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SCIENCE

Ionizing Waves of Potential Gradient

Luminous pulses in electrical breakdown, with velocities a third that of light, have a common basis.

Leonard B. Loeb

The occurrence of luminous pulses accompanied by ionization of gases and traveling at speeds approaching that of light has long been known. As high-resolution devices for studying such phenomena have been developed in recent years, more manifestations of such pulses in all gases over a wide range of pressures, as well as in liquids, have been discovered under diverse circumstances. In this article an attempt is made to collect these diverse observations under the general descriptive term "ionizing waves of potential gradient." When they are thus viewed under a unifying heading, the common circumstances causing their appearance and the relations involved in their propagation become clear. Collected and discussed here are numerous recently discovered examples of such phenomena, observed in this laboratory and elsewhere, some of which are just being reported in print.

Introduction

The transition from the nonconducting, or somewhat-conducting (glow discharge or corona), state to a transient or continuing arc of high conductivity may be achieved in two ways. The first is the classical mechanism in which conventional ionization and heating by current flow gradually build up the conducting state. The fastest growth occurs on a time scale of multiples of the electron transit time across the gap. This growth rate is limited by the velocity of the ionizing electrons in the gas (of the order of 10^7 cm/sec).

The second mechanism involves one very rapid luminous pulse of ionization, or more often a succession of pulses, that have been clocked at speeds ranging from 10^7 to 10^{10} cm/sec. They have been observed to occur in a wide diversity of phenomena in almost all gases at pressures ranging from 10^{-2} torr to 760 torr and above. They unquestionably appear in the very fast breakdown of liquids and solids, but as yet little work on these states has been carried out.

In 1957 the diversity of these phenomena led me to recognize their universal character and to ascribe them to a characteristic common circumstance, though the detailed mechanisms differ in each case. At that time I termed them "ionizing potential space waves" (*1*, *2*). It has been suggested that the term *ionizing waves of potential gradient* is less likely to lead to confusion. In order best to describe and relate the phenomena, I present the material here in chronological sequence.

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Early Observations in Long Low-Pressure Tubes

In 1893, J. J. Thomson (*3*), on applying a powerful induction-coil potential to the anode of a glass tube 15 meters long and 5 millimeters in diameter, filled with air at pressure of about 1 torr, observed the passage of an extremely rapid luminous pulse. With a rotating mirror he estimated the speed to be of the order of 10^{10} cm/sec, a third that of light. James (*4*), in 1904, used the predecessor of the Kerr cell shutter to measure the speed, but the cell was incapable of resolving the short temporal interval. By 1926, Beams (*5*) had improved the Kerr cell shutter. In the course of measuring the duration of luminosity of spectral lines he also resolved the time interval of transit of Thomson's light pulse, confirming Thomson's estimate of the speed. In 1930, having perfected a mirror that rotated at 3000 revolutions per minute, Beams (*6*) discovered that these fast light pulses always started from the high-potential electrode, whether positive or negative. They traversed a tube 4.9 meters long and 5 millimeters in diameter at speeds of about 4×10^9 cm/sec in air, or in H_2, at pressure of 0.04 to 0.5 torr. Beams initiated the pulses by means of triggered spark gaps that broke down abruptly at potentials between 20 and 40 kilovolts. A high-potential source relative to ground, with a very rapid rise in the voltage applied to one electrode, is required to produce such waves.

Observations on Lightning Channels, Velocity Calculations

By 1933 Schonland (*7*) and his associates had perfected the Boys rotating-lens camera to the point where good resolution of the lightning flash was achieved. They observed the negatively charged, downward-branching, stepped leader in the cloud-to-ground stroke. The arrival of the leader at the ground was followed by a return stroke that advanced up the previously ionized channel at speeds up to 10^{10} cm/sec. At later intervals of the order of 10^{-2} second the initial path was traversed by luminous dart leaders advancing from the cloud at speeds from 10^8 to some 10^9 cm/sec; these were followed by new return strokes.

In 1934 Cravath (*8*) showed that a corona discharge in air at pressure of 760 torr produced almost as much photoionization of the air molecules as photoemission from a slightly oxidized copper surface. The absorption coefficient for this radiation in air was 10 cm^{-1}. This indicated that photoionization traveling at the speed of light could act effectively to provide initial ionization of a gas. In 1935 Cravath and I (*9*) attempted to use this concept to explain Schonland's high-velocity pulses. While the photoionization as we attempted to use it did not suffice to solve the problem, we arrived at a mechanism in which the observed speeds could be achieved by existing electrons moving within the limits of their known velocities (*10*). In principle, the theory of Cravath assumes that occurrence of an intensely ionized channel, with a space charge, adjacent to a less highly ionized region leads to build-up of an intense electrical field ahead of the highly ionized region. In this field the existing electrons are accelerated to ionizing energies so that in a number of such collisions cumulative ionization in the high-field region extends the high-potential conducting space. This theory does not require that the electrons traverse the whole distance of advance. A numerical calculation showed that this mechanism was capable of giving the observed speeds.

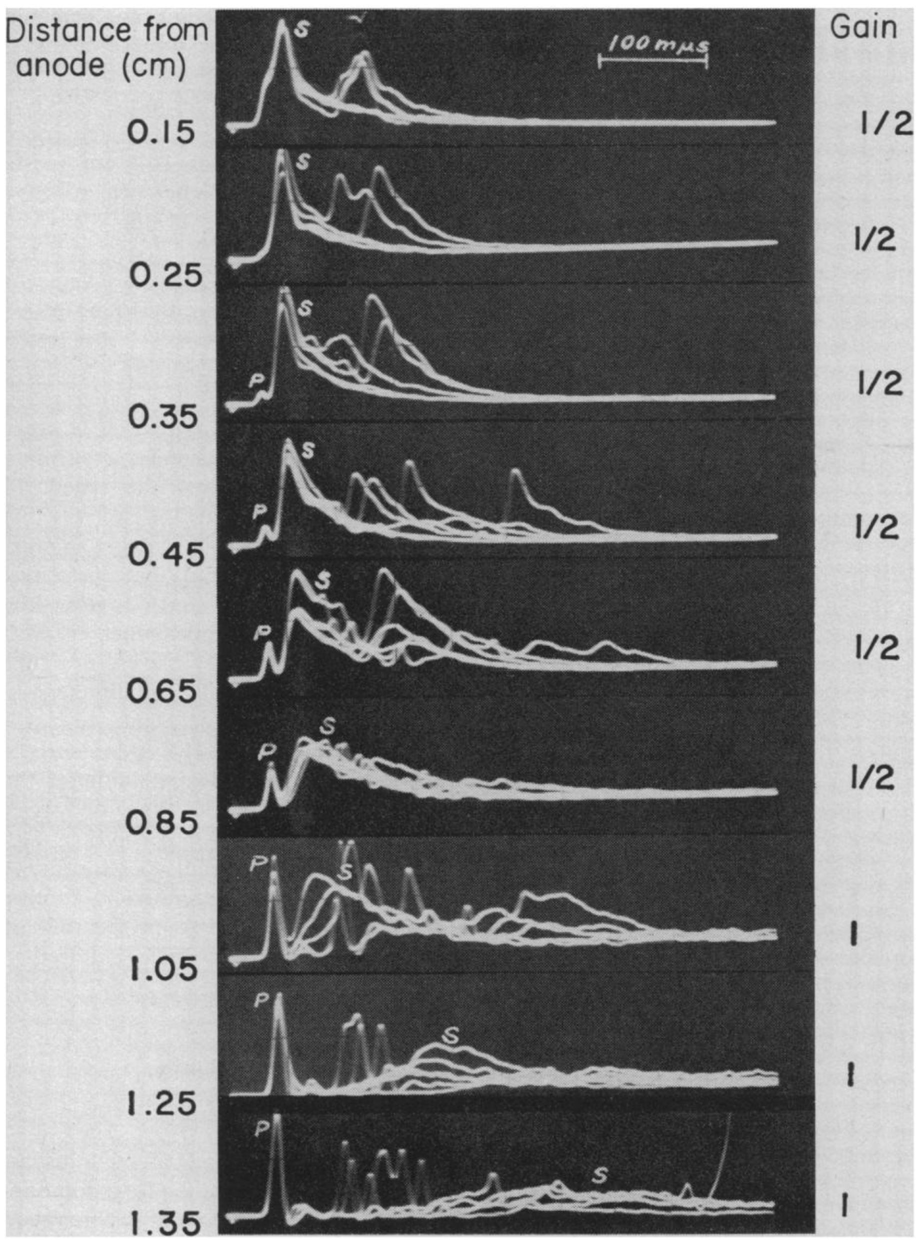


Fig. 1. Hudson's photomultiplier traces of primary and secondary streamers in spark breakdown. Anode r (radius of point), 0.62 cm; gap length δ, 1.5 cm. Time progresses from left to right; the time scale, in units of 10^{-9} second, is shown at top. Each signal represents five or more single sweeps of the photomultiplier scanner; the distances of the scanner from the anode point are shown at left. The relative gains on the photomultiplier are shown at right. The primary trace is quite reproducible, but the secondaries show much variation. Traces for the main arc phase are not shown.

Schonland (*11*) accepted this suggestion and derived an approximate relation for calculating the speed of such gradients. If one takes the cube root of the electron density, n, one has an expression for the number of electrons per centimeter in the field direction. The reciprocal of this is the average distance between electrons. He indicated that if each of the electrons advances the distance of separation at the normal drift velocity $\bar{v}$ of electrons in the field, the time t for advance is $1/(n^{1/3}\bar{v})$. In this time the ionization has advanced a distance d with an average speed

$$v_i = n^{1/3}\,\bar{v}d$$

This relation gives a satisfactory value for the observed v_i of dart leaders, on the basis of reasonable assumptions as to values of n and d.

More properly, the relation for speed of propagation with a given gradient across the distance d should be based on the time t needed for cumulative ionization by electrons. The cumulative ionization required to reach a value n_1 characteristic of the electron density in the space wave to be generated follows the law

$$n = n_o\,e^{\alpha x} = n_o e^{\alpha\,\bar{v}\,t_1}$$

where $\bar{v}$ is the drift velocity of electrons in the field, n_0 is the initial density of free electrons, and α is the number of ions per centimeter advance in the field direction created by one electron.

The continuity condition for advance over the distance d implies that, when n equals n_i, the ionized front has propagated a distance d. Equation 1, then, is the continuity equation for propagation of a given gradient. Since $v_i = d/t_i$, we have an expression for the wave velocity that reads

$$v_i = \alpha\,\bar{v}\,d/\ln n_i/n_o$$

If the advance is into un-ionized gas where photoionization is required, then n_0 is given by the density of photoelectrons created within d by photons from the wave front. Thus, if a potential declines linearly over a distance d at a pressure p, the field E, pressure p, α, and $\bar{v}$ are known, and if n_0 and n_i are given, v_i can be calculated.

Further Long-Tube Studies

The studies cited prompted Snoddy, Dieterich, and Beams (*12*), in 1936, to extend their work by using oscilloscopes as well as a mirror. They applied impulse potentials of 74 to 171 kilovolts to long tubes, ranging in diameter from 5 to 1.7 millimeters, at pressures from 0.17 to 0.24 torr. They observed pulses on either polarity of the high-potential electrode. In each case the first pulse from high potential to ground was followed by a faster return pulse. Where the initial pulse had speeds of the order of 10^9 cm/sec, the return pulse reached 10^{10} cm/sec. At lower pressures speed increased as pressures increased. At higher pressures the reverse was true. Carbon dioxide and hydrogen gave essentially the same speeds as air. Speed seemed to be a linear function of the applied potential from 75 to 180 kilovolts. Speeds in small tubes were lower than those in larger tubes, but the two could be equated by raising the pressure in the smaller tube—a finding which indicates that ion loss by diffusion was a factor. In their paper Snoddy and his associates stated that these light pulses were related to similar phenomena in lightning and might be of influence in sparks. It should be noted that here the asymmetrical nature of the field at the high-potential electrode created the propagating gradient. The value of n_0 was that of the rarified gas in the tube or that produced by photoionization in the gas.

The Breakdown Streamer in Sparking and Return Strokes

In 1935 Flegler and Raether (*13*), on the basis of Raether's cloud-track pictures obtained in uniform-field spark breakdown experiments with timed square-wave impulse potentials at near-atmospheric pressures, developed what is today known as the streamer theory of the electrical spark. Quite independently, on the basis of visual observations of pre-breakdown streamers from an anode needle in a point-to-plane gap in air, I developed, in 1936, nearly the same streamer theory of spark breakdown (*14*). The theory was further developed by Meek and Loeb (*15*) and by Raether (*15*). Raether and his students have made advances in their study of the uniform field process, while my students have made advances in their study of the asymmetrical fields.

The streamer develops when an electron avalanche arrives at the anode (or it develops in midgap for overvolted uniform fields), with the creation of some 10^8 electrons and positive ions. The electron cloud advancing toward the anode leaves behind it the cloud of relatively immobile positive ions. If these two clouds are created within a small enough volume, the field of the space-charge tip of the electron cloud is such that, when it is added to the imposed field, the negatively charged cloud enters the anode, or from midgap advances toward the anode by photoionization in advance, and by electron multiplication in the combined field. The space-charge field of the positively charged cloud draws into its tip photoelectrons created by photons in the initial avalanche head and advances toward the cathode, either from the anode or from midgap. The speeds of both these streamers, because of photoionization in advance and the distortion of the field, are greater than the speed of the initial electron avalanche. Raether assumed that, once the gap was bridged by positive, or by negative and positive, streamers, the arc characteristic of the spark channel materialized by conventional current growth.

Regarding the anode streamers in point-to-plane geometry, I based my reasoning on the return stroke of lightning, the return stroke in long sparks observed by Allibone and Meek (*17*), and the light flashes at the time of streamer impact on the cathode observed by Kip (*18*). I concluded that a *return stroke* was needed to complete the arc. Very recent observations of the luminosity in streamer growth, by Tholl, Wagner, and Richter (*19*), in Raethers' laboratory, now support the view that return strokes are occurring. In asymmetrical gaps the return strokes appear to play a prominent role.

In 1938 the fast-time-resolved photographs of long sparks ($\approx$ 1 m) ob-

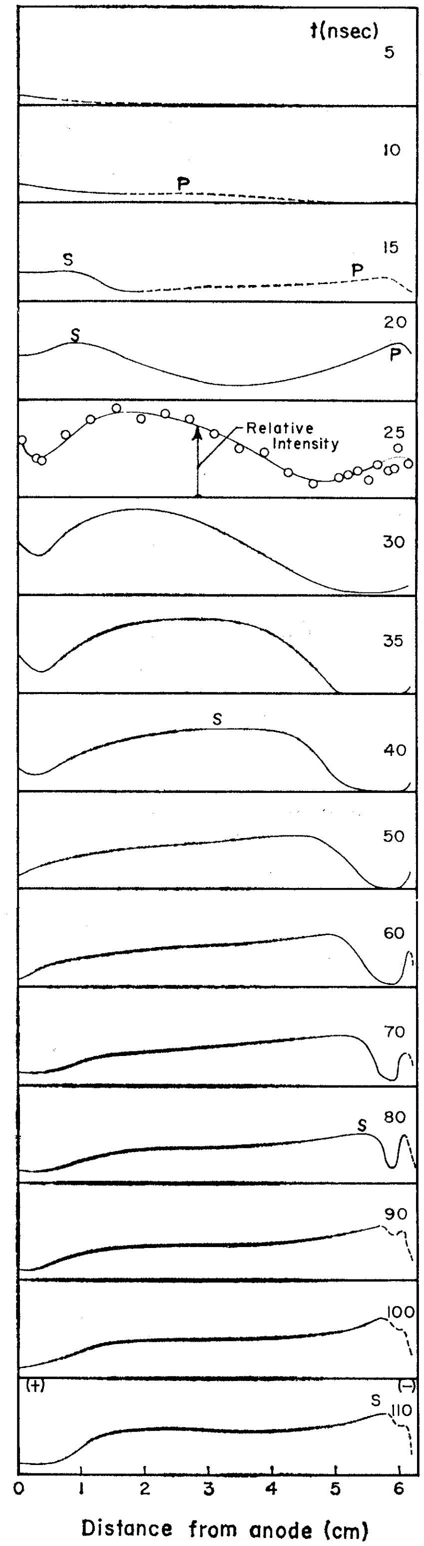


Fig. 2. Hudson's cross plots of luminosity at various points across the gap, recorded at different times. The dashed portions of the curves are of uncertain shape, due to variation on separate sweeps. The primary waves could well be of greater amplitude than the curves indicate. The circled points show average values for clearly defined secondaries. Note the rapid rise in intensity across the gap on arrival of the primary streamers at the cathode, caused by the return pulse of ionization at speeds of the order of 5×10^8 cm/sec.

tained by Allibone and Meek (*17*) with moving-film camera revealed bright but relatively slow streamers ($\approx 10^6$ cm/sec) and the very fast return stroke in the streamer channel in sparks at pressure of 760 torr. This return stroke is typical of ionizing waves of potential akin to those in lightning and in long tubes at low pressure.

Final Studies in Long Tubes

Following World War II, improved instrumentation led Mitchell and Snoddy (*20*) to extend Snoddy's earlier investigations, with full knowledge of the studies so far cited. Their new tubes were 14 centimeters in diameter and 12 meters long. Potentials from below 20 up to 115 kilovolts at pressures, of dry air or H_2, from 0.006 to 8 torr were used. They were able to produce breakdown pulses following the slower process limited by electron drift velocities, as well as the ultrarapid pulses. The slow pulses appeared when higher pressures ($\approx$ 8 torr) and lower potentials were used. At high potentials, with rapid rise times, the fast pulses appeared. Speeds were 50 percent higher for the negative impulses than for the positive ones; H_2 yielded speeds 20 to 50 percent higher than those yielded by air. Studies of the ratios of field strength to pressure were made in connection with the slow pulses. From values of this ratio ranging from 20 to 120 volts cm^{-1} $torr^{-1}$, the speed increased linearly from 10^7 to 1.8×10^8 cm/sec. These are typical values for electron drift velocity in conventional breakdown.

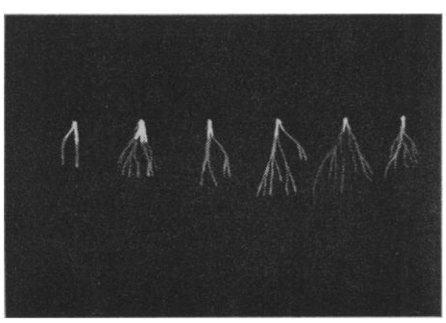


Fig. 3. Pre-breakdown streamers in a point-to-plane gap, photographed by G. A. Dawson. The anode point is on top, the cathode plane is below. (Far right) The gap is of maximum length and streamers do not cross the gap. (Second from right) A few streamer tips are crossing. (Third from right) Many streamer-tip branches are crossing, and the bright flashes at the cathode, signaling the wave arrival, may be seen; return pulses have swept toward the anode along the channels for about 0.25 of the gap length; note the heavy trunks of the secondary streamers in all cases. (Far left) The shortest gap, at about spark breakdowns; repeated pulses from the cathode to the tip of the secondary streamer and back to the cathode have extended the secondary streamers pretty well across the gap along three primary channels. Had the power supply been adequate, the photograph would have been obliterated by the bright arc channel along one of these three branches.

Mitchell and Snoddy assumed that photoionization was occurring in the gas. Combining Schonland's (*11*) equation (Eq. 1) with Cravath's (*8*) photoelectric absorption coefficient of 10 cm^{-1} for air at pressure of 760 torr, they were able to obtain fair agreement with their observed velocities v_i if they chose n_0 as $10^2/cm^3$. As noted above, both my more logical Eq. 2 and Schonland's equation give a slow variation of v_i with n_0. Actually, it is unlikely that, in Mitchell and Snoddy's attenuated gas, n_0 is as high as $10^2/cm^3$.

The use by Amin and Hudson (*21*) of two photomultipliers, one scanning the anode, the other placed at various points across the gap, together with a fast oscilloscope, led to further information on sparks in short gaps. Using anodes ranging from points to spheres of 30-centimeter diameter opposite a plane, with gaps ranging from 1 to 9 centimeters, Hudson observed positively charged primary light pulses moving from anode to cathode at speeds ranging from 10^7 to 2×10^8 or more centimeters per second. The speed of the pulses at breakdown potential was nearly uniform across the gap, and their luminosity increased as they crossed. The primary light pulse was followed by a secondary pulse of speeds about one tenth that of the primary pulse. The secondaries were brighter at the anode and decreased in brightness as they crossed the gap. Their arrival at the cathode triggered the chief luminosity of the transient arc, or main spark. Figure 1 shows an oscillogram with primary and secondary pulses recorded at various points across the gap. From cross plots of luminosity at various points across the gap, plotted from the light pulse amplitudes recorded at various times, Hudson was able to display the luminous shapes of these pulses, as seen in Fig. 2. These plots indicated that when the primary streamer reached the cathode there was a sudden increase in luminosity across the whole gap, indicating a possible fast return stroke. Recent uniform-field studies by Tholl indicate the same sort of increase. Hudson also observed, in still photographs taken just before spark breakdown, that the streamers from the anode were heavily branched. Where branches reached the cathode bright flashes were seen, and secondary streamers down a few of the channels are also clearly delineated near the anode point. These are shown in Fig. 3. Hudson's work was completed in 1957 but was not published until later.

More Complete Studies on Propagation in Glow Discharges

In attempting to create pulses in a glow discharge, Westberg (*2*) discovered that changes in potential applied at the cathode might be transmitted at high speed. He extended the length of his discharge tube to the 1.5 meters needed in such a study. He used many clean gases at pressures ranging from 0.1 to 4 torr in a tube 4 centimeters in diameter. With these conditions he discovered that if a glow discharge was

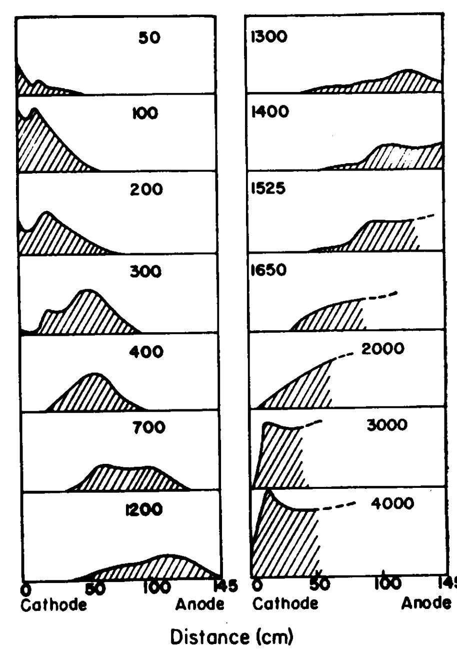
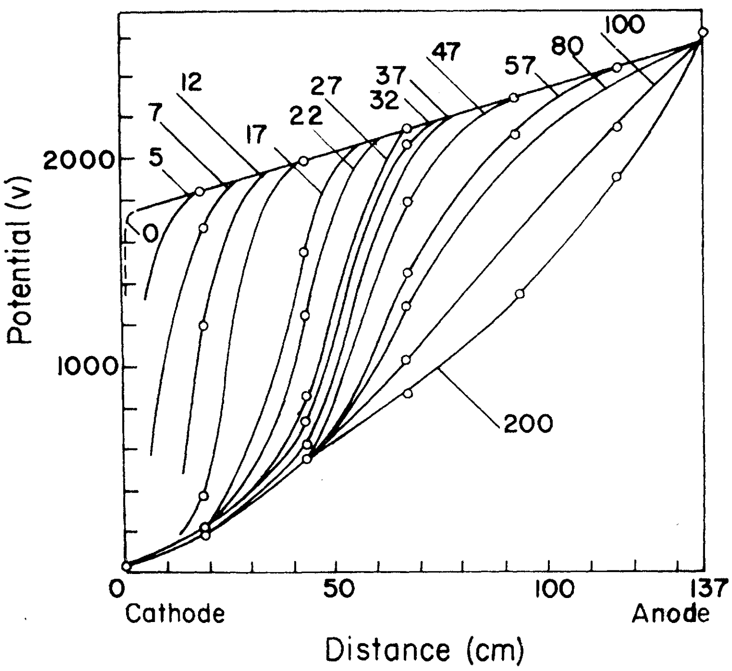


Fig. 4. Westberg's cross plots of the pulse luminosity in N_2 gas (pressure, 184 μ-Hg; voltage, 1740 v) at various times (indicated in nanoseconds) after oxide film breakdown at the cathode. The cathode-to-anode pulse is seen up to 1200 nsec in the sequence at left. The plots at right show the anode-to-cathode return pulses passing through the cathode pulse at 1300 nsec and the faster anode-to-cathode pulse, with increased luminosity, reaching the cathode at 4000 nsec, thus completing the arc channel. The arc did not fully materialize because of fall in potential at the source through current drain.



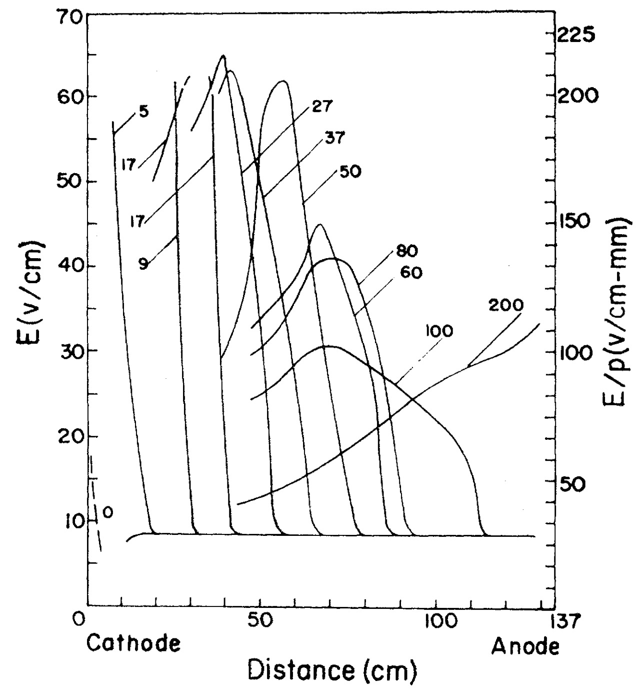


Fig. 5 (left). The profiles of the negative-potential fronts (as indicated by probes inserted along the tube) at various times (shown on the curves in nanoseconds), all multiples of 10^{-9} second, ranging from zero; (N_2 gas pressure, 174 μ-Hg; voltage, 2600 v). The potential at zero time is indicated by the gently sloping line near the top of the figure, with the steep decline at the cathode. At about 100 nsec the cathode-to-anode pulse has arrived, and the return pulse from the anode is passing through it. (The distortions of the head of the reflected pulse superpose on the tail of the advancing front. If the waves were infinitely sharp they would not "pass through" each other or superpose.) At 200 nsec the weak peak of anode-to-cathode pulse is at about 50 cm. Note that speeds at 2600 volts are higher than those at the 1740 volts of Fig. 4. Fig. 6 (right). Westberg's field strength E, and ratio of field strength to pressure (E/p), from the potential plots of Fig. 5, at the various times shown (in nanoseconds) on the curves. The fields are read on the scale at left; the E/p values, on the scale at right ("cm" is gap width; "mm" is pressure in millimeters of mercury). Notice how the potential gradient declines as the wave expands by electron repulsion and by diffusion with time, as it advances. The lower value of E and E/p of the return anode-to-cathode pulse at 200 nsec is clearly delineated.

started in the normal mode with approximately 2 milliamperes of current and the potential was raised relatively rapidly by a few percent, the discharge went into the abnormal glow mode at a current of about 20 milliamperes. Some few seconds to minutes after the change in current to the abnormal glow mode, a sudden transition to a transient power arc occurred. In this transition a brilliantly luminous pulse started from the cathode at high velocity and reached the anode. This pulse was followed by a return pulse, of perhaps greater luminosity, moving at high speed back to the cathode. Westberg studied these pulses with a photomultiplier and by means of a series of probes inserted along the tube, using a fast oscilloscope. In this fashion he obtained data for cross plots of ratios of luminosity, potentials, fields, and field strength to pressure for the pulses as they crossed the gap.

These waves were akin to those of Thomson and Snoddy except that they moved in the previously ionized medium of the glow discharge column. Furthermore, they were not triggered by the relatively small and slow potential pulse that changed the glow mode. They were shown to occur only when a film of insulating metal oxide on the cathode thinned by sputtering. This film was highly charged on the outer surface by positive ions and abruptly broken down by a field-emission-triggered discharge yielding a very heavy burst of electrons. These electrons, accelerated in the potential fall at the cathode, produced an enormously dense negative glow with a high negative gradient at its anode-facing edge. This space wave of field distortion swept down the tube to the anode at speeds up to 10^9 cm/sec. Figure 4 shows cross plots of the luminosity at various times. Figure 5 shows the progress of the potential wave, and Fig. 6 shows the ratio of field strength to pressure. The pulse of ionization which launched this wave was one in which the current measured at the cathode rose from 20 milliamperes to 12 amperes in 2×10^{-9} second. No current change was registered at the anode until the pulse reached it.

This work furnished the clue to the nature of the conditions leading to the buildup of such waves or pulses: (i) a change in potential distribution, sufficient to yield a high gradient over some distance d, is produced within a time so short that normal diffusive processes cannot operate; (ii) accompanying this change there must be an initial density of free electrons n_0, either previously existing or created by photoelectrons from the initial disturbance yielding the space-charge gradient. Under these conditions the indicated propagation continuity, Eq. 2, yields a velocity of $v_i = \alpha \bar{v} d / \ln(n_i/n_0)$. This criterion requires relatively instantaneous fields E over a distance d such that, from the value of E/p, where p is the existing gas pressure, ionization by collision through random motion of electrons yields the Townsend coefficient α. If pressures become so low that electrons propagate without randomization—that is, unidirectionally—this mechanism ceases to operate and the velocity of the pulses is that given for electrons moving in near-vacuum with a velocity given by their initial energy or potential fall. At very high pressures the potential fall requires high ion density and extends over much smaller values of d. This means that sharper pulses and photons of shorter wavelength are required. Westberg in producing his glow plasmas did not require photoionization. However, in O_2, when the pressure was such that photoionization became effective, speeds jumped from 10^9 to 4×10^9 cm/sec. When clean, oxide-free cathodes were used, Westberg's burst of ionization did not occur and there were no pulses. One more fact emerged: the reflected or return pulse from cathode to anode was somewhat brighter than the initial pulse and at least as fast. This was true despite a much lower value of E/p, because of the increased value of d and the increase in n_0 in the column, resulting from the initial pulse. The reason for the occurrence of such return pulses lies in the short time t_1 over which the initial pulse acts on the electrons in any one region of the gap, owing to the high pulse speed. This does not allow time for many cumulative steps of ionization to occur in that distance d, so that gradients capable of propagating still exist in the gap and reflected waves originate at electrodes.

On the basis of these considerations, in a paper presented in 1957 before the 3rd International Conference on Ionized Gases (*1*), I grouped the phenomena described above, including the primary breakdown streamer in sparks, under the single title of "ionizing potential space waves."

Attempts at a Hydrodynamic Analysis

In 1961 Fowler (*22*) recognized that in his electrically driven shock tubes he was observing waves similar to those discovered first by Thomson. He and his students developed a theory, based on the application of hydrodynamics, to explain their propagation, using the conservation laws with certain simplifying assumptions. Making estimates of the potential-gradients involved, they calculated velocities for such waves in argon gas, both for low pressures and for the anode streamers observed in a study by Westberg, Huang, and myself. Fair agreement was achieved between theory and observation in both cases. Unfortunately, the asymmetric character of the point-to-plane gap field of Westberg and Huang was not considered by Fowler in that calculation. Thus, the initiating gradient was underestimated by a factor of at least 10, so that the agreement reported in that case was purely fortuitous. It is doubtful whether the conditions existing where such pulses propagate, under the varying conditions observed, permit such generalized calculations.

At the 5th International Conference on Ionization in Gases, Amin (*23*) reported studies, made in ignorance of Westberg's work, on a prolonged breakdown in a pulsed low-pressure tube. Studies of current, of the charge delivered, and of potentials measured at two points along the tube were made. Lichtenberg figures on film outside the tube were also used to measure potentials in the pulses in addition to the potential from probes. Amin's chief

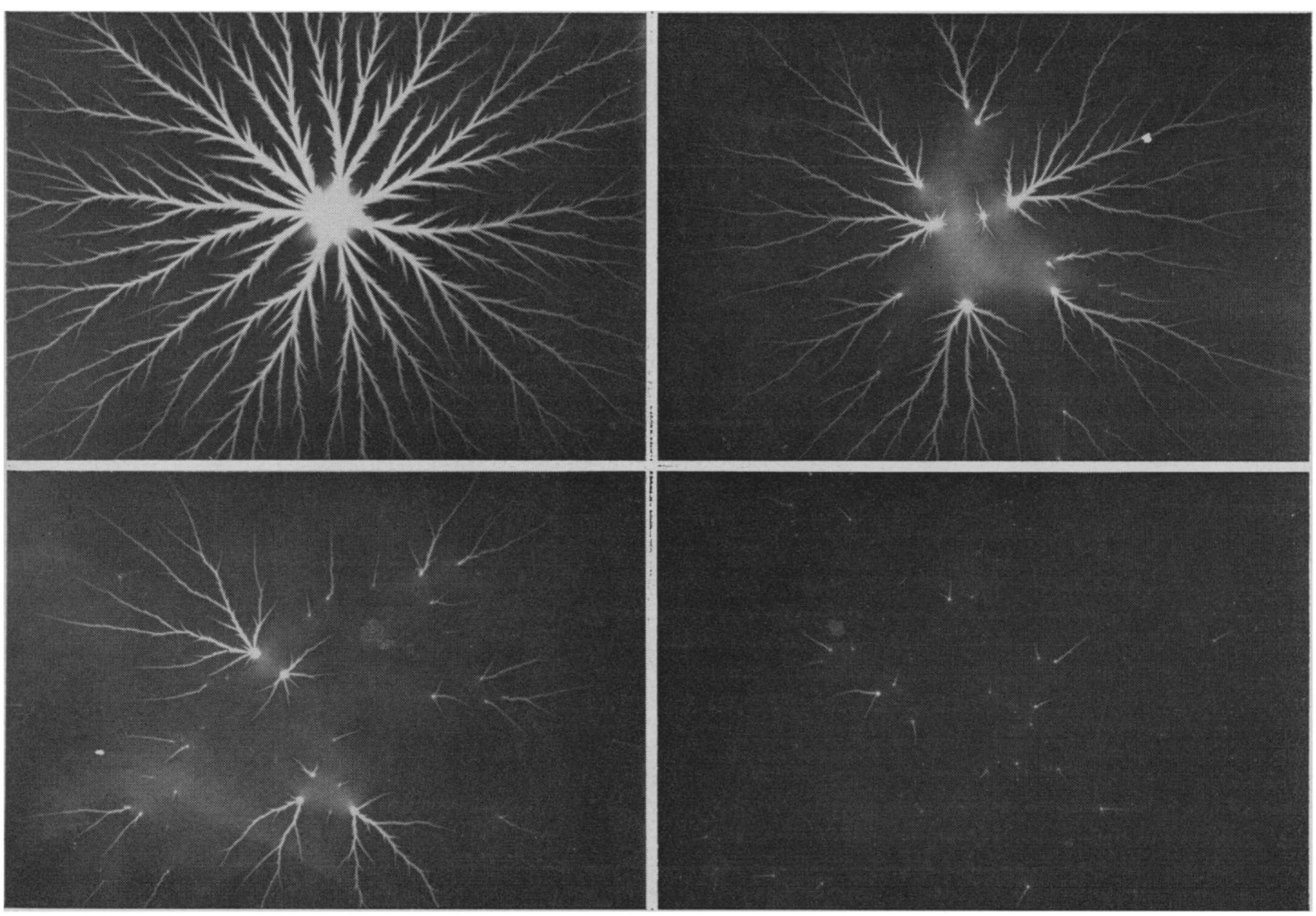


Fig. 7. A series of autographs of branching anode streamers as they pass over the surface of a photographic film placed normal to the anode-point axis in a point-to-plane gap. (Top left) the film was in contact with the point. (Top right and bottom left and right) The film was moved away from the point; (bottom right) the film was near the cathode, and autograph shows tips of the streamers that just manage to cross the gap. The length of the longest branches in each autograph is directly proportional to the potential at the point of impact of the streamer passing through air from above onto the film. [E. Nasser]

conclusion was that the conductivity of the discharge channel has an important bearing on its propagation.

In 1960 Nasser (*24*) had studied, with Lichtenberg figures, the primary streamer process in a point-to-plane gap and had indicated the identity of the positive and negative Lichtenberg figures with the positive and negative streamers. The streamers move through the air above the film but very close to its surface through the inductive attraction of the tip of the positive streamer. This permits single streamers too faint to be photographed directly to "write their autograph" on the film surface. Nasser indicated the very heavy branching of streamers in the point-to-plane geometry. He showed that, with impulse potentials, streamers started at the corona threshold, and that primary streamers crossed the gap at potentials well below spark breakdown. The axial range of the streamers was proportional to the anode potential. Simultaneously, in the same laboratory in West Berlin, Tetzner (*25*) carried out a parallel study, using the same technique in oil, and identified the streamers, thus extending the space-wave concept to the impulsive rapid breakdown of liquids. Nasser continued his studies in our laboratory, and further work on streamers was carried on by Waidmann (*26*) and by Winn. Figure 7 shows typical figures for a film normal to the point axis. Figures 8 and 9 show the figures obtained with the film in the plane of the anode point. Photoelectric ionization in air was indicated by the action of O_2 and H_2O on the streamer range, in the studies by Waidmann and by Winn. Waidmann also measured the velocities of the streamer tips across the gaps, using the Lichtenberg technique, and showed them to be the same as Hudson's primary photomultiplier pulses under similar conditions. Nasser also showed that negative streamers were less effective and had shorter ranges than positive streamers. Photoionizing efficiency is an important factor in causing branching; this relationship requires further study.

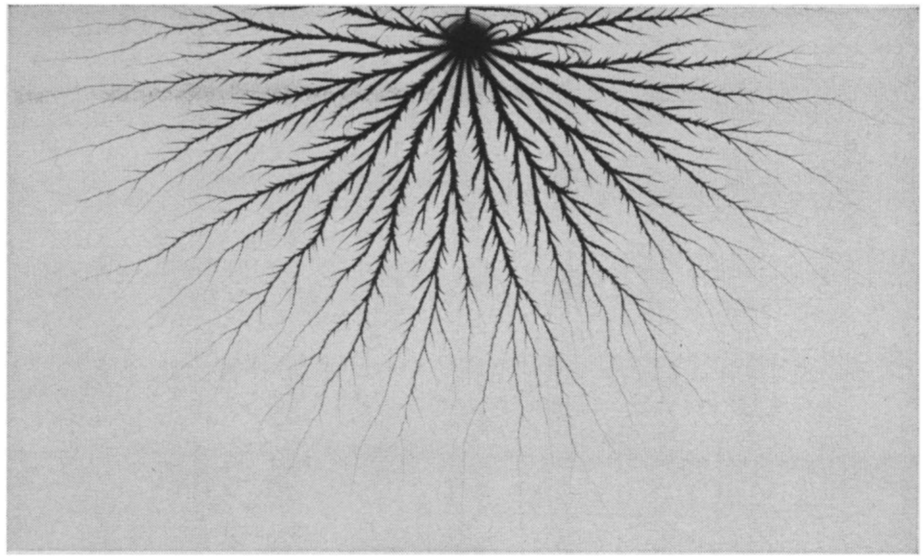


Fig. 8. Autograph of a streamer branching on a film in the plane of the point axis. The streamer came from a positive-potential pulse of about 40 kv, of rise time 2×10^{-8} second but of 100-μsec duration, with gradual decline. [W. P. Winn and G. A. Dawson]

Breakdown Streamers and Return Strokes in Long Sparks

In 1963 Kritzinger (*27*) reported an extensive study of streamers from sparks produced by means of impulse potentials, in point-to-plane gaps ranging from 10 to 50 centimeters. Using many, but improved, techniques of the past, he observed much previously unrecorded detail in the mechanism of spark breakdown, owing to his higher currents and longer gaps. Kritzinger, like Hudson, observed the primary streamers. At potentials below breakdown they crossed the gap but slowed down as they left the anode region and grew fainter. Where they approached the cathode their speed increased, and the luminosity was constant or it increased, as in Hudson's experiments. When the tips reached the cathode Kritzinger noted the bright flashes seen by Kip and Hudson. There were sudden increases of current when these flashes occurred, and very fast pulses (5×10^8 cm/sec) were seen to move from cathode to anode (these were termed globules by Kritzinger). When these light pulses arrived at the anode, a very bright luminous streak appeared at the anode and a new pulse of ionization swept toward the cathode. When this new pulse arrived at the cathode, a second pulse swept up to the anode. As

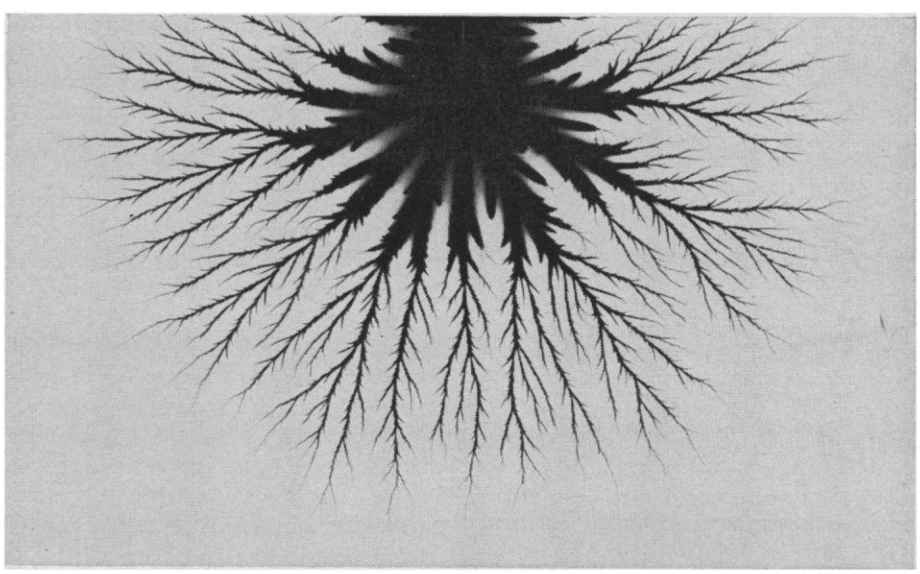


Fig. 9. Autograph from a 40-kv square pulse of 40-nsec duration, with rise and decline times of 1 nsec. This autograph shows both primary, long, thin streamer tracks and the heavy, shorter, secondary streamer tracks. The latter are enhanced by the fall in potential pulse [G. A. Dawson]. It should be noted that in Fig. 8, produced under somewhat similar circumstances but with a long decline time of the potential pulse, the secondary streamer does not appear as a distinct entity, probably because of the continued luminosity caused by current flow during the long decline in the absence of a sharp fall in potential signal.

(a)
(b)
(c)
(d)
(e)
(f)
(g)
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(k)

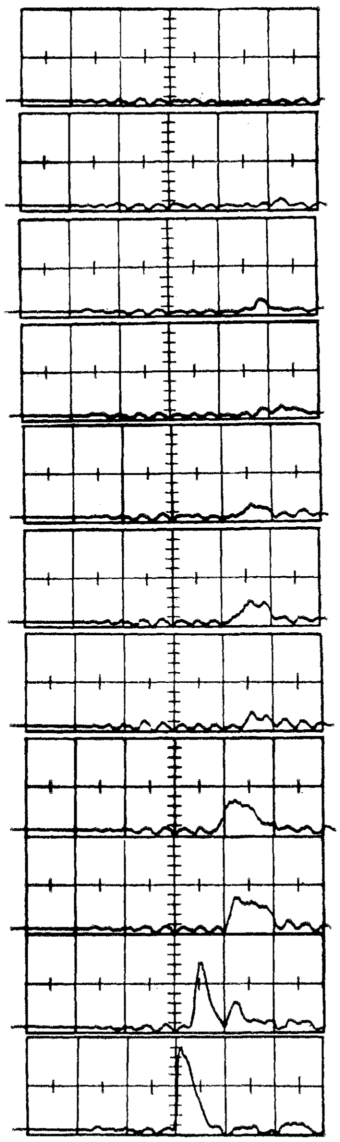

Fig. 10. Dawson's oscillograms, obtained when a square potential pulse of 40-nsec duration and rise and decline times of 1 nsec is applied to a 5-cm positive point-to-plane gap. The photomultiplier is 4.5 cm from the anode (which is at left). Displayed are a series of pulses observed; time progresses from left to right, each centimeter of the scale dimensions representing 20 nsec. The pulse began at graticule 1.5 and ceased at graticule 3.5. In trace *a* there was no streamer, and thus no light. This trace represents background "noise" caused by the pulse generator. Trace *b* shows a weak streamer tip at graticule 5.25. The streamer persisted 35 nsec after potential fall to zero at the anode. Other traces, such as *c*, *d*, *e*, and *f*, show pulses advancing from 20 to 30 nsec after cutoff. Trace *k* shows a particularly fast and vigorous streamer that reached to 4.5 cm from the anode in 30 nsec. Different streamers from the point vary greatly in vigor and speed. This variation arises because pulses may not start at zero time on the 40-nsec pulse and not all pulses have the same energy, owing to statistical fluctuation in avalanche growth. Traces *h*, *i*, *j*, and *k* indicate several vigorous branches, some of which reach the photomultiplier at later times, and progress for up to 40 nsec after cutoff.

many as three such pulses could be resolved, and doubtless more occurred. This succession of pulses prolonged the bright streak from the anode. This streak developed across the gap at a speed about one-tenth that of the primary streamer. It was called a "leader" by Kritzinger, and was identified with Meek and Allibone's photographed "streamer." It is identical with Hudson's secondary streamers, as recently shown by Dawson (*28*, *29*).

Recent Contributions on Streamers and Their Theory

Nasser's Lichtenberg figures, made with a potential pulse of 10^{-8} second rise time but millisecond duration and slow decline, failed to show the secondary streamers. In order to extend Kritzinger's observations to shorter gaps (1 to 5 cm), Dawson undertook an extensive investigation of the breakdown, using all previously developed techniques. He observed the primary streamers and obtained evidence of the occurrence of a secondary streamer. He observed the large, rapid increase in current that occurred when the primary tip reached the cathode, noted by Kritzinger, Buchet, and others, and demonstrated that it coincided with the arrival of the tip of the luminous primary streamer. Owing to complications produced by the arrival of the more radial branch tips at the cathode he could not, with certainty, identify the fast return stroke, although there were pulses giving strong indication that it occurred. Contrary to Kritzinger's observations, Dawson found that the secondary streamer started before the arrival of the tip of the first primary streamer at the cathode. The secondary streamer represents increase in current in the anode trunk, fed by currents from the branches and augmented by ionization in the point anode field. Dawson showed that further extension of the secondary streamer begins as a slow current increase by conventional processes but depends for its advance on the fast space waves from the cathode. Owing to its high conductivity the secondary streamer projects a fraction of the anode potential into the gap at its tip. This accounts for the high potentials inferred by Nasser, from Lichtenberg figures, near and above spark-breakdown potentials.

In the point-to-plane gap—in contrast to the uniform field gap, where the progress of the streamer is in part de-

cm
0
0
.32
.48
.64
.80
.96
1.12
1.6

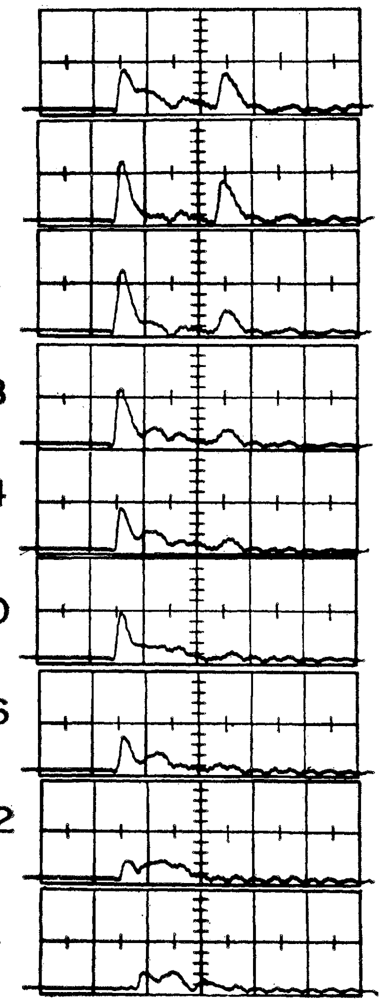

Fig. 11. Oscillograms recorded by a photomultiplier placed at various distances (shown at left of trace) from the anode point (left) when a sharp, square, 40-nsec pulse was applied to the anode. Time progresses from left to right; 1 cm on abscissa represents 20 nsec. Two sharp pulses near the anode may be seen, the one at time near zero, when the primary streamer passes the slit, and the other 40 nsec later. This second pulse is clearly visible on traces for scanning distances out to about 1.5 cm. It diminishes in intensity, as does the secondary streamer advancing from the anode out into this gap. The second pulse results from a fall in potential signal produced by a negatively charged space wave of electrons that flows from the metal anode suddenly reduced to zero potential relative to the adjacent plasma with positive potential of 40 kv. It results from a large burst of photoelectrons from the metal, intensified by the field between charged plasma and anode now at zero. This wave travels at 5×10^{-8} cm or more per second down the conducting secondary channel. As the conductivity falls to low values, at a distance from the anode of about 1.5 cm, the luminosity decreases and the advance ceases. These oscillograms are in agreement with the observations of Fig. 9.

pendent on the imposed field—the primary streamer has all its energy stored in its tip during its sojourn in the high-potential region. This high charge and energy carries the streamer tip, with some dissipation by branching, ionization, and excitation, across the very-low-field regions of the gap. In crossing these regions the streamer leaves behind only a weakly conducting channel. Dawson and Winn (*28*) developed the theory that such a streamer is an ionizing space wave of such potential that it is just able to propagate in zero field. Their calculated values for the diameter, charge per centimeter of advance, velocity, and other predicted properties of such a wave have been confirmed by measurement, within the limits of experimental error.

That such a space wave can propagate after the anode potential is cut off is shown by applying to a gap a 40-kilovolt pulse of 40-nanosecond duration, with rise and decline times of 1 nanosecond. Figure 10 shows a series of photomultiplier traces in which streamer tips may be seen to progress for from 10 to 35 nanoseconds after the anode potential is zero. The variation in the energy of individual streamers yields the different times shown.

Dawson (*29*) further showed that if a streamer tip near the end of its range entered a region where a delayed potential pulse could again reenergize it, it would continue to progress. By letting it traverse a hole in the cathode of a point-to-plane gap to enter a series of three fields created by plates with similar holes, to which the pulse could be serially applied by means of delay lines, he was able to extend the range of this ionizing space wave by a factor of 3. Statistical fluctuations in starting times and variations in speeds attendant thereon made further range extension unprofitable.

Dawson (*29*) next fixed his attention on the anode when the pulse of short rise and decline times was applied. Here it was seen that, with the gap and point used, the primary streamer signal appeared, out to 1.5 centimeters from the anode, at the time appropriate to the high speed near the anode. At each point scanned by the photomultiplier out to 1.5 centimeters, a second luminous pulse followed just 40 nanoseconds after the primary pulse. This second pulse diminished in intensity as the distance increased, as seen in Fig. 11. This space wave of luminosity is explainable by the fact that the potential of the secondary-streamer plasma at the anode was 40 kilovolts when the anode potential dropped to zero. In consequence, a flood of photoelectrons, liberated by plasma radiations from the now relatively highly negative anode, sent a space wave of ionization at a speed in excess of 5×10^8 cm/sec down the more highly conducting secondary-streamer channel. The wave ceased to propagate much beyond the conducting region. This explanation is beautifully confirmed in Fig. 9, where the film in the plane of the anode point shows the dark secondary branched pattern of the Lichtenberg figure against the longer faint primary streamers obtained with the square-pulsed potential. Figure 9 should be compared with the conventional Fig. 8, where, because of the long duration and slow decline of the anode potential, the diffusive processes smooth out the traces.

Generation and Observations in Decaying Spark Channels

Finally, despite great difficulty, Winn (*30*) has now succeeded in applying a pulse of 30 kilovolts with 8-nanosecond duration and 1-nanosecond rise and decline times at various times after an ordinary spark has traversed an 11-centimeter gap. The spark channel was scanned with a photomultiplier. Application of the impulse potential, 30 microseconds after the spark, launched a space wave of luminosity that propagated down the channel to a distance of about 8 centimeters with a speed of 1.9×10^9 cm/sec. If the pulse was applied 300 microseconds after the spark, the pulse had a speed of 3×10^8 cm/sec and attenuated in a much shorter distance.

Newer Analysis of Waves in Long Low-Pressure Tubes

Haberstich (*31*) applied Westberg's general diagnostic techniques, with modifications, to the study of waves, produced by impulse potentials, in an un-ionized medium. He used a tube of 2.5-centimeter diameter, and helium and argon at pressures of 0.17 to 7 torr. The tube was surrounded by a coaxially conducting cylindrical metal shield, which formed, with the ionized plasma, a condenser of capacitance C per unit length. Two photomultipliers were used in fixed positions at various distances from the electrodes. Two external ring electrodes were used to measure the potentials. Microwave probing beams were used to measure the electron densities behind the waves as they passed. Mitchell and Snoddy had measured currents and verified the law $I = C_1 V_2 v_w$. Several diagnostic techniques were applied. Of interest was the potential V_2 across the wave front; this bore a 1-to-1 correspondence to the velocity of the wave (v_w) which was linear under some conditions. The wave velocity was measured as a function of pressure and showed a well-defined peak within the range studied. Of further interest was the length d of the front over which the potential acted. The charge Q collected is given by $Q = C_1 V_2 l$, where l is the length of the conducting channel. The current is

$$I = dQ/dt = C_1 V_2 (dl/dt) = C_1 V_2 v_w$$

This relationship was first deduced by Snoddy. The energy expended in a time t is

$$U = C_1 v_w V_2 t.$$

The energy stored in the field is

$$U = \tfrac{1}{2} C_1 V_2^2 l,$$

so that the energy available to create the plasma is

$$\tfrac{1}{2} C_1 V_2^2 l.$$

This relationship was used to calculate the number of ion pairs. The values observed as functions of V_2 were about twice the observed number of ion pairs. This discrepancy arose because the energy spent in excitation was not included in the calculation, since it would have been only an approximation. Haberstich then attempted to estimate the average field E_n across the point. If the surface charge density of excess ions or electrons in the propagating front is σ, then the mechanical force (F) per unit area (A) at the tip of the front is

$$F/A = 2\pi\sigma^2 = \frac{\bar{E}_n^2}{8\pi}$$

since

$$U = Fl = \tfrac{1}{2} C_1 V_2^2 l, \quad F = \tfrac{1}{2} C_1 V_2^2,$$

and

$$\bar{E}^2 = \frac{8\pi C_1 V_2^2}{2A}.$$

Since V_2 is measured by the probe and C_1 is known, the average field can be estimated. The value of $\bar{E}_n$ can be compared with the potential drop V_2/d.

Here difficulty arises, since the photomultiplier values of d are much lower than the probe values. This stems from the fact that the external ring probes, because of the geometry, sense the potential front well in advance of wave arrival. Here Haberstich would have done better to have used Langmuir probes of small area, placed inside the tube; Westberg used such probes and got more realistic potential profiles. Finally, Haberstich derived a one-dimensional theory of propagation of the front, from classical electrical relations for the continuity of advance of an ionizing wave, using the Townsend ionizing coefficient α. The calculated results for ion density as a function of V_2 agree with observation somewhat better than the energy calculation does. Here the error probably comes from the use of $\overline{E}_n$ as derived above. In principle this sort of calculation does not differ radically from Dawson and Winn's zero-field streamer theory, although the present approach is more general. Probably the greatest difficulty lies in the implied assumption that propagation requires only one electron ahead of the front. In actuality, Haberstich's waves depend on photoelectric ionization in the gas, and this mechanism is not considered. Furthermore, recent results of Tholl (see *32*), as well as conclusions of mine, indicate that thresholds for breakdown and a propagation of a discharge are radically altered by preexisting electron densities.

Recent Theoretical Indications

Very recently Köhrmann (*33*) has shown by calculation of the growth, in a uniform field, of glow-discharge breakdown in H_2 that, at one stage of the space-charge development, an ionizing wave of potential progresses from the anode to the cathode at about five times the electron drift velocity, increasing ionization fourfold. He compares this wave with Westberg's waves.

It is hoped that consideration of these related phenomena under the single title "ionizing waves of potential gradient" will stimulate further investigation of these important agencies.

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