The Mechanism of the Positive Point-to-Plane Corona in Air at Atmospheric Pressure

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(Received November 5, 1938)

Attention is called to the fluctuating character of the current in the positive point-to-plane corona in air at atmospheric pressure. It is shown that in the self-sustaining corona the current is due to a large number of individual current-pulses or bursts which are distributed over the surface of the point in regions of adequate field strength. The bursts of current are quite random in time, space, and intensity, and in general are composed of many successive avalanches of electron ionization which flow into regions of high field strength caused by space charges left by preceding avalanches. These bursts propagate outward across the gaps until extinguished by space charge accumulations, diffusion, self-repulsion, and ion migration in the field as well as by infelicitous coincidences of avalanche and the space charge distribution in the gap. The succeeding electron avalanches are initiated in air by photoelectrons produced in the gas ahead of the point. Evidence of an electrical, visual, and photographic character is presented confirming the existence of bursts and giving orders of magnitude of various features under operating conditions. The ionization produced is most intense at the point in the early stages and the number and intensity of the bursts increase with field strength. The development of a burst at one spot is exceedingly rapid (about 10^{-8} sec.) and is followed by a longer period (of about 10^{-6} sec.) as regards that spot, in which the field clears the space charge. In air it appears that the *self-sustaining* corona requires a high enough potential to overcome the space charge, an adequate current to furnish photoelectrons, and in addition the formation of negative ions to insure that fluctuations shall not break off the discharge. As both the field at the point and clearing field increase, the bursts propagate further into the gap and ultimately form streamers from 6 to 11 mm long. When these catch up with previous extinct space charge streamers further out in the gap, they project themselves further and further towards the cathode much in the manner of the leader-strokes in lightning discharge. If such a streamer striking the cathode creates an active cathode spot the return discharge produces a spark or an arc.

THE late W. A. Hillebrand called attention to the presence in positive point-to-plane corona of luminous streamers in regions where field strengths adequate to support ionization by collision would not be expected to exist. A visual study of such streamers produced in experiments by Leigh convinced Loeb[1] that the fine blue lines observed against the lavender glow in these regions were due to discrete discharges like minute lightning strokes. In the present investigation the discontinuous nature of the current in the positive point-to-plane corona is demonstrated electrically and the orders of magnitude of the essential characteristic are determined.

The circuit arrangement for the electrical study of the characteristics of the positive point-to-plane corona is shown in Fig. 1. Signals from the shock-excited antenna circuit containing the point are picked up by a tuned radio receiver consisting of a simple biased detector circuit with resistance-coupled amplifier. The output of this receiver could be fed into a DuMont oscillograph, an output meter, a counter, or earphones. The signals were strongest when the radio set was tuned to a specific frequency which varied from 2 to 4×10^6 cycles/sec. The source of potential was a conventional 25-kv, Kenotron rectifier. The discharge gap was completely enclosed in a metal box about one meter on the side, inside of which was placed the radio set used to pick up the corona signals. The box was grounded and all leads to and from the radio set were through shielded cables, the shields being grounded to the box. Potentials were measured by a 25-kilovolt electrostatic voltmeter which was calibrated against one of the standard Taylor resistance towers of the Physics Department. Since this voltmeter was not sensitive to small changes in voltage, a 200-megohm resistance tower, R_1, was used in conjunction with one section of a White potentiometer as a secondary method; the potentiometer resistor was set so that it checked with the full scale reading of the electrostatic voltmeter. The potentiometer was capable of reading differences of potential of ten volts. Current was measured by a Weston microammeter, P_0, having

[1] W. Leigh and L. B. Loeb, Phys. Rev. **51**, 149 (1937).

three and thirty microampere scales and also by measuring the voltage drop across a 1000-ohm resistor, R_2, with the remaining section of the White potentiometer. This last instrument was sensitive to changes of current of the order of 10^{-11} ampere. The discharge gap used in open air consisted of a six-inch brass plate, P_s, having rounded edges as the grounded electrode and points of several different materials and shapes as the high potential electrode. Most experiments were conducted with platinum points having a cylindrical body and a hemispherical end. A few experiments were made with sharp points (commercial sewing needles) having a conical point with an included angle of about 30 degrees, and one experiment was performed with a set of confocal paraboloids as a discharge gap. Several types of pick-up were used. Either a radio antenna T could be tuned to pick up signals at a frequency determined by the small coil C inserted in series with the point, or else it could be connected through a capacity C_1 across the resistor R_3 in series with the plate. At times a tuned circuit was placed across R_3, giving large signals of calculable frequency which could be picked up by the circuit. In general the signals picked up by the radio antenna and by the untuned resistor R_3 were quite similar, and in discussion we will present only those oscillograms picked up by R_3. The tuned circuit connected with R_3 complicated the oscillograms by superposing oscillations on already complicated signals. They served, however, clearly to show the high rate of current change in the states of corona current and their random character.

Typical oscillograms obtained are shown in Figs. 2 and 3. Fig. 2*A* shows an oscillogram obtained of the *intermittent* corona near onset with low amplification. The fluctuations giving rise to the *noise* are the *small* irregularities. The larger vertical lines apparently indicate *points of temporary extinction of corona.* These observations apply to the very upper limit of the Geiger counter regime discussed by Kip.[2] The amplitude of the current change between corona and no corona relative to the resolved *fluctuations* of the corona itself are of the order of forty-fold.

[2] A. F. Kip, Phys. Rev. 54, 139 (1938).

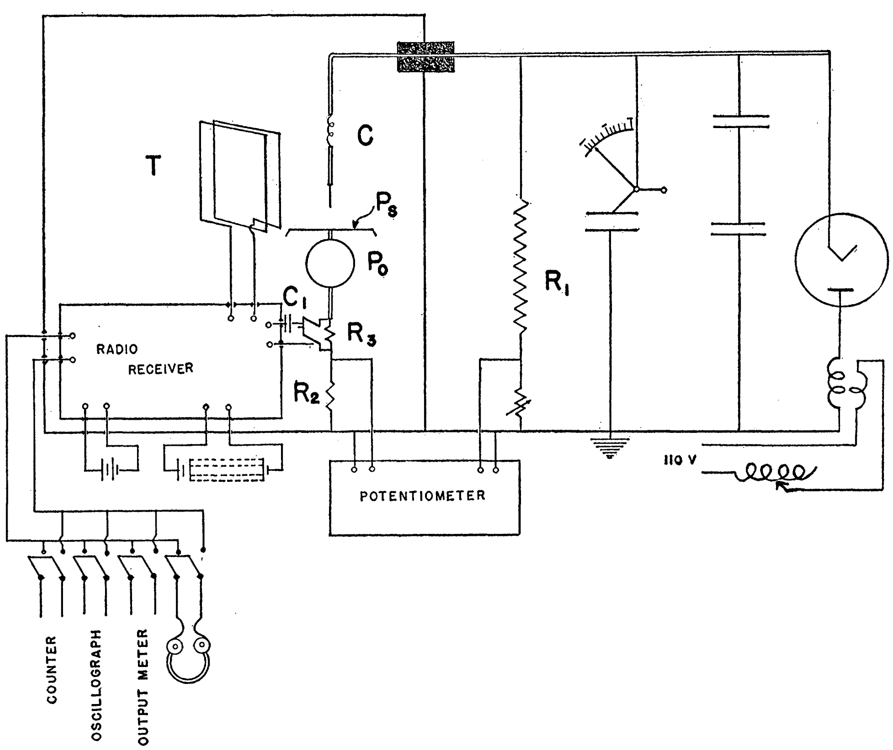


FIG. 1. Diagram of connections used in the study of positive point-to-plane corona.

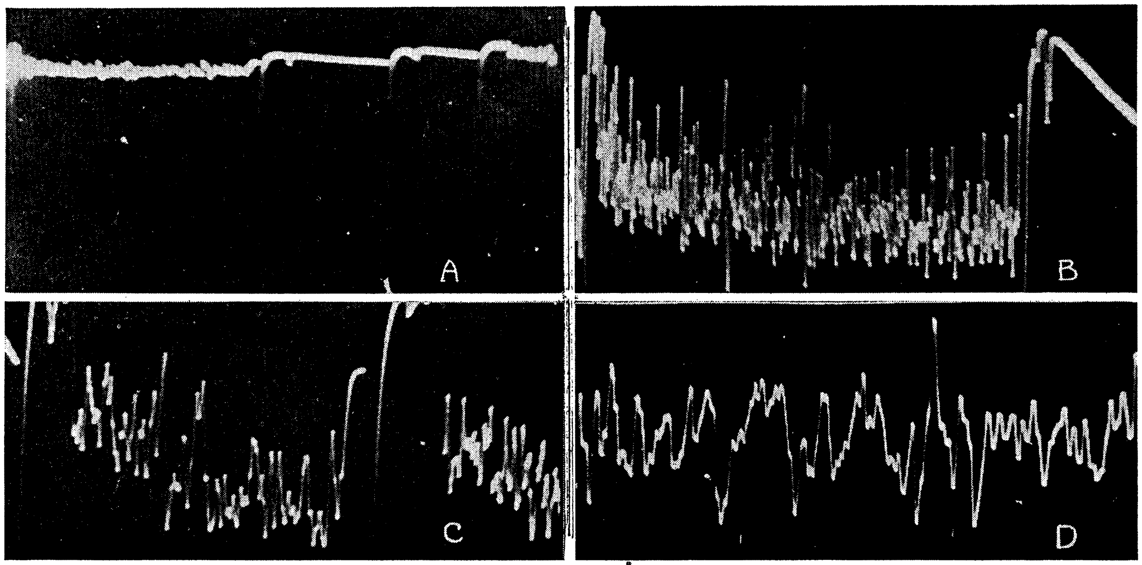


FIG. 2. *A*. Oscillogram of an intermittent positive corona for a current near onset with low magnification. Steady current is 20 to 40 times the amplitude of the oscillations. *B*. Same as 2*A* with large amplification and slower sweep. *C*. Same as 2*A* with larger amplification and the same sweeping rate. *D*. Oscillogram of a section of stable positive corona at 62,500 resolved fluctuations per second, at 1μA current.

Further below onset the fluctuations are relatively much greater. Fig. 2*B* shows the same sort of occurrence at large amplification and with a slower sweep, while Fig. 2*C* shows the greater amplification with the higher sweeping rate. Fig. 2*D* shows the results obtained with 62,500 fluctuations per second and 1μA current. Fig. 3 shows:—*A*, an 8000-cycle timing wave, *B*, the parasitic background of oscillations (no corona and full gain on the amplifier); *C*, *D*, and *E*, the corona in a gap of 3 cm with a point 0.5 mm in diameter with, respectively, 0.5, 1 and 2 microamperes of corona current. It is to be noted that the amplitude of the fluctuations is the greater the smaller the corona current. The self-sustaining corona began at 4.84 kv with current about 0.1μA. It was preceded above 4.75 kv by a region of intermittent corona with vanishingly small currents. Individual bursts of intermittent corona could be seen visually on the oscillograph. We were, however, never fortunate enough to photograph one.[3]

The above observations make it clear that the positive point-to-plane corona current is made up of imperfectly resolved current impulses of extremely high frequency. The fluctuations observed make up only a small fraction of the nearly steady background once the stable corona is established.

To determine the frequency of the current impulses, assumed random, from the frequency of the observed fluctuations the following method was adopted. The oscillograph and amplifier were capable of resolving evenly spaced pulses having frequencies up to 2×10^5 per sec. From the theory of fluctuations if N_0 is the limit of resolution for evenly spaced pulses and if N is the number of individual fluctuations assumed to be random the number z of fluctuations recorded is given by $z=Ne^{-N/N_0}$. In this case z is about 6×10^4 and N_0 about 2×10^5. It follows from the above that N may have either of two values, 10^5 and 3.5×10^5. The fact that the resolution of the fluctuations relative to the whole current is so far from complete favors the assumption of the higher value of the frequency. It also seems to be true that the higher the current, i.e., N, the lower the value of z. This conclusion is also borne out by the fact that no matter how the point circuit was modified the radio pick-up could not be detected at frequencies below 1.8×10^6 cycles.

[3] Very recently individual intermittent bursts of corona in the Geiger region have been photographed by Kip below regular onset by using radioactive ion sources (see Fig. 8).

With low onset current at frequencies N much above 10^6 per sec. the fluctuations in the current despite high rates of change would not have had energy enough to broadcast with the observed intensities.

If we assume, therefore, for convenience that for a corona current of $1\mu A$ from a point 0.5 mm in diameter N is 5×10^5 we can draw the following conclusions. First, the average current per impulse or burst consists of roughly 1.25×10^7 ions. Visual observation with a telemicroscope shows that with this current the point is covered with a thin sheath of glow of maximum intensity *at* the surface of electrode. The glow just covers the hemispherical end over an area of 0.39 mm². It is most intense at the point and fades towards the edges where the field is weak. Persistence of vision causes the eye to see as a continuous film of luminosity all the 5×10^4 pulses in about 0.1 second. This gives an area per burst of 7.8×10^{-6}

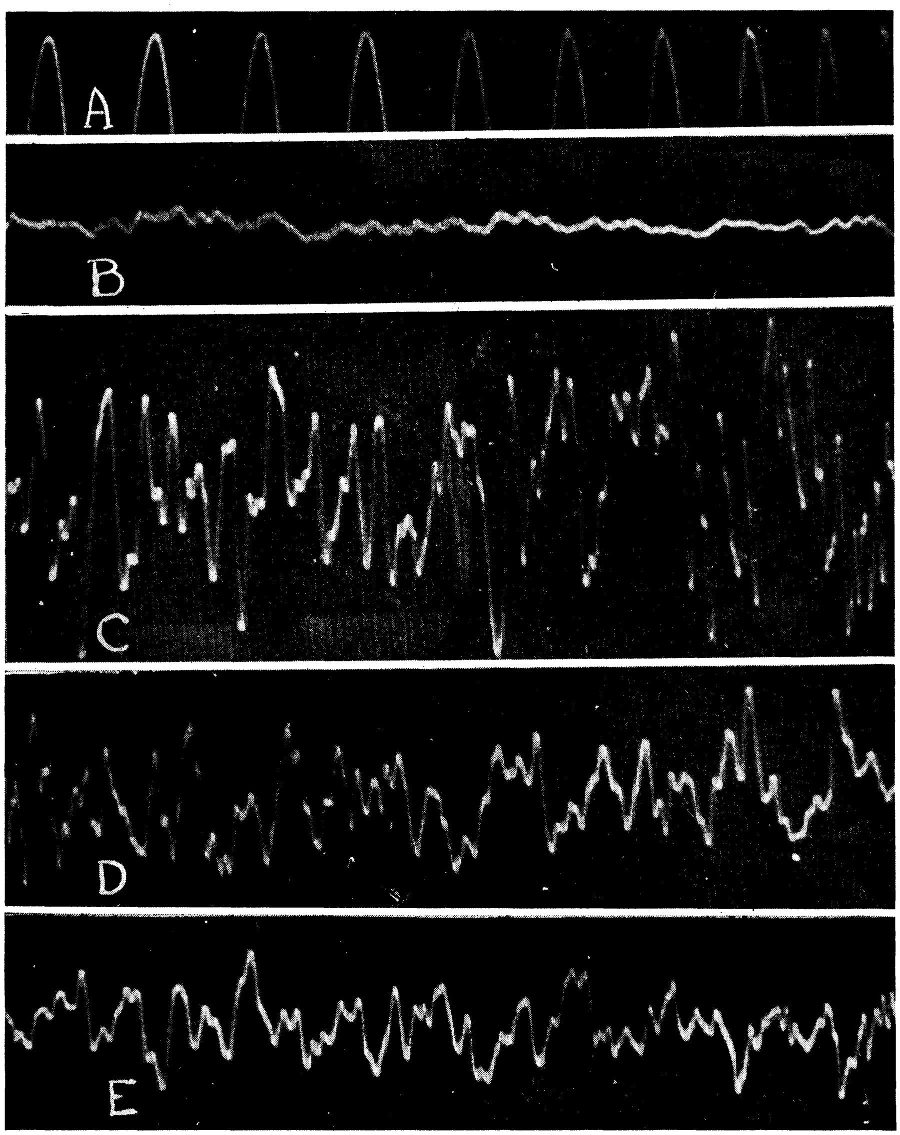


FIG. 3. *A*. An 8000 cycle per second timing wave. *B*. Parasitic background oscillations with full gain on the amplifier and no corona. *C*. Corona with 0.5-mm diameter point, current $0.5\mu A$. *D*. Same as *C* current $1\mu A$. *E*. Same as *C* current $2\mu A$.

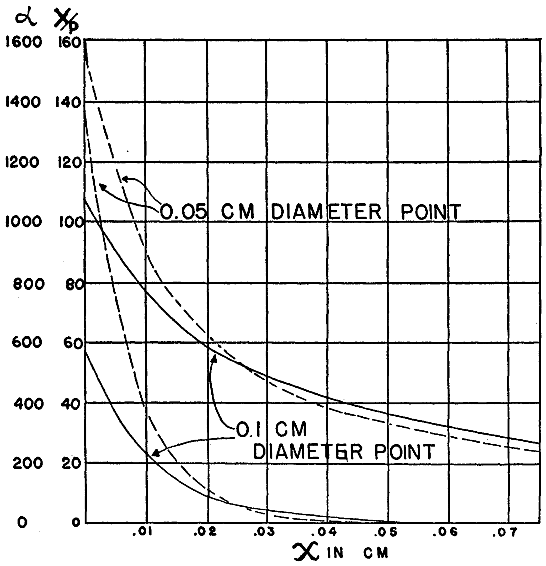


FIG. 4. Field strength divided by pressure, X/p, after Kip and Townsend's coefficient α for ionization by electron impact in air after Sanders as a function of distance from point for 0.05 (dashed) and 0.1 (full) cm diameter points at starting potentials for positive corona. The curves above give the values of X/p. Those asymptotic at about 0.04 cm give the values of α.

mm^2 or individual bursts spaced at about 2.8×10^{-3} mm. These could not be resolved as separate in the telemicroscope and the glow appears continuous. It has the color of the spark spectrum of nitrogen and this is confirmed by recent spectrographs taken by Kip. At higher field strengths when the discharge penetrates into the gap some of the separate steamers, especially with sharp points, can be visually resolved as stated in the introduction.[4] It is seen, therefore, that the estimated frequency of pulses is consistent with visual data.

The character of the current bursts or pulses giving rise to the fluctuations can be inferred from field strength data taken by Kip[5] using confocal paraboloids as electrodes. These estimates may be applied without serious error to the case of the point-to-plane discharge with a point of 0.5-mm diameter and 3-cm gap length. The data are accurate to about ten percent when the fields are undistorted by space charge. The field strength, or better, the ratio of field strength to pressure X/p, can be computed for the onset of the steady-state corona as a function of distance from the point in cm, as shown by the curves of Fig. 4 for points 0.5 and 0.1 mm in diameter. From Sanders' data on the first Townsend coefficient α as a function of X/p for air it is possible to plot the curve of the coefficient α as a function of the distance x from the points. From Townsend's equation for ionization by collision, which says that $n=n_0e^{\alpha x}$, it is possible to determine the greatest distance x at which in these fields an electron from the outside can produce a second electron by setting $n/n_0=2$ and solving for x from the values of α. This gives x as approximately 0.04 cm and a value of $X/p=40$. The values are not materially changed for a point 0.1 mm in diameter. For negative ions the work of Loeb[6] has shown that a value of $X/p=90$ is required before the electron is detached so that it can ionize. Hence if negative ions are to start a burst they must start only from 0.005 cm for the 0.5-mm point and from 0.01 cm for the 0.1-mm point. Since an electron produces αdx ions in a distance dx if one starts with n electrons the number of ions produced in dx will be $dn=\alpha n dx$. Now α as we have seen is a function $f(x)$ of x. Hence $dn/n=f(x)dx$. The number of ions produced by one electron starting at $x=0.04$ cm from the point in its path to the point is given by $n=n_0\int_{0.04}^{0}f(x)dx$. This graphically integrated for the cases above gives $\int_{0.04}^{0}f(x)dx=6.2$ and 11.2 so that $n=450$ for the 1.0-mm point and 73,000 for the 0.5-mm[7] point. Of course occasional electrons will by chance

[4] The appearance of the long separate visible streamers with increasing potential seems to be relatively sudden. This makes the exact process of the development of visible streamers from bursts somewhat difficult to picture. The streamers are most prominent with needle points and can be produced according to recent results of Kip at lower fields by sources of energetic α-rays or properly timed ions. Thus one must not at present speculate too freely on the mechanism of streamer production, except to state that streamers appear to be bursts propagating under certain favorable field conditions.

[5] There is a transposition in Kip's article (reference 2) on page 145, column 1, line 6, after subtitle, *Field Intensities at Onset.* Referring to the 80 and 120 kv/cm in the line above the words *small and large* should be transposed; that is, field strength X is *greater near the small point* than the large point, but changes further out and becomes smaller.

[6] L. B. Loeb, Phys. Rev. **48**, 685 (1935).

[7] It is to be noted that owing to the rapid increase in α with X/p and the short distances involved, the electron multiplication near the smaller point gives larger avalanches at onset than the larger point. This must continue until the point reaches such a size that the distance x, despite large values of α is insufficient for effective ionization. The fields at large points eventually become effective as the effective field becomes large enough at large values of x so that small values of α will suffice.

start out further in the gap and be fortunate enough to ionize producing more ions, and others will give less. Such ion production by a single incoming electron or ion we will call an *electron avalanche.* In the case of a negative *ion* the avalanche because of the short distance will consist of some 10 to 1100 electrons. At higher fields with larger currents or with larger radii the values of x for appreciable field strengths are greater and the avalanches will be larger. It is also clear that the ionization produced will be cumulative towards the point and that the highest ion density, and hence greatest luminosity, will lie at the surface of the point as is observed. This is in marked contrast to the negative point discharge. The high fields will also insure the excitation of spark lines.

The avalanche size which is here computed in contrast to the magnitude of 10^7 ions in the current pulses or bursts in the initial stages of corona discharge, clearly indicates that these two are not the same. There must therefore be some mechanism active in the normal self-sustaining positive point corona which produces pulses, bursts or stabs in place of the usual avalanches. It may, at this juncture, be stated that if by radioactive ionization *enough electrons are furnished* so that the current can be taken care of by the *electron multiplication in avalanches alone,* the pulses or stabs disappear. The clue to the process active comes from the appearance of streamers at higher fields and leads to the following picture. A single electron or ion wandering into the point produces an avalanche of some 10 to 10^5 electrons, perhaps more, depending on point radius and applied potential. These are rapidly drawn into the point and leave a positive space charge ahead of the point, which slowly moves outwards. Such a space charge distorts the field and constitutes a virtual prolongation of the point with an intense local field at its tip, as shown in Fig. 5. In the process of ionization in the first avalanche, especially near the point, the high fields excite the emission of spark lines. These ionize molecules ahead of the space charge photoelectrically.[8] If a new electron finds itself at the proper point ahead of the space charge, it will give a *new avalanche,* still further extending the space charge into the gap. This process of avalanches can repeat itself until the tip of the burst or incipient streamer advances to gradients too weak to allow it to continue, or until the coincidence of electrons from widely different directions of the gas about the space-charge-point so adds to the space charge as to decrease the field intensity about it to such a value that photoelectrons are no longer capable of propagating the point further by successive avalanches. Diffusion and self-repulsion of positive space charge, as well as its motion from the point, will aid in this attenuating action. From the values of the distances and

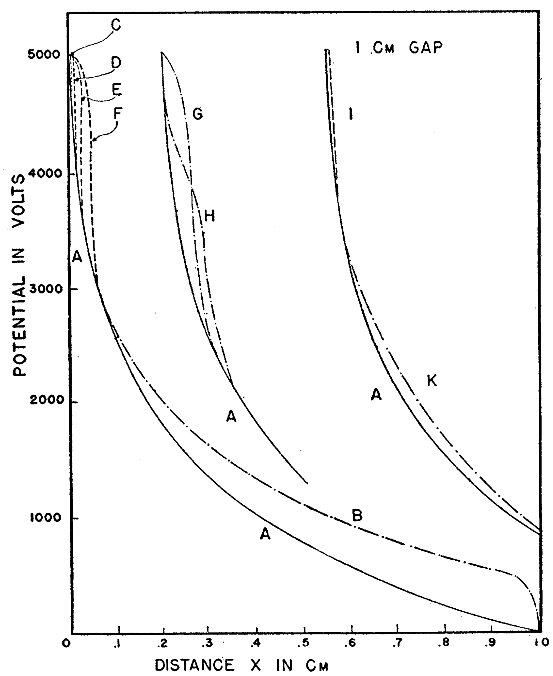


FIG. 5. Potential distribution and burst formation with a 0.5-mm diameter point 1μA current and 1-cm gap. Curve A is the undistorted potential in each case. Curve B shows the space charge distortion near the *cathode* due to extinct bursts. Curves C, D, E, and F show successively the approximate potentials after the first, second, fifth, and tenth avalanches in burst formation. Curves G and H show later stages of a burst where diffusion and movement in the field occur. Curves I and K show a new burst starting as the old one recedes. At higher fields this may overtake the old burst forming a streamer.

[8] In the absence of ionization by positive (reference 9) ions, and of a cathode to furnish electrons photoelectrically or by positive ion impact, the photoelectric ionization in the gas is the only possible mechanism. Such ionization has been directly observed by both Cravath and Dechene (reference 10).

[9] See L. B. Loeb, Rev. Mod. Phys. **8**, 267 (1936).

[10] A. M. Cravath, Phys. Rev. **47**, 254 (1935); C. Dechene, J. de. phys. et rad. **7**, 533 (1936).

fields involved in the process of successive avalanches, the time consumed between producing the burst and its extinction must be exceedingly short; not more than 10^{-9} sec. is required per avalanche and thus perhaps 10^{-8} second for the whole burst. Depending on field distortion and other purely chance factors, the ion production in a *series of such avalanches* will fluctuate widely and may vary from 10^4 to 10^8 or more ions. Such a succession of electron avalanches occurring very closely in time at one point constitute the burst or current stab and are the cause of the fluctuations studied. The average currents in each burst which are of the order of 10^{-12} ampere are at onset apparently large enough to shock-excite the circuit to give a signal, and the rate of change of current responsible must be of the order of 10^{-4} ampere per sec. The number of ions per burst, it is clear, must depend on the field strength, and will increase as the field strength becomes higher and as it extends further into the gap. At first the bursts will be very small and extend but very slightly into the gap as the analysis showed. They will, however, extend well beyond the 0.04 mm calculated for the undistorted field. With adequate fields in a gap devoid of space charge, the burst becomes a streamer extending one or two cm from the point even below onset. If the gap is fouled by space charge the streamers cannot form, and only relatively short bursts are observed. With increasing potentials above onset and in the region of the linear current-potential ratio of Kip[2] the bursts again extend into the gap.

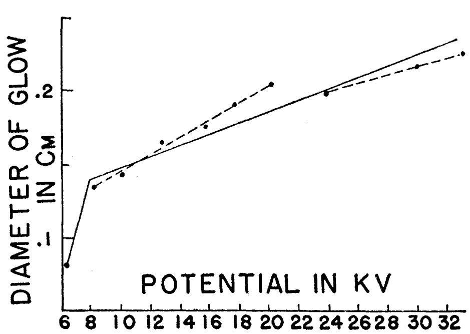


FIG. 6. Plot of the diameter of the glow of the positive point corona as the potential increases.

After the bursts have terminated, the immediate region occupied by them is no longer active until the space charge can be dissipated by the movement of the positive ions in the field away from the point. There is thus a period of inactivity which will be longer the lower the field. The length of this period must lie in the vicinity of the time for positive ions to move 10^{-3} to 10^{-2} cm in fields of 50,000 volts/cm or from 10^{-8} to 10^{-7} second. The photoionization may, however, have started a burst at another neighboring spot on the surface of the point so that wherever the field is adequate there will be a succession of bursts or stabs of current which are completely random in phase and size.

Because of the high electron mobility, electrons are swept out long before the positive space charge can clear itself. Hence there must be a sufficient number of stabs or a sufficient intensity of photoionization so that in the microseconds required for the clearing of the space charge from extinct bursts, new electrons or ions are at hand to again initiate the discharge. In air this action is facilitated by the formation of negative ions by electron attachment in the gas. If ions can be formed from 0.5 cm to 1 cm from the point in sufficient numbers, calculation shows that there will always be a mechanism for the self-sustaining corona. Obviously the *ions* need not always initiate the new burst since timely photoionization by a more distant burst may also be active. However, evidence strongly indicates *that the negative ions are necessary in some gases.* Very pure N_2 gas where photoionization occurs, where electrons are free and where the ionizing radiations are absorbed about as much as in air, *does not give any evidence of bursts, current fluctuations or noise* unless soiled with minute traces of O_2. Pure H_2, which also has free electrons and in which *photoionization of the gas is not likely*, on the other hand does give fluctuations much like air. The presumption is that in the case of H_2, the transparency of H_2 to radiations allows electron emission from distant electrodes and the glass walls, these electrons then arrive in time to perpetuate the discharge. This is confirmed by recent observations in air.

In any case, it is clear that for the self-sustaining corona in air, a value of $X/p=90$ requisite for the detachment of an electron from a negative ion is required at some distance from the electrode, together with sufficient current to

FIG. 7. *A*. Photograph of the positive point corona just before the appearance of streamers. A few incipient streamers may be seen beyond the edge of the glow. Potential 20.0 kv. *B*. Photograph of streamers propagating across the gap shortly after streamer onset. The cathode is distinguished by the glow over its surface. Potential 21.5 kv.

insure a continuous supply of ions or electrons. If the current is too small for this and the field strength becomes so low that adequate avalanches cannot be produced, we reach the Geiger-counter regime studied by Kip[2] in which bursts initiated by a single electron continue for longer or shorter intervals until the space charge of positive ions in transit in the gap so lowers the field that bursts cannot form, or until some inauspicious chance distribution of ions causes the discharge to break off. This is nicely seen in the Figs. 2*A*, 2*B* and 2*C*, and even more strikingly in recent observations of Kip well below the threshold for self-sustaining corona (see Fig. 8). While these discontinuities can be observed by the oscillograph, the light from a single short burst cannot readily be seen at the point, though it might be photographed.

As one raises the potential of a given point, burst production can occur over larger areas of the point as the field in such regions becomes large enough. Hence the glow, unlike the case of the negative corona, spreads evenly and progressively over the surface. At the same time the number of ions per avalanche and per burst increase and extend further into the gap. This extension shortly after onset of self-sustaining corona is not perceptible to the eye but is shown by the camera. From his photographs Kip has plotted the apparent size of the glow for the point and gap discussed in this paper as a function of potential. This is shown in Fig. 6, and it is seen that, except for the first point, the increase is approximately linear. As seen in Fig. 7*A* for the needle point at a potential of 20 kilovolts near breakdown, the high field so clears the space charge that the bursts again begin to propagate as individual streamers of 10^9 to 10^{10} ions, which are longer than the average. Fig. 7*B* shows the same needle point at 21.5 kilovolts. Here the appearance of many streamers can be seen, some of which propagate across the gap. By putting a high resistance in series with the point, breakdown can be inhibited and the gradual spread of the individual streamers across the gap can be seen with the naked eye.

The phenomenon is best seen with the finer points as the voltage range of streamer production is then extended. Eventually the field becomes so high that an extinct positive ion streamer moving away from the point towards the cathode in the field has not progressed very far when some later adjacent streamer propagates out sufficiently rapidly and far to overtake and utilize the ionized path of the extinct streamer. It is thus able to propagate further than its predecessor or than it could have done otherwise. One has then streamer propagation of the leader-stroke character observed by Schonland and Collens.[11] The use of old channels in this fashion can nicely be shown by blowing air

[11] B. F. J. Schonland, Proc. Roy. Soc. **A164**, 132 (1938); also B. F. J. Schonland and H. Collens, Proc. Roy. Soc. **A145**, 654 (1934); **A152**, 595 (1935).

across the lower ends of the streamers. The deflection of the ionized channels by the air blast in the weak field near the cathode causes them to be deflected and the luminosity follows the old channels. When finally the streamers or bursts propagate all the way to the cathode, and create fields at it sufficient to start efficient secondary electron emission at some spot, the leader stroke channel is utilized by the return stroke and results in a spark or an arc. This mechanism thus not only describes the character of the onset and the mechanism of the positive point-to-plane corona in air, but its eventual development to a spark as well. In this regard the later phases show remarkable similarity to lightning stroke propagation in air and to the long sparks photographed by Allibone and Meek.[12]

The writer wishes to acknowledge his indebtedness to Professor Leonard B. Loeb, at whose suggestion the problem was undertaken and under whose guidance it was carried out, for his considerable assistance in interpreting the complicated phenomena observed. He further wishes to express his sincere thanks to Professor L. F. Fuller, Chairman of the Department of Electrical Engineering, for his timely advice and the many courtesies accorded him, and to Professor L. C. Marshall and Dr. T. A. Rogers of the Department of Electrical Engineering, for their kindly advice and the use of the facilities of their oscillographic laboratory. Thanks are also due to A. F. Kip for his assistance in taking oscillographs and for the photographs of corona discharge here shown. To Mr. Walter Noller and to Mr. Ben Davis, senior students in Electrical Engineering, he expresses his thanks for their assistance with the mechanical oscillograph. Finally the writer must acknowledge his sincere thanks for the help afforded by the W.P.A. workers, Mr. Edward Nunes and Mr. R. L. Melton, in building the amplifiers and counters used, and to Mr. F. T. Bogard for his aid in preparing the drawings for this and a previous paper.

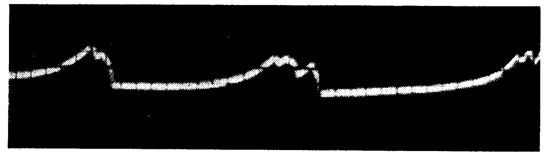
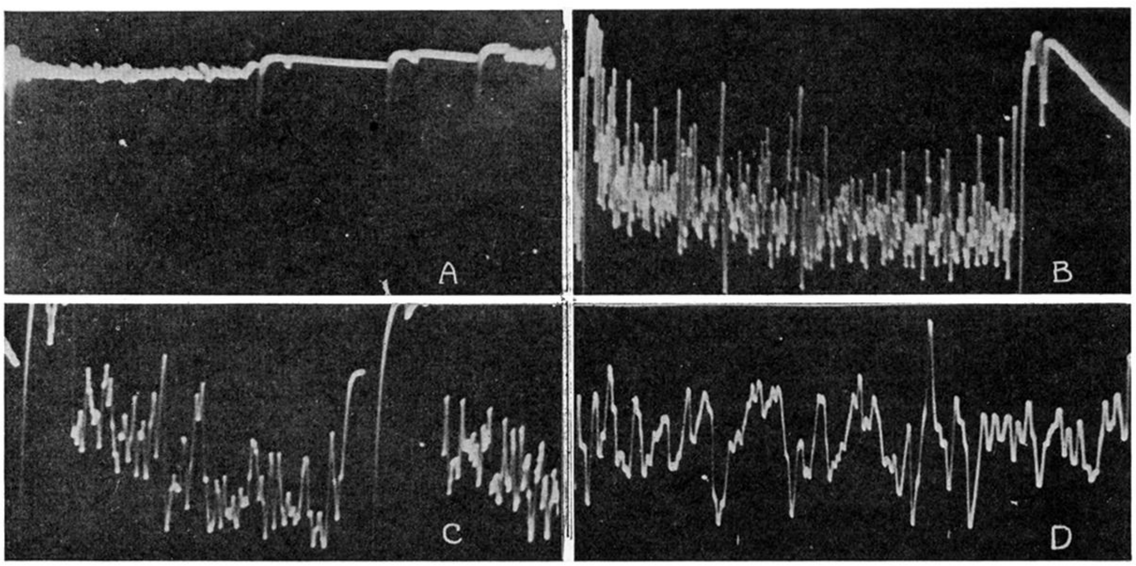


FIG. 8. Oscillograph by Kip showing the intermittent corona just below onset. Three intermittent discharges are seen. The fluctuations cannot be clearly resolved. The sweep is from right to left and the time covered in the oscillogram is 0.015 sec. The asymptotic decline to the left is instrumental.

[12] T. E. Allibone and J. M. Meek, Proc. Roy. Soc. **A166**, 97 (1938).



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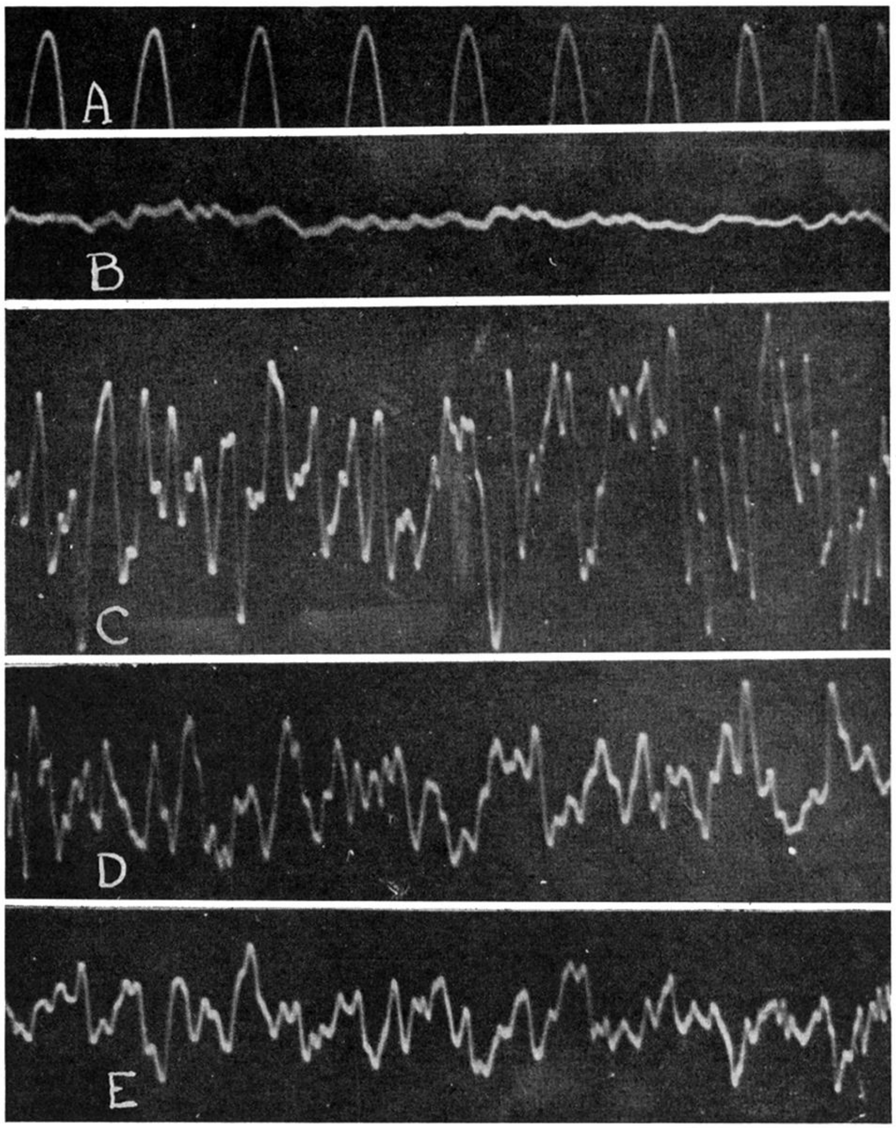


FIG. 3. *A*. An 8000 cycle per second timing wave. *B*. Parasitic background oscillations with full gain on the amplifier and no corona. *C*. Corona with 0.5-mm diameter point, current 0.5μA. *D*. Same as *C* current 1μA. *E*. Same as *C* current 2μA.

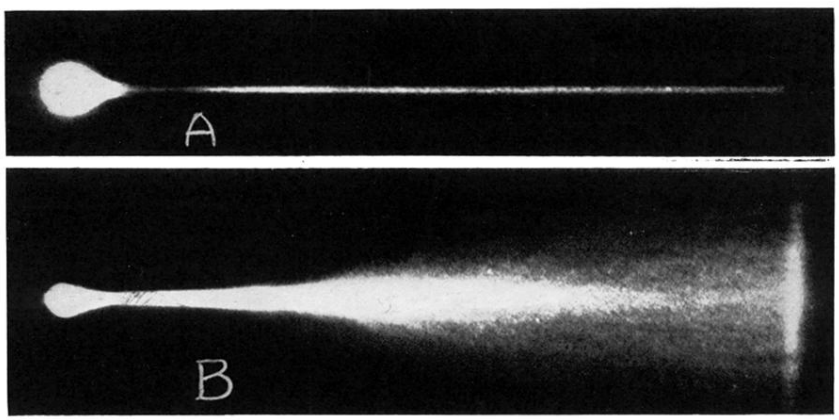
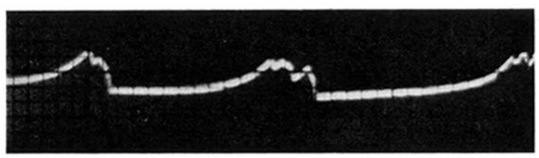


FIG. 7. *A*. Photograph of the positive point corona just before the appearance of streamers. A few incipient streamers may be seen beyond the edge of the glow. Potential 20.0 kv. *B*. Photograph of streamers propagating across the gap shortly after streamer onset. The cathode is distinguished by the glow over its surface. Potential 21.5 kv.



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