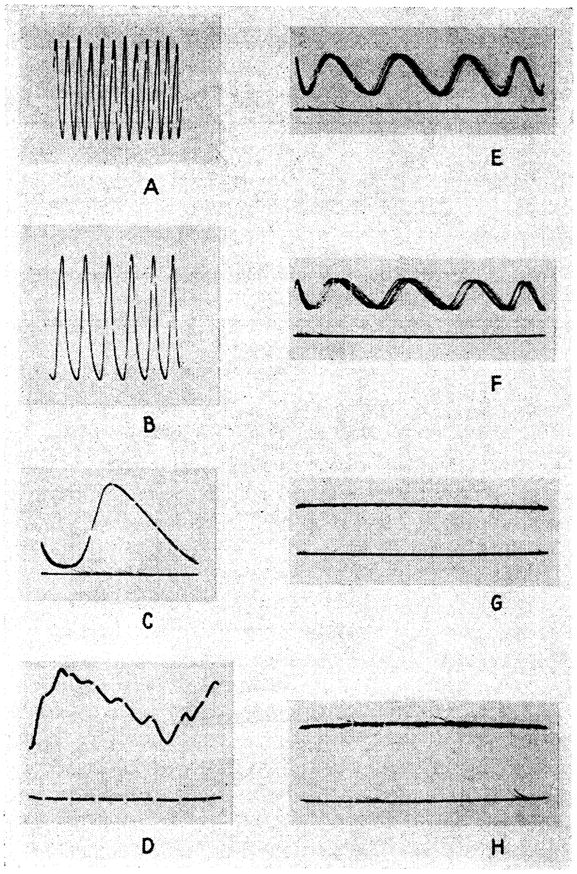

FIG. 4. Voltage and intensity oscillations in argon at 12 mm and 30 mm pressure. Time markers are spaced 100 μs. In *C*, *D*, *E*, *F*, and *G* the lower trace is the line of zero intensity provided by an electronic switch.

12 mm pressure
A: Voltage oscillation at 31.0 ma.
B: Light intensity 20 cm from cathode at 31.0 ma; frequency, 1866 $\sec^{-1}$.
C: Light intensity at 114 ma; frequency, 1470 $\sec^{-1}$.
D: Light intensity at 195 ma; frequency, 1665 $\sec^{-1}$.
30 mm pressure
E: Light intensity 25.2 cm from cathode at 95.2 ma; frequency, 2600 $\sec^{-1}$.
F: Light intensity 25.2 cm from cathode at 144.0 ma; frequency, 2460 $\sec^{-1}$.
G: Light intensity 25.2 cm from cathode at 150.0 ma.
H: Light intensity 25.2 cm from cathode at 270.0 ma.

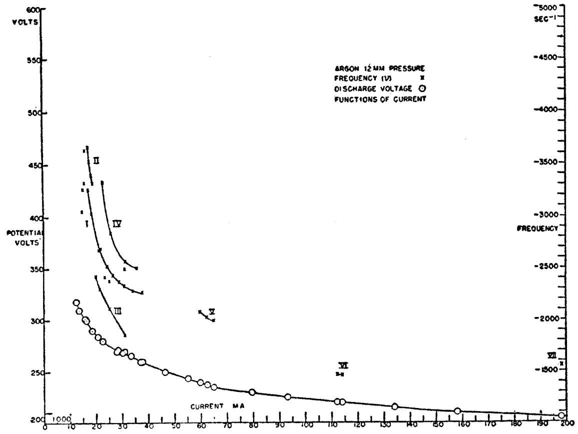

FIG. 3. Total discharge voltage ⊙ and frequency of oscillations x as functions of the current for an argon glow discharge at 12 mm pressure.

The results of such analysis are summarized in Fig. 7. The abscissa is plotted as the distance of the place of the observation from the cathode, and the ordinate as the time when a particular maximum passes this spot.

The neighboring spots can be connected by a curve and this curve represents the motion of a particular striation.

TABLE I. Stationary and moving striations in argon at 12 mm.

Current (ma)	Mode (see Fig. 3)	λ (cm)	Speed (m/sec)	Frequency (sec^{-1})	d_s (cm)
31.0	III	1.88	25–42	1870	0.94
25.4	I	2.44	56–62	2440	1.22
24.9	I	2.46	55–62	2390	1.23
19.35	III	2.47	53–70	2500	1.24

TABLE II. Speed of moving striations in and between stationary striations argon, 12 mm, 31.0 ma.

Moving striations	
Frequency (ν):	1866 sec^{-1}
Separation (λ):	1.88 cm
Average speed (v av):	35.2 m/sec

Stationary striations and measured speed of moving striations

Minima		Maxima	
Position (cm from anode)	Speed (m/sec)	Position (cm from anode)	Speed (m/sec)
11.98	40	12.35	29
12.92	42	13.29	30
13.86	40	14.23	26
14.80	47	15.17	28
15.74			

As the frequency of the oscillations is 2438 sec^{-1} the period is 410 μsec. The figure has, therefore, a strict periodicity in the vertical direction with a period of 410 μsec. If extended toward the right the figure would show an approximate periodicity in the horizontal direction, less rigorous than the time periodicity, throughout the positive column.

Figure 7 shows that there are two types of striation. The curve of one type slopes up toward the left. This means that these striations move from the anode toward the cathode. The slope is considerable which implies a moderate velocity of propagation which is, moreover, not constant (from 33 to 350 m/sec with an average value of 65 m/sec). This type of striation we call *positive* striation. This is the type of moving striation observed before in many cases. It is marked with a dot over the maxima in the oscillograms of Figs. 5 and 6.

The other type of striation, here called *negative* striation, moves from the cathode toward the anode. Its velocity is much faster than that of the positive striation. The negative striations never seem to have been observed before. All those not marked with a dot in Figs. 5 and 6 are negative striations.

Obviously the positive striation is a positive space charge, the negative striation a negative space charge, which move in the appropriate direction in the electric field which exists within the discharge tube. Presumably the negative charge consists of electrons and because of its high mobility can move faster than the positive space charge consisting of positive ions. We must, however, consider also the possibility of neutralization at the trailing edge of the positive space charge and fresh ionization on the leading edge as a mechanism for motion, in which thus the individual ions do not necessarily move with the same velocity as the center of the space charge.

Whenever a positive striation and a negative striation meet, they neutralize each other and there is then a true plasma formed with the field strength very small. We observe then for a time interval varying here from 20 to close to 100 μsec no motion at all. After this interval a negative and a positive striation each emerge from this plasma travelling in opposite directions.

Figures 5 and 6 represent actual oscillograph traces and Fig. 7 is directly derived from such traces and represents, therefore, the behavior in an actual tube with some irregularities caused by wall conditions.

The method of treating the oscillographic evidence can be better discussed with the help of Fig. 8, which presents drawings of typical oscillograph patterns of light intensity as function of the time for eight positions in the positive column successively closer to the cathode. For each of these the time at which a peak in the intensity occurs is then plotted on the lower right part

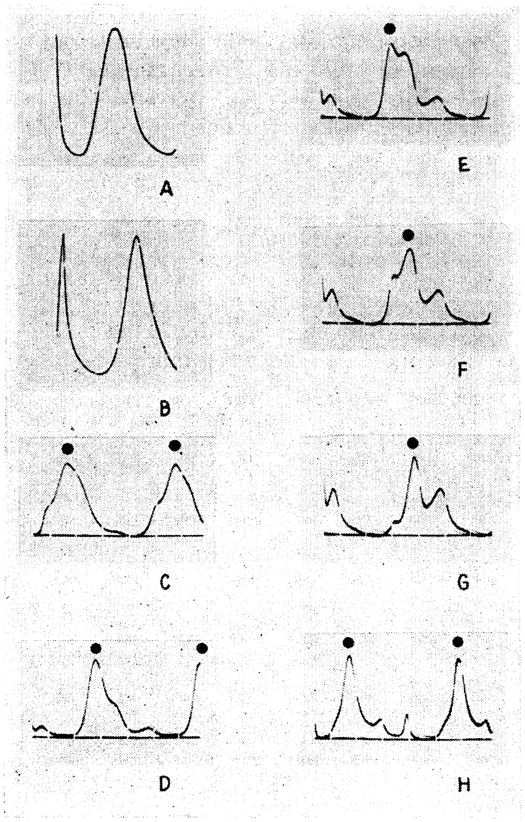

FIG. 5. Oscillograph pictures of moving striations in argon at 12 mm pressure. The markers on the sweep are 100 μs apart. The zero line (*C–H*) is provided by an electronic switch. The dot identifies the principal positive striations (*C–H*).

A: Light intensity 12.45 cm from anode at 31.0 ma.
B: Light intensity 14.75 cm from anode at 31.0 ma.
C–H: Light intensity in positive column at 19.20 ma; frequency, 2438 sec^{-1}.
C: 4.83 cm from cathode.
D: 4.05 cm.
E: 3.80 cm.
F: 3.67 cm from cathode.
G: 3.45 cm.
H: 2.53 cm.

of the figure for the points which are numbered in correspondence with the oscillograph traces. Thus at point (1), closest to the anode, intensity peaks occur at 50, 200, 250, and 450 μsec and are so plotted on the graph. It is seen that at the neighboring points (2), (3), etc., the peak marked (+) occur at successively later times while the other peaks occur earlier but only slightly so. The peak marked (+) moves therefore toward the cathode and represents a positive striation, whereas peaks (*a*) and (*b*) move in the opposite direction but with a much higher velocity and represent negative striations.

If we fix now our attention to peaks (+) and (*a*) we find that they approach each other continually until at point (5) they are only separated by 43 μsec. The intensity does not fall to zero during the time between these peaks near point (5).

At point (6) the two peaks are again more widely separated and through comparison with (7) and (8) it is apparent that the left peak is now the negative and the right one the positive striation. This can only be interpreted to mean that at point (5) the striations pause for about 45 μsec. While this happens they are intermingled and form a true plasma. The light intensity drops but not to zero and rises again when they are ready to separate.

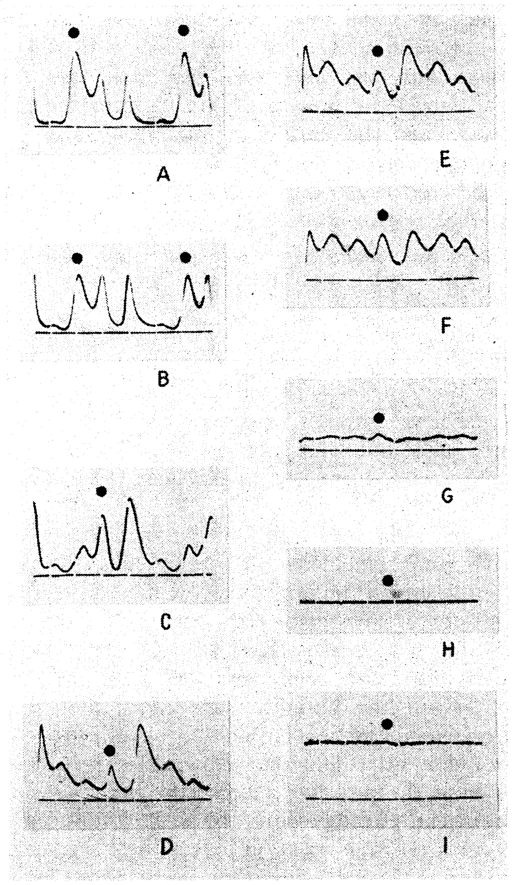

FIG. 6. Oscillograph pictures of moving striations near the cathode in argon at 12 mm pressure. Markers 100μs apart; current, 19.20 ma. The dot identifies the principal positive striations.

A: 2.18 cm from cathode.
B: 2.05 cm (Faraday dark space).
C: 1.89 cm.
D: 1.72 cm.
E: 1.60 cm (Negative glow).
F: 1.56 cm.
G: 1.50 cm.
H: 0.70 cm (Crookes dark space).
I: 0.22 cm (Cathode glow).

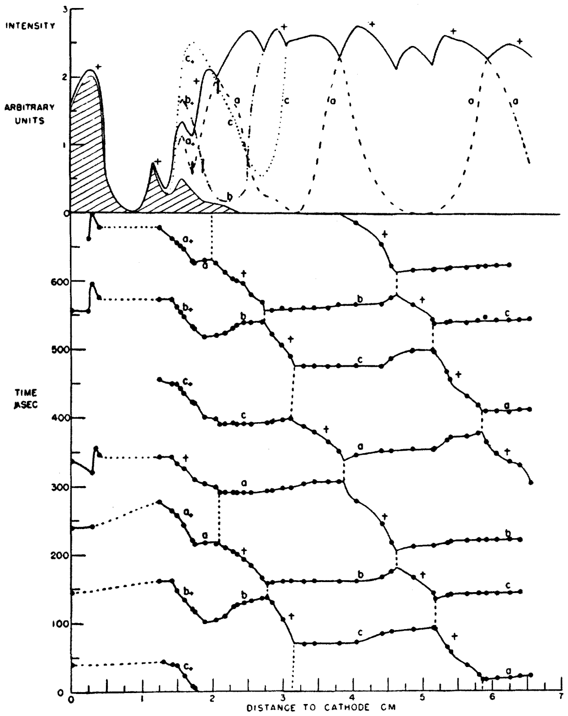

FIG. 7. Time-position curves for the moving striations near the cathode in argon at 12 mm pressure and 19.20 ma current. At the top of the figure is plotted the amplitude of the light intensity for each of these striations as a function of position. These curves are labeled to correspond with the striation paths plotted in the bottom part of the figure. The full curves are not drawn for *b*, *c*, a_+, b_+.

In Fig. 8 peaks separated by 400 μsec are designated by the same letter. They are manifestations of the same striation one period apart. In our example there are two negative striations (*a* and *b*) to each positive one. If the distance between points (1) and (8) is 2.5 cm the average speed of the negative striations is 1000 m/sec, that of the positive striations 100 m/sec.

Figure 7, the diagram of an actual tube, is somewhat more complicated than Fig. 8 because different parts of the discharge may be quite different in the behavior of the striations, particularly near the cathode.

As one follows a particular positive striation along the tube in Fig. 7 it meets three negative striations in a cycle. Its intensity is a maximum between the meeting points, a minimum at the meeting points. These intensities of the striations, i.e., the values of the intensity maxima in each oscillogram, are indicated in the upper part of Fig. 7 in which the particular striations are

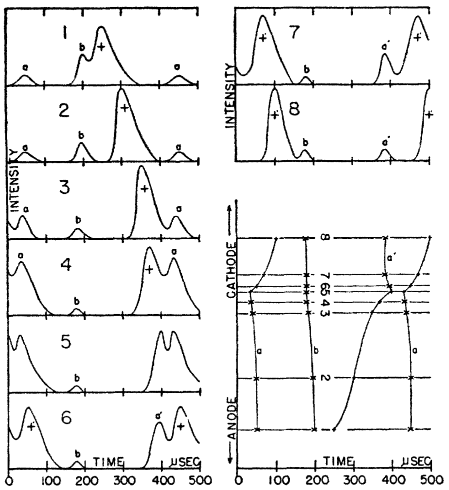

FIG. 8. This drawing demonstrates the method used to plot space-time curves for the striations from oscillographic data giving light intensity as a function of time at eight positions in the positive column. Each intensity curve is numbered to correspond with the position where the times of its maxima are plotted on the graph.

identified by letters corresponding to parts in the lower half of the figure.

The intensity of only one negative striation, the one marked (a) is plotted throughout (dashed line). The intensity curves for the other two (b) and (c), are discontinued where they first meet the positive striation (+). (a), (b), and (c) all originate in the negative glow between 1.75 cm and 2.12 cm from the cathode. At the same points positive striations arise which go into the negative glow. These are marked (a_+), (b_+), and (c_+). The intensity curves, for example of (a) and (a_+), are continuous. A vertical bar indicates on the intensity plots where the change occurs. Only the curves for (+) and (c_+) are continued all the way to the cathode to avoid crowding. The minima between striations are uniformly zero except near the cathode where there is a considerable steady non-oscillating part in the intensity which is indicated by the cross-hatched area. The negative glow, which extends from about 1.05 cm to about 2.05 cm, has a pronounced structure. The division at 1.4 cm has apparently never been noticed previously. One might say that the positive column begins where the steady part in the intensity becomes zero.

The meeting places of the positive and negative striations are at fixed spots in the tube (positive column). Although the amplitudes of the striations are brightest between these meeting points, the average intensity is larger at the meeting points because the striations remain there longer and the intensity does not go down completely to zero while the striations are at rest. The time average of intensity is, therefore, higher near these meeting points and they appear as stationary striations.[13]

Since all the positive striations meet negative ones always in the same spot it follows necessarily that the number of stationary striations within one wavelength must be an integer, a fact which was mentioned earlier. This wavelength (the distance between points in the tube with the same phase) is constant where the phenomena are truly periodic in space. Where such a periodicity is not established, as in the region near the cathode, or is not interfered with as, for example, in the positive column through local differences in the properties of the tube wall, the wavelength will vary.

Well inside the positive column the negative striations are not very conspicuous as their amplitude is small. They have a uniformly high speed (about 1500 m/sec, see Fig. 9). The time delay at the meeting place with the positive striations is small. The meeting point can always be found from an observation of the positive striations as the maximum of the oscillograph traces is broadest there (Fig. 5A as compared with Fig. 5B). The left part of Fig. 9 gives a fairly typical picture of the situation throughout most of the positive column, where the delay at the meeting points is appreciable.

As is evident from Figs. 5 to 7 the discharge near the cathode shows the greatest detail of structure in the oscillations and this part is of greatest significance for an understanding of the mechanism of the striations.

In the Crookes dark space (Fig. 6H) the intensity is so low that no striation can be followed through it in this case. In the *cathode glow* most of the intensity is steady but weak oscillations are superimposed. The observations are difficult and the situation not quite clear but there is definite evidence that these are negative striations moving away from the cathode through the Crookes dark space (although they cannot be traced here) into the negative glow. The departure of these striations from the cathode is important in connection with the voltage oscillations to be discussed later.

The arrival of this cathode negative striation in the negative glow coincides with the arrival of a positive striation there. In the negative glow most of the intensity is due to the steady component. The oscillating part is due to positive striations only, four of nearly equal amplitude in each cycle, (Figs. 6E and 6F). Going toward the Faraday dark space they change their relative intensities considerably (Figs. 6C and 6D). Figure 7 shows that only one of these positive striations comes from the positive column, the other two originating in the Faraday dark space. It is noticed that whenever a positive striation leaves the Faraday dark space toward the cathode a negative striation leaves it to move in the opposite direction.

The picture near the anode is presented in Fig. 9 for a condition very similar to that of Fig. 7. The current here is slightly higher (19.35 ma) and the frequency a little lower (2425 $\sec^{-1}$). There is no great difference in the structure of the striations in the positive column until very close to the anode. The negative striations

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[13] This type of stationary striation appears to be different from the typical stationary striations observed in some diatomic gases.

are observed to travel all the way to the electrode. In the present case the positive striations are seen first a very short distance in front of the anode shortly after a negative striation has passed. This is considered to be accidental since there are many cases in which no correspondence can be established between the arrival of negative striations and the departure of positives. Whenever a striation arrives at or leaves the anode a maximum in the tube voltage and a minimum in the current is observed.

There is in this case, and very frequently in others, a definite asymmetry in the positive striations near the anode, alternate ones travelling in a slightly different way. This distinction disappears before much of the positive column is traversed.

Since it is impracticable to present a complete position-time graph here for a tube 40 cm long, we have sketched (Fig. 10) what the striation behavior should be for a tube having only five stationary striations in the positive column. Actual data are represented near the anode and the cathode and in the voltage oscillation, but the central portion of the positive column has been telescoped in such a way that the phase relation between cathode, anode, and voltage oscillations remains correct. The speed of striation motion has been idealized to uniformity. The diminution of the delay time when striations meet in the central part of the positive column is indicated and real. Arrows at the bottom of the figure point to these meeting places; i.e., to the maxima of the stationary striations. The precise correspondence between voltage peaks and striations at the anode and between voltage minima and striations at the cathode should be noted. Here, in contrast to Fig. 9, positive striations leave the anode a long while after negative striations have gone in. It should be also noted that the striations repeat in groups of three. This complex periodicity is quite a common phenomenon.

VI. ARGON AT 2.1, 4.4, AND 30 MM PRESSURE

The phenomena in the argon discharge at pressures of 2.1, 4.4, and 30 mm are essentially the same as those observed at 12 mm pressure. Because of the appearance of different modes, the data are not sufficient to determine the general dependence of the oscillatory phenomena on pressure. For this reason only the significant differences appearing at different pressures will be mentioned which supplement the data observed at 12 mm.

Figures 11 and 12 show the behavior at 2.1 mm and 3.83 ma current. The frequency of the oscillations is 5000 sec^{-1} which makes the period 200 μsec. The average wavelength is 3.39 cm and the average speed 169 m/sec. The striations are very regular. The time position diagram (Fig. 12) is very similar to that at 12 mm (Fig. 7). There are two negative striations to each positive one in the positive column, a weak third one is observed near the Faraday dark space. The speed of the main negative striation is 2300 m/sec and can be measured rather accurately. The left side of Fig. 12 shows the voltage fluctuations about which more will be said in Sec. 7.

At 4.4 mm the oscillations seem at first sight much more complicated than at 12 mm (see Fig. 13). This is due to the fact that there are nine negative striations for every two positive striations. Furthermore, alternate positive striations do not meet negative striations at the same point. The minima of the one set of stationary striations thus produced coincide almost exactly with the maxima of the other set. The positive column thus appears to be entirely homogeneous to the eye. There is an odd effect in the cathode glow when negative striations leave toward the negative glow. From the same point striations can be seen which run around the edge of the cathode and back towards its rear.

At 30 mm there are simple oscillations at the lower currents with the negative striations not much in evidence. At 150 ma the oscillations disappear completely and the discharge is steady (Fig. 4*G*). This state of affairs prevails up to the highest currents (270 ma) at which observations could be made.

VII. CURRENT AND VOLTAGE OSCILLATIONS

It has already been noted that intensity oscillations are always accompanied by voltage oscillations. Also the discharge current shows oscillations.

The relationship between the current oscillations at either electrode, the voltage oscillation across the tube, and the intensity oscillations is most simply studied with a circuit such as that of Fig. 14. When SW_2 is closed, with SW_1 open, the voltage oscillation can be measured. When SW_2 is open and SW_1 closed in position

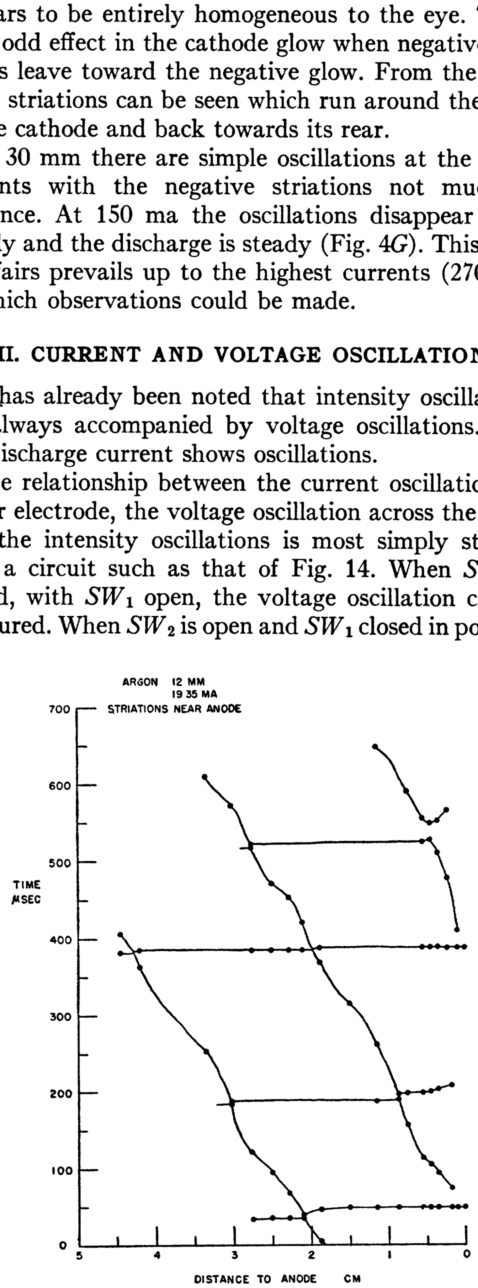

FIG. 9. Time-positive curves for the moving striations near the anode in argon at 12 mm pressure and 19.35 ma current.

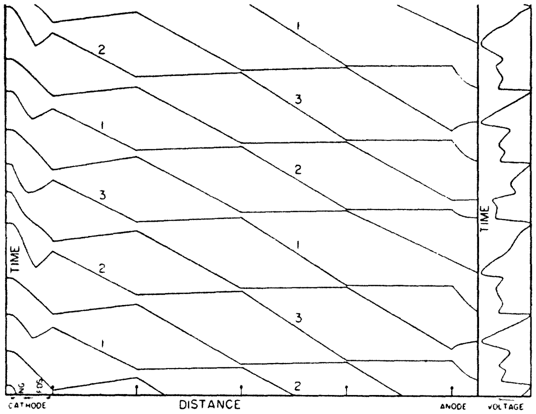

FIG. 10. Plot of time-position curves showing striation behavior completely from anode to cathode. These curves are representative of the motion of striations in general, but a specific case is reproduced only near the anode and cathode and in the voltage oscillation. The curves are drawn as straight lines in the positive column. In an actual case the slope would vary. Arrows locate the maxima of stationary striations.

A the current oscillations at the cathode are displayed on the oscillograph, and similarly those at the anode for SW_1 in position *B*. R_A and R_C are both 6000 ohms. Because it is not proper to ground permanently any point in this circuit, the trigger for the sweep must come from the photocurrent fluctuations for some convenient and fixed point in the discharge.

For a number of discharges the current and voltage oscillations were compared when the series resistance *R* was altered and the emf changed to maintain a constant discharge condition; i.e., identical dc ammeter reading and identical striation behavior. The relationship of i_c, the current at the cathode; i_a, the current at the anode; and the difference in potential between these electrodes may be summarized easily for the simpler types of oscillations such as those in argon at 12 mm, at 30 mm, for low current at 2.1 mm, and in mercury vapor. The current fluctuations are identical at both electrodes except in amplitude. Their amplitude varies with the series resistance *R*, in such a way as to keep ΔV, the magnitude of the voltage oscillation constant, where

$$\Delta V = -[R_c\Delta i_c + (R+R_a)\Delta i_a].$$

An example of this effect in argon at 12 mm for a current of 21.7 ma and a frequency of 3400 sec^{-1} is presented in Table III.

As we have pointed out, a current peak will occur whenever there is seen at the cathode a moving striation and a current minimum will occur whenever one is seen at the anode. In fact, it is possible to predict with fair accuracy the form of the voltage or current oscillation from an observation of the light intensity patterns near the electrodes.

It was seen that the magnitude of the current oscillations depends markedly on the external circuits while the voltage oscillations are much more characteristic of the discharge.

There is strong indication that the voltage oscillations are closely associated with the excitation and ionization potentials of the gas.

The relationship is expressed in Table IV for some of the gases for which data are available. This shows that the voltage oscillations (ΔV) show the same trend as the excitation potentials (V_e). The relationship is not exact and cannot be as the amplitude of the voltage oscillations may depend on the discharge conditions. The values given are typical values. There are often many subsidiary voltage peaks with different amplitudes.

VIII. OSCILLATIONS IN OTHER GASES

Many observations were made on oscillations and moving striations in other gases besides argon. Such oscillations occur under a great variety of conditions in He, Ne, Kr, Xe, Hg vapor, H_2, and air and probably other gases. This shows that the moving striations are a rather universal phenomenon in glow discharges and that any theory of the discharge mechanism should take account of them.

Some of the gases show oscillation phenomena with features considerably different from those observed in argon. We expect to deal with them in a subsequent paper.

A few remarks may be useful on oscillations in mercury vapor discharges. Mercury vapor discharge tubes are in general use now for many purposes, for example, in fluorescent lighting tubes, germicidal tubes, sun lamps, etc. Oscillations and moving striations can be observed easily in most of them and it matters little whether they have a hot or cold cathode.

Almost all such mercury tubes have a rare gas filling in which the discharge is started when the tube is cold. The heat produced by the discharge evaporates the mercury, and the discharge is then almost completely in the mercury vapor. The striations observed in such a tube are then characteristic for mercury vapor and not for the rare gas. This was verified with a tube with a side chamber which could be immersed in liquid air. It took about a week to distill all of the mercury from the main part of the tube through which the discharge passed into the side tube. The removal of the mercury could be verified when the spectrum of the discharge was a pure argon spectrum. The type of oscillations changed then from those typical of a mercury discharge into those typical of argon.

In mercury there was also the tendency for several modes. In the range of currents where the modes overlapped there was a conspicuous tendency toward instability (Figs. 2A and 2B) which was due to a change-over between such modes.

The magnitude of the voltage oscillations is usually between 4 and 5.75 volts although at low currents amplitudes as low as 1.6 volts have been observed.

In one tube two sharply defined modes could be observed which could be excited independently over a wide current range. The dc characteristics for the two modes are found to be distinctly different. In other mercury tubes more than six different modes could be observed.

Although a large amount of data on mercury discharges is available, there seems to be little point in going into details here. Conditions in an ordinary mercury discharge are not very simple. Unless special precautions are taken the vapor density will depend on the current and, furthermore, the situation is complicated by the presence of the rare gas. A mercury discharge, however, is particularly well suited for observations of the striations in the monochromatic light of a single spectrum line, which will be discussed in the next section.

IX. SPECTROSCOPIC OBSERVATIONS IN THE STRIATIONS

For this purpose a General Electric type H-6 quartz mercury tube was used which has a diameter of about 0.25 cm and the electrodes 2.8 cm apart. The tube was used at low currents (about 1–10 ma). The discharge was then a glow discharge and showed typical oscillations. At 2.35 ma, for instance, the frequency was 10750 sec^{-1} and the voltage oscillation as high as 50 volts.

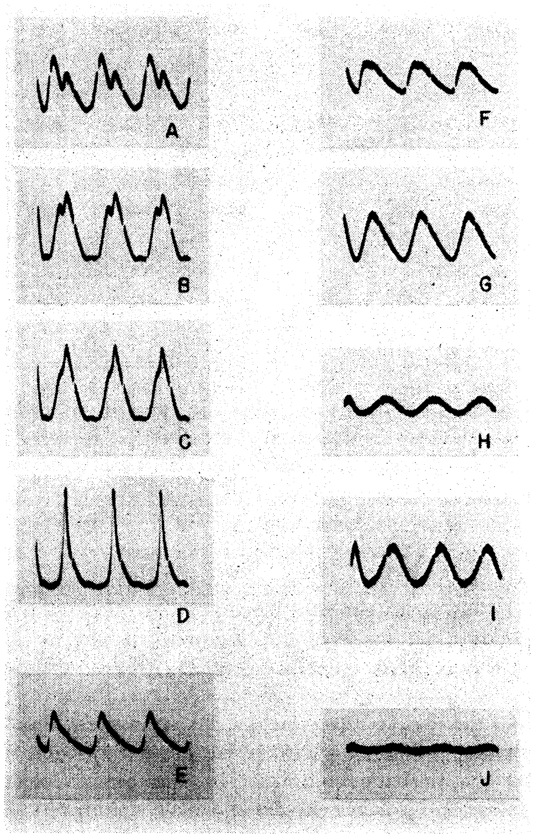

Fig. 11. Light intensity oscillations in argon at 2.1 mm pressure and 3.83 ma current. Time markers are 100 μs apart.

A: 12.54 cm from cathode.
B: 12.24 cm.
C: 12.16 cm.
D: 11.80 cm.
E: 2.68 cm.
F: 2.15 cm from cathode.
G: 2.16 cm.
H: 1.70 cm (Faraday dark space).
I: 1.29 cm (Negative glow).
J: 0.83 cm (Crookes dark space).

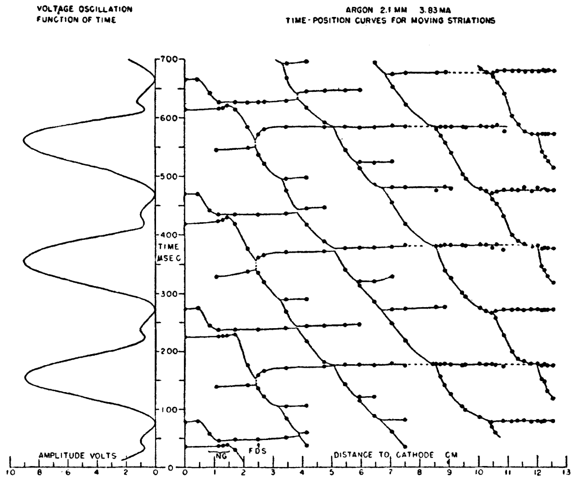

Fig. 12. Time-position curves and voltage oscillation for striations (see Figure 11) in argon at 2.1 mm pressure and 3.83 ma current.

An image of the discharge tube was focused on the entrance slit of a one meter grating spectrograph by means of a system of mirrors indicated in Fig. 15. This made it possible to examine spectroscopically any point in the discharge. An exit slit on the focal curve of the spectrograph would isolate any desired spectral line. A multiplier photo-tube received the light of this line and the output of the photo-tube was analyzed with the oscillograph in the manner described earlier. In this way the five mercury lines at 2537A, 4358A, 4047A, 5461A, and 3660A were investigated. The three lines 4047, 4358, and 5461 have the same initial state (7^3S) with an excitation potential of 7.69 volts. These three lines should have the same excitation characteristics and this was found to be true. The initial state of the 3660 line ($6^3D \rightarrow 6^3P_2$) has an excitation potential of 8.80 volts and is not sufficiently different for any changes in excitation to show up experimentally. Within the limits of experimental errors this line behaves in the discharge like the three visible lines. The 2537 line, on the other hand, has a considerably lower excitation potential (4.9 volts) and it behaves differently in the discharge.

When the intensity oscillations are observed at a given place in the tube, it turns out that the 2537 striation is definitely ahead of the other striations by about 15 μsec. Although this is a small effect it is consistent and unmistakable. Self-absorption, which may be considerable for 2537 if the mercury pressure is high, probably plays no significant part at the low currents (5.6 ma) and short path lengths. Even if there were appreciable self-absorption it is hard to see how this could shift the position of the maximum. We must conclude, therefore, that the atoms responsible for the emission

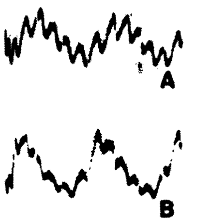

FIG. 13. Light intensity oscillations in argon at 4.4 mm pressure and 8.60 ma current. *A*, 3.31 cm from the cathode; *B*, 3.68 cm from the cathode. The small peaks are due to negative striations.

of the 2537 line travel ahead of the atoms in a higher state of excitation.

X. INTERPRETATION

The results reported in this paper indicate that any theory of the glow discharge should contain oscillations and moving striations as an essential or at least very important feature. For the work here presented shows that oscillations occur almost universally in glow discharges and under conditions hitherto believed to produce stationary discharges. Oscillations and moving striations are not exceptional cases but are almost always present within a large range of pressure and current *whenever a positive column exists*. Therefore, it is to be suspected that they play an essential part in the mechanism of the glow discharge. The rare cases in which striations are absent probably should be regarded as exceptions.

While many of the fundamental properties of the oscillations have been presented in this paper, this work is by no means complete. Work on other important features of oscillating glow discharges has by this time been nearly completed in this laboratory and the results are scheduled for early publication. Thus the experimental data are not yet complete. An attempt to develop a detailed theory of the glow discharge must wait until these further quantitative experimental data are available.

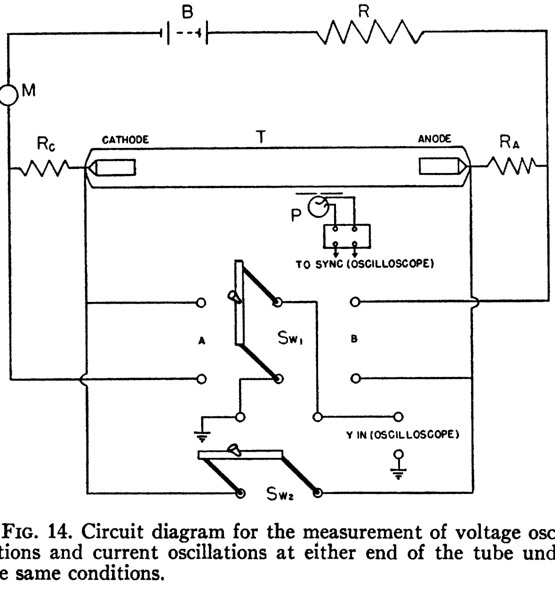

FIG. 14. Circuit diagram for the measurement of voltage oscillations and current oscillations at either end of the tube under the same conditions.

B: Twenty-five dry batteries, 45 volts each.
R: Variable resistance, 0–100,000 ohms.
R_c, R_a: 6000 ohms.
P: Photo-tube.
SW_1: Permits observation of cathode current in position *A*.
SW_2: Permits observation of anode current in position *B*.
SW_2: When closed with SW_1 open permits observations of voltage oscillations.

However, the observations reported here do suggest a tentative mechanism which is presented as a working hypothesis for the guidance of further experiments, rather than as a definite theory. This mechanism, which suggests the principal role of the moving striations in sustaining a glow discharge, fits in a qualitative way much that has been discovered about the striations thus far, though it by no means explains everything. In particular, it should be noted that the following sections do not apply to discharges through diatomic gases.

Although the problem of describing the distribution of potential, positive, and negative ion current, and electron temperatures as functions of the total current density, the gas pressure, and the type of gas molecule has never been satisfactorily solved either in the case of a discharge with or without positive column, still a fairly consistent picture of the mechanism of gaseous conduction has been developed. In terms of this mechanism the current at the electrodes would suffer fluctuations in time of a statistical nature only. Each of the electrons produced per positive ion striking the cathode must produce $1/\gamma$ ion pairs in the fall space where γ is the number of electrons emitted per positive ion. The primary and secondary electrons after passing out of the region of high field strength in the cathode fall and after losing energy in the negative glow then travel into the positive column. The number of electrons passing any surface in the positive column per unit time is essentially constant. Thus there is a steady current at the cathode and at the anode.

TABLE III. Voltage and current oscillations in argon, $p=12$ mm. Direct current: 21.7 ma. Frequency: 3400 sec^{-1} (Mode IV).

Time of peak (μsec)	Δi_a (ma)	Δi_c (ma)	$(R+R_a)\Delta i_a$ (volts)	$R_c\Delta i_c$ (volts)	ΔV (measured) volts
			$R=20{,}000$ ohms		
150	0.36	0.38	9.3	2.3	11.5
190	0.28	0.26	7.4	1.6	8.9
240	0.46	0.43	11.9	2.5	14.4
			$R=12{,}500$ ohms		
150	0.46	0.49	8.6	2.9	11.5
190	0.37	0.36	6.8	2.1	8.9
240	0.56	0.49	10.4	3.0	13.4
			$R=6{,}000$ ohms		
150	0.62	0.64	7.5	3.9	11.3
190	0.48	0.49	5.8	2.9	8.8
240	0.68	0.67	8.1	4.0	12.2

However, one critical phase of this process has been generally overlooked. There is a difficulty concerning the process whereby the electrons, after passing out of the region of large positive space charge in the fall space

TABLE IV. Relation between the observed voltage oscillations (ΔV) and excitation potentials of the vapor atoms.

	V_e (ev)	V_i (ev)	ΔV (v)
Hg	4.9	10.4	5.4
Kr	9.9	14.0	10.1
A	11.6	15.8	12.4
Ne	16.6	21.6	14.4
He	19.8	24.6	16.6

and losing a considerable part of their energy by excitation in the negative glow, pass into the supposedly uniform field region of the positive column. There is certain to be a considerable accumulation of electrons in the negative glow, for somewhere in this glow the sign of the space charge must change and become negative. There is even good evidence that the electric field becomes negative there. Thus there would actually be a minimum in the potential near the Faraday dark space and a trap would exist for electrons in the negative glow around the corresponding potential maximum. Unless it can be shown that electron diffusion against this field is sufficient, the current delivered to the positive column will not be steady but will decrease as the negative space charge in the negative glow increases and spreads toward the cathode. The attendant decline in the field of the Crookes dark space will then cause the current at the cathode to diminish and presumably the discharge would tend to be extinguished due to the critical nature of the value of the cathode fall.

To arrest this process before it has developed too far it is necessary to find a means of removing the excess electrons which have accumulated in the negative glow. It seems certain that the moving striations of the positive type are regions of high positive space charge which travel toward the negative glow. When one of these striations preceded by a region of high field has come sufficiently close to the trapped electrons the barrier will be lowered and the electrons will be released to travel as a burst toward the positive striation. Such a burst is a negative striation. These striations are indeed observed to originate in the rear of the negative glow (see Fig. 7 at 620 μsec, 510 μsec, and 400 μsec, or Fig. 12). When the electrons leave they apparently leave behind a positive space charge which begins at once to travel toward the cathode through the negative glow. This advancing potential wave raises the cathode fall, causing enhanced emission at the cathode and the resulting flow of electrons appears as a negative striation which travels across the Crookes dark space and meets the oncoming positive striation at the cathode edge of the negative glow. There the positive and negative space charge waves tend to neutralize each other and the process of electron entrapment begins again because the positive striation in the positive column by this time has been neutralized by the negative striation which it drew out of the rear of the negative glow.

A trapping procedure similar to that in the negative glow will also be effective in the positive striation. Obviously, there is high excitation in the positive striation, the electrons losing energy in inelastic collisions, and a concentration of electrons builds up. The flood of electrons in the negative striation feeds so much charge into this trap that a plasma of low total charge density is formed, both striations stop, excitation and light emission decrease, and the positive striation ceases to be an effective agent for the removal of electrons from the negative glow. Once again the discharge current decreases and electrons accumulate in the negative glow.

However, another positive striation will eventually draw close enough to the place where the first pair stopped to release the trapped electrons there. The negative striation is then observed to leave this region and to travel to the oncoming positive striation, causing it to stop in its turn. However, the release of electrons leaves the first positive striation, now somewhat reduced in strength due to loss of ions while it was stopped, free to move again toward the negative glow. It increases in strength until once again it is able to release electrons from the glow.

The cycle described above is then repeated since eventually the second positive striation will lose its trapped electrons as a negative striation to a third and move on toward the cathode and the first trapped striation.

Eventually the first striation becomes free so close to the negative glow that it travels all the way to the

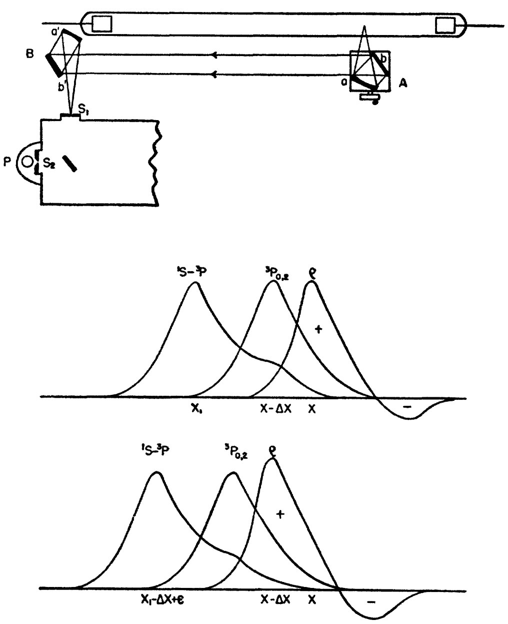

FIG. 15.

Top: Optical system used to observe individual spectral lines in moving striations. *A*: Carriage with pinion which moves on a rack parallel to the discharge tube. *a*, *a′*: Spherical mirrors. *b*, *b′*: Plane mirrors making a 45° angle with *a* and *a′*. s_1, s_2: Entrance and exit slits of a one-meter Eagle grating spectrograph. *P*: Photo-tube.

Bottom: Possible distribution of space charge, ρ, of mercury atoms in the metastable states, $^3P_0$ and $^3P_2$, and the probability of the $^3P \rightarrow {}^1S$ transition at times t and $t+\Delta t$.

cathode edge of the glow where it is met by a negative striation from the cathode. This is usually an occasion of absolute maximum light emission and current in the cathode layers.

The entire cycle is then repeated with the second positive striation now drawing negative striations from the negative glow. The number of negative striations leaving the glow between the times two positive striations reach it determines the number of stationary striations (electron entrapment) per wavelength in the positive column.

The cathode fall, it should be noted, is never so much reduced that the process of ionic bombardment and electron emission at the cathode is greatly impaired. The fluctuations in current are usually only a small percentage of the total current. The negative glow never becomes dark, and there is always a steady undercurrent of electrons through the positive column as is attested by the fact that even while the positive and negative striations are bound to each other and at rest, light emission does not fall completely to zero in that region. This steady stream of electrons, however, is of low energy between positive striations and does not cause any excitation there except during the period when it is enhanced by a negative striation and both current density and field are strong.

It should be emphasized that the time of current maximum at the cathode is that instant at which electron emission is copious due to the reduced negative charge in the negative glow; i.e., when a negative striation leaves the cathode. This is inevitably observed to be the case.

In the positive column the electron bunches pass from one positive striation to the next, each positive striation periodically releasing them from the one ahead of it and traveling toward the cathode between entrapments. It remains to say how the positive striations arise in the first place near the anode. For this the picture is not too clear. Positive striations are always observed to leave the anode at a time of current minimum; i.e., when the voltage across the discharge tube is maximum between the occasions of strong emission (striations) at the cathode. Apparently, as one positive striation draws away from the anode the electrons traveling between this striation and the anode arrive near the anode with ever increasing energy (for the total tube voltage is also increasing) until they have built up a large cloud of ions in front of the anode. This space charge to a certain extent will shield the anode and the current will drop until the space charge has built up enough to be moved away from the electrode by the mechanism of striation movement described in the next section. Thus it becomes a positive striation and sets out for the cathode until it stops a negative striation somewhere near the anode. This negative space charge is usually released to the anode itself when the anode has risen to a potential high enough to draw it away.

Evidence which further supports this qualitative picture has been obtained and will soon be reported.

XI. CUMULATIVE IONIZATION IN MOVING STRIATIONS

At least two important points remain to be discussed. These are the matter of how ionization takes place in the positive column and of why the positive striations move. It is possible that the two processes are related; that the manner in which ionization occurs near a striation tends to cause the positive ion concentration to shift toward the cathode. Suppose, for example, that in a gas the only levels excited to any appreciable extent in the positive column by collisions between electrons and unexcited atoms are those low lying ones of which some are metastable, and that the only effective process by which large numbers can attain higher levels of excitation and ionization is collision between electrons and metastable excited atoms. In other words, electrons with energies much greater than the first critical potential of the gas rarely occur in the field of a positive striation. Then at some instant, if there should exist in the gas the following distribution of ions and excited atoms, such a configuration should tend to preserve itself by moving in the direction of the cathode.

Let there be a positive space charge peak at some point x. Here, for a reason which will become clear, the concentration of metastables should be low, but should rise to a maximum just on the cathode side of x, say at $x-\Delta x$ (Fig. 15). Finally, suppose that at the same moment the rate of production of metastable atoms, due to impacts by electrons which have gained energy in the field of the positive space charge, is greatest still farther toward the cathode at x_1. This situation would exist if the electrons had risen in energy so that the peak in their energy distribution were just above the energy levels of the metastable states when they arrive at x_1. Near x_1, then, much excitation of these levels but little in any higher levels would take place. The electrons leaving x_1, after a sharp drop in energy due to inelastic collisions there, would gain energy again in the region to the cathode side of x where the space charge concentration exists. Thus when they get to $x-\Delta x$ where the concentration of metastables is high they would begin to produce highly excited atoms as well as ions. At x not much ionization would take place due to the low concentration of metastable atoms there and due to the losses in electron energy near $x-\Delta x$. Thus in time a concentration of metastable atoms would be built at x_1, while the ion concentration would rise and the metastable population decline at $x-\Delta x$. At x no new ions are being produced, so the ion concentration there falls due to the various factors which contribute to the loss of ions, such as lateral motion to the walls and recombination in the gas. Beyond x the electrons which even at x could not produce many excited atoms because of their low energy and because of the scarcity of metastable atoms, lose energy in a negative field and no longer contribute any excitation. Thus after a time Δt the space charge configuration which was at x has moved to $x-\Delta x$, the metastable peak which was at $x-\Delta x$ has moved toward x_1, while the number of metastable atoms at $x-\Delta x$ has declined due to the cumulative excitation and ionization which have removed them. In turn the peak production of metastable atoms is no longer at x_1, but at $x_1-\Delta x\pm\epsilon$ because of the shift in space and perhaps in strength of the source of the local field. Such a mechanism would tend to produce a movement in the striations. Whether it is sufficient to explain the entire motion remains to be determined.

There are two consequences of such a theory which can be tested easily. First of all the speed of the striations should depend on the rate of production of metastable atoms and their consequent removal by collisions into higher states in such a way that the striations are fastest when they are brightest. This is indeed a very noticeable feature of the moving striations. On the other hand, it is not a property uniquely belonging to this mechanism. For if the motion were entirely due to the fact that the striations are positively charged configurations in an electric field, the electric force would be highest when the total number of ions (hence also the number of excited atoms) is highest, and high speed and strong emission would again coincide.

The second consequence would have to do with the spectroscopic study of the striations. In a mercury vapor discharge, for instance, it would be possible at any instant to locate the point x_1, because this point at which the excitation of the metastable levels of the Hg triplet ^3P is at a maximum would also correspond to a maximum in the radiation at $\lambda=2537$A due to transitions from the one level of the three that is not metastable. This peak in 2537A should lie at a given time to the cathode side of the peaks of radiation at all other wavelengths which should *coincide* at the point $x-\Delta x$. The intensity of 2537A emissions at $x-\Delta x$ should surely not be as high as it is at x_1 for a few electrons attain sufficient energy at $x-\Delta x$ to produce the $^3P_1$ level directly and only a fraction (much less than unity) of those atoms raised from $^3P_0$ or $^3P_2$ to higher levels return to the ground state via $^3P_1$. Beyond x all radiation should decrease. Of course, it would be necessary for the peak excitation of the higher levels to reach x_1 in a time short enough that an appreciable population of metastables could still be present there. An interval of about 10^{-5} sec does not seem to be inordinately large.

These are just the results of the investigation in a mercury vapor discharge as described in Sec. IX. In fact, when the oscillograph traces of intensity at 2537A, 4358A, and 3660A are compared, it is difficult to find any interpretation of the results but the one outlined above. It will be noted, finally, that the 4358 and 3660A peaks follow the 2537A past no point by more than 2×10^{-5} sec. There should be a large number of metastable atoms left after a period so short.

The foregoing picture is vague in many respects and will need to be implemented or changed to account for some of the observed phenomena. The chief purpose of the experiments now under way is to gather material with which the further development of the theory can be freed from uncertainties. In particular, it is desirable to develop the theory to such an extent that it will yield quantitative results which can then be compared with the large body of quantitative data furnished by the experiments.

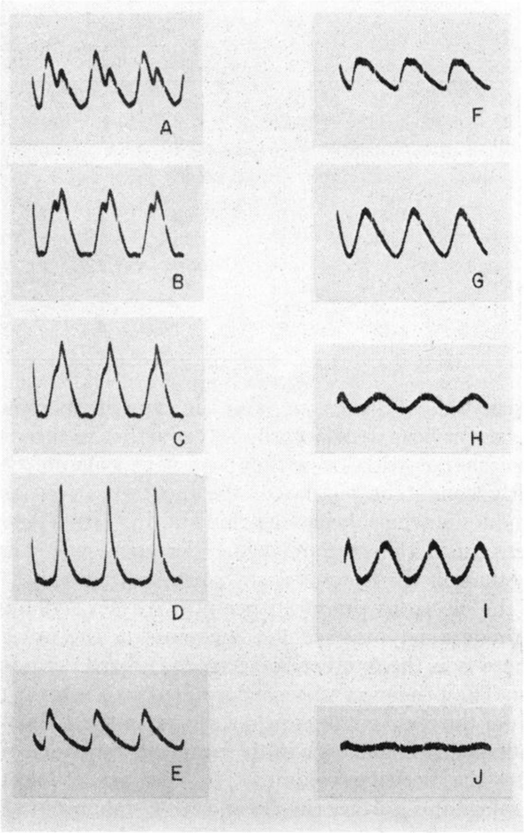

Fig. 11. Light intensity oscillations in argon at 2.1 mm pressure and 3.83 ma current. Time markers are 100 μs apart.

A: 12.54 cm from cathode.
B: 12.24 cm.
C: 12.16 cm.
D: 11.80 cm.
E: 2.68 cm.
F: 2.15 cm from cathode.
G: 2.16 cm.
H: 1.70 cm (Faraday dark space).
I: 1.29 cm (Negative glow).
J: 0.83 cm (Crookes dark space).

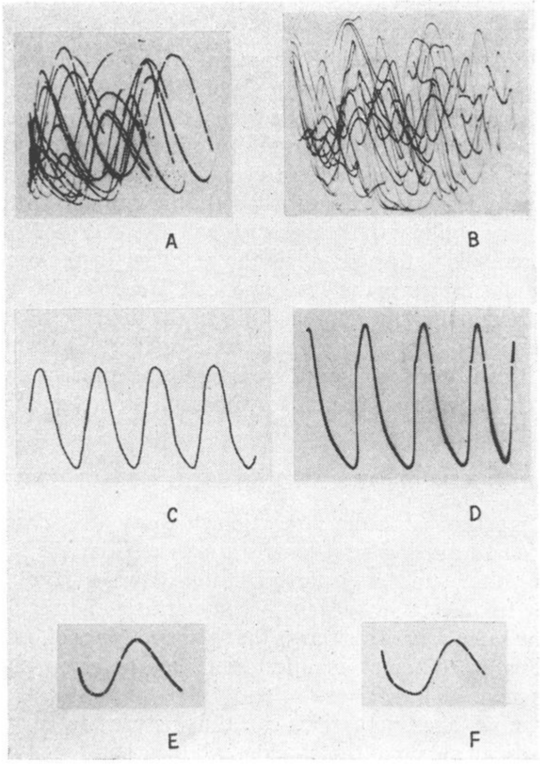

FIG. 2. Voltage and light intensity oscillations in a dc mercury vapor-argon glow discharge. The argon pressure was 4 mm. The sweep-length is 1000 μs with markers every 100 μs for A, B, E, and F.

A: Light intensity 4.83 cm from anode; current, 6.00 ma.
B: Voltage oscillation; magnitude 7 volts for same conditions as A.
C: Light intensity 11.60 cm from anode; current 6.00 ma.
D: Voltage; amplitude of sharp rise 5.72 v for same conditions as C.
In C and D the sweep-length is about 3500μs.
E: Light intensity 5.70 cm from anode; current, 5.12 ma.
F: Light intensity 6.04 cm from anode; same conditions as E.

The frequency in E and F is 1333 sec^{-1}.

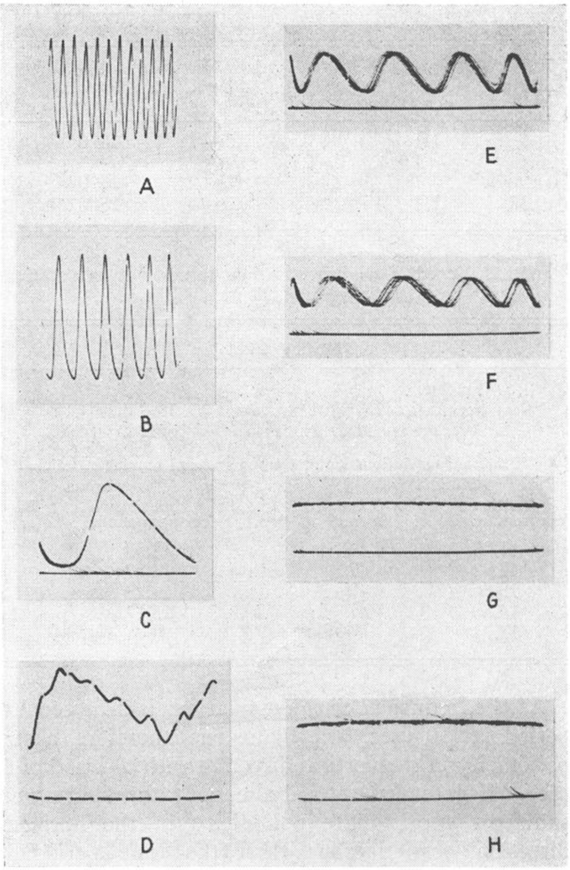

FIG. 4. Voltage and intensity oscillations in argon at 12 mm and 30 mm pressure. Time markers are spaced 100 μs. In *C*, *D*, *E*, *F*, and *G* the lower trace is the line of zero intensity provided by an electronic switch.

12 mm pressure
A: Voltage oscillation at 31.0 ma.
B: Light intensity 20 cm from cathode at 31.0 ma; frequency, 1866 sec^{-1}.
C: Light intensity at 114 ma; frequency, 1470 sec^{-1}.
D: Light intensity at 195 ma; frequency, 1665 sec^{-1}.
30 mm pressure
E: Light intensity 25.2 cm from cathode at 95.2 ma; frequency, 2600 sec^{-1}.
F: Light intensity 25.2 cm from cathode at 144.0 ma; frequency, 2460 sec^{-1}.
G: Light intensity 25.2 cm from cathode at 150.0 ma.
H: Light intensity 25.2 cm from cathode at 270.0 ma.

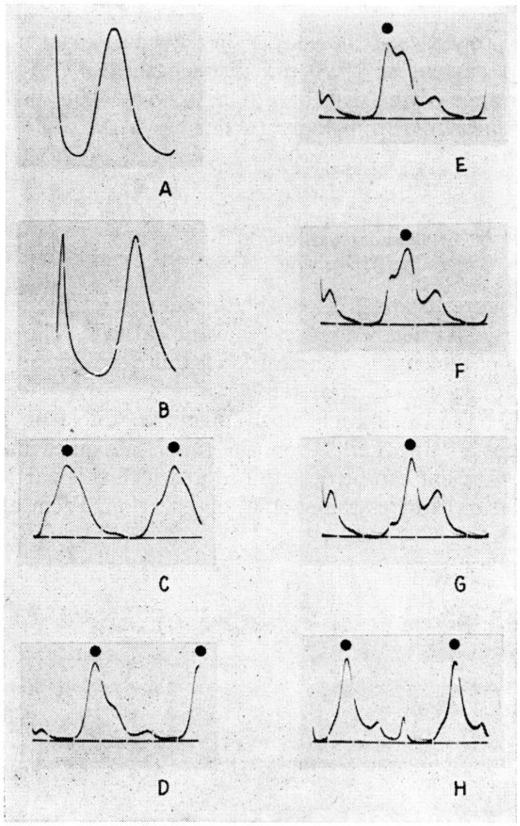

FIG. 5. Oscillograph pictures of moving striations in argon at 12 mm pressure. The markers on the sweep are 100 μs apart. The zero line (C–H) is provided by an electronic switch. The dot identifies the principal positive striations (C–H).

A: Light intensity 12.45 cm from anode at 31.0 ma.
B: Light intensity 14.75 cm from anode at 31.0 ma.
C–H: Light intensity in positive column at 19.20 ma; frequency, 2438 sec^{-1}.
C: 4.83 cm from cathode.
D: 4.05 cm.
E: 3.80 cm.
F: 3.67 cm from cathode.
G: 3.45 cm.
H: 2.53 cm.

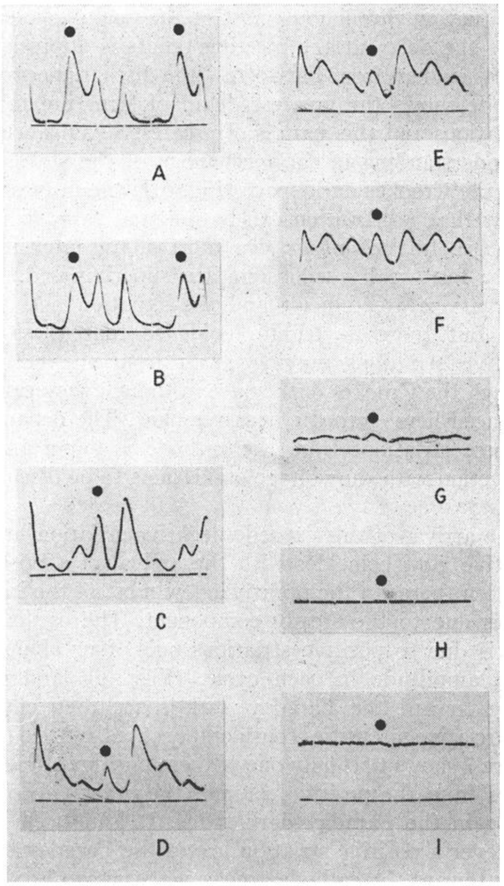

FIG. 6. Oscillograph pictures of moving striations near the cathode in argon at 12 mm pressure. Markers 100μs apart; current, 19.20 ma. The dot identifies the principal positive striations.

A: 2.18 cm from cathode.
B: 2.05 cm (Faraday dark space).
C: 1.89 cm.
D: 1.72 cm.
E: 1.60 cm (Negative glow).
F: 1.56 cm.
G: 1.50 cm.
H: 0.70 cm (Crookes dark space).
I: 0.22 cm (Cathode glow).