Miniature Whirlwinds Produced in the Laboratory by High-Voltage Electrical Discharges

Abstract. *Laboratory experiments showed that under certain conditions of vorticity the electrical heating produced by a high-voltage discharge at atmospheric pressure can cause the formation of a miniature tornado-like vortex. Once it forms, this vortex stabilizes the electrical discharge along its axis and changes its character from that of a spark to a high-pressure variety of a glow discharge. Electrical and dynamic parameters were measured. By relating observations and measurements made in these experiments to previous work and to analogous situations in nature, it is concluded that the heating produced by electrical discharges in a large storm may play a significant role in forming and maintaining natural tornadoes.*

Abdullah and others (*1*, *2*) have noted that a primary difficulty in accounting for the extraordinarily high winds of the tornado is to explain the anomalously high concentration of energy that exists in the vortex. One possible explanation for this mystery, which has received increasing attention during the past decade, is that energetic electrification, the hallmark of tornado-producing thunderstorms, may be playing an important part in the formation and maintenance of the tornado (*2–6*).

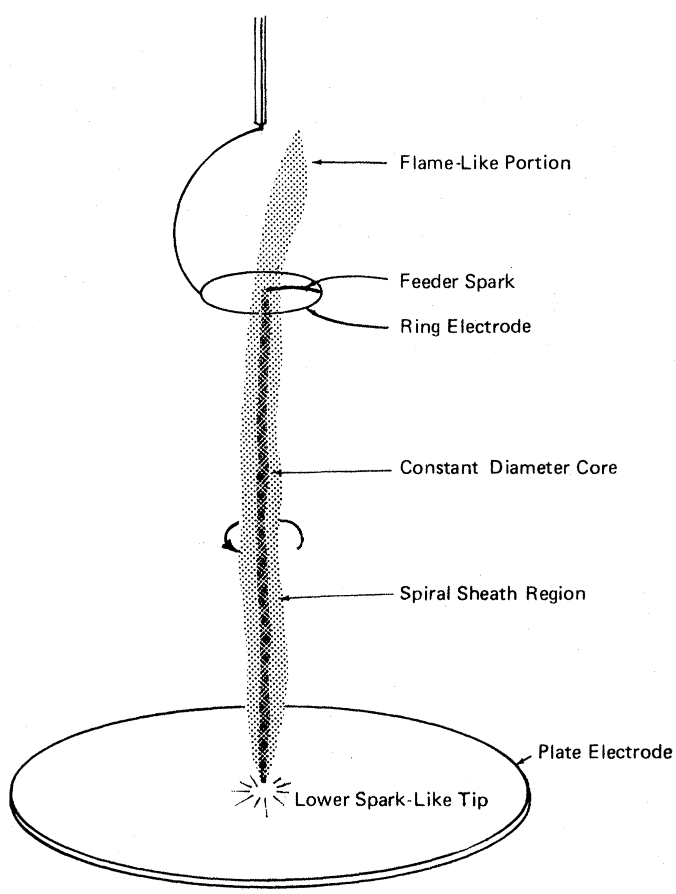
During recent years investigators have attempted to examine the validity of some of these proposals by laboratory experiments (*3–5*). The experiments to be described here show that under suitable conditions a high-voltage discharge might produce a stable vortex by electrical heating, without a blower being needed to produce a region of low pressure.

The apparatus used in these experiments has been adapted from that devised by previous investigators for producing miniature tornado-like vortices and small fire whirlwinds in the laboratory. We have used two apparatus in our experiments: a rotating cylindrical cage and, for most of our experiments, a large fixed chamber apparatus in which angular momentum is imparted to the air by a series of louvers instead of by a rotating cage. The chamber, in the shape of a truncated cone, consists of 12 pieces of plywood (60 by 240 cm) arranged in a 12-sided pattern on a 240- by 240-cm elevated base in such a way that there is a 10-cm gap between overlapping panels on the base, with the panels tilting inward so that they rest on one another at the top. The electrical heating is supplied by a powerful electrical discharge from a 5-kv, d-c power supply (smoothed, solid-state rectified, three-phase, 60-hz alternating current) capable of providing currents up to 5 amperes. To limit the current in the discharge, we employ a 1000-ohm current-limiting resistor consisting of about 100 m of 27-gauge Nichrome wire wound on an open frame.

The electrode configuration consists of a lower circular electrode made of a steel plate 1 m in diameter and an upper electrode made of a 10-cm-diameter ring bent from 6-mm-diameter copper rod (see Fig. 1). The electrical heat from the vortex forms a vigorous vortex usually about 20 seconds after the spark is struck. The vortex in turn stabilizes the discharge, as shown in Fig. 2, and it can be extended to heights in excess of 70 cm with a current flow of 2.5 amperes and a voltage drop of approximately 2 kv between the electrodes.

It is worth noting that, if we do not impart angular momentum to the air in these experiments by the use of the louvers, the electric discharge remains random and unstable and the vortex never forms.

Different regions can be recognized in the stable discharge that are indicated in Fig. 1. The first is a small, narrow sparklike region at the lower tip of the discharge, where it makes contact with the lower electrode plate. Here there is a convergence of cold, un-ionized air flowing into the vortex. A short distance above the electrode, the discharge loses its bright sparklike appearance and assumes a diffuse glowlike character. The stabilized glow discharge in the vortex consists of two regions: a constant-diameter core about 1 cm in diameter, and an outer sheath that increases from zero thickness at the lower part of the



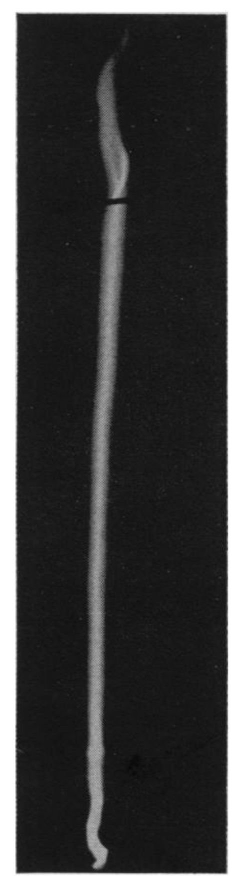


Fig. 1 (left). Schematic diagram showing the various regions of the d-c glow discharge in the large apparatus. Fig. 2 (right). Voltage-stabilized, d-c discharge. Current, 2.5 amperes; voltage drop, 2 kv between electrodes; height, approximately 1 m.

discharge to a thickness of about 2 cm at the upper electrode. The core, which we believe carries most of the current, is blue in color; the outer sheath is red-orange. The outer region has a noticeable spiral motion, whereas the core shows little, if any, rotation. A high-frequency glow discharge with a similar core and luminous sheath appearance has been reported by Cobine *et al.* (*7*).

When the upper part of a glow discharge does not make direct contact with the upper ring-shaped electrode, as is usually the case, it gives rise to a fourth region in the electric discharge. This is a thin, bright, somewhat irregular horizontal discharge, which we call the "feeder spark"; it bridges the space between the upper electrode and the core portion of the discharge. The feeder spark is usually bowed outward by the vortex airflow, as is shown in Figs. 1 and 2, and sometimes the influence of this force will cause it to rotate inside the ring in the direction of the flow. The feeder spark, like the sparklike discharge at the base of the plasma, is not in steady state but is constantly establishing a new conductive, heated, and ionized path in a continuing flow of cold, un-ionized atmosphere. The topmost portion of the discharge is a flamelike extension of the sheathed region, which is the hot ionized gas in the vortex that is rising above the electrode and feeder spark. It looks very much like the upper part of the flame from a Bunsen burner. This part of the discharge is obviously not carrying any electric current.

When the vortex-stabilized discharge is in operation, it emits a crackling sparklike noise. Although some of the sound is probably produced by the main glow discharge, the principal source seems to be the feeder spark and, to a lesser extent, the sparklike region at the lower electrode. The sound is loudest when the feeder spark is long, and it decreases markedly when the feeder spark becomes short. When the length of the feeder spark increases because the vortex moves away from the upper electrode, not only does the sound increase but, at the same time, the electric current flowing through the system drops appreciably.

When the stabilized electric discharge is extended by raising the upper electrode, it finally becomes unstable and goes out. Studies made of this flameout phenomenon by slowly increasing the discharge length and measuring the current and voltage just before the discharge ceases are in general agreement with similar measurements made by Wilkins and McConnell (*5*) for discharge flameout in a blower-driven vortex. Cinematographic studies of the flameout phenomenon made at framing speeds of 1000 to 2000 per second with a current-indicating oscilloscope also in the field of view show that, whereas a luminous plasma persists in the axis for about 40 msec after the current ceases to flow, the bright core of the vortex and the feeder spark disappear immediately.

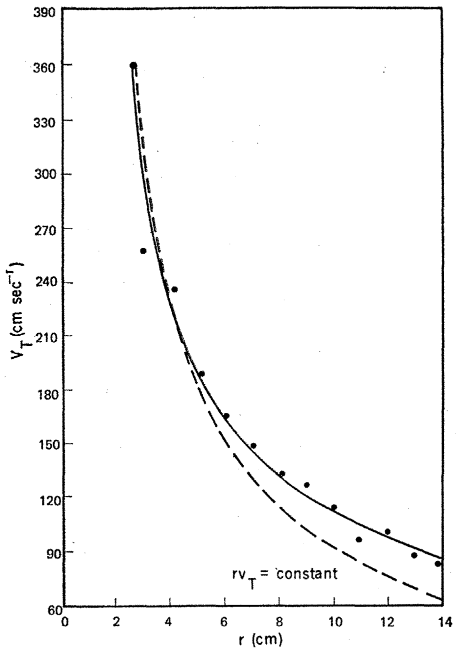


Fig. 3. Tangential velocity profile in the air circulating around the d-c discharge as determined by the use of cottonwood seeds as tracers.

On occasion in the high-speed pictures we see discrete plasma globules that form spontaneously at the lower electrode and move up the core of the discharge until they are no longer identifiable after they have risen approximately 25 cm. These globules appear to be qualitatively similar to the ones that Langmuir (*8*) reported in a low-pressure argon electric discharge. A puzzling aspect of these globules is that their apparent vertical velocity is of the order of 15 m sec^{-1}, over five times the value that we determine by injecting lithium stearate tracer particles in the discharge. The pressure drop in the vortex is 0.1 mb, as measured by inserting a Pyrex glass tube 5 mm in diameter through a hole in the lower plate electrode and connecting it with an inclined tube oil manometer; the pressure does not change appreciably as the tube is lowered or raised.

Fluffy pieces of cottonwood seeds about 2 mm in radius with a terminal velocity of about 5 cm sec^{-1} are used as tracers to obtain the tangential velocity profile in the air circulating around the discharge. The velocity of the particles is determined by photographing from directly above the chamber the motion of the particle over a grid (5 by 5 cm) drawn on the lower plate electrode. The profile is shown in Fig. 3. Measurements closer than 2.5 cm from the vortex axis are not possible because the particles are never observed to be closer to the axis than 2.5 cm.

The observations that are made of the vortex structure by the use of the tracers show that it has three regions of motion. In the outer region ($r \gtrsim 3$ cm), the flow is predominantly tangential with a very small vertical component. In the inner region ($r \lesssim 1$ cm), which is the core region of the discharge, the flow is predominantly vertical with little, if any, rotation. The space between these two regions ($1 \lesssim r \lesssim 3$ cm) is a "transitional" zone of about equal tangential and vertical components. This region includes the luminous sheath portion of the electric discharge. This structure is similar to the one described for a vortex formed by using an exhaust blower and a modified Dines vortex cage (*4*).

We believe it is an important finding of our experiments that a stable vortex can be initiated and maintained by the use of a high-voltage electric discharge without the externally provided pressure sink that we and other investigators had previously found to be necessary (*3*, *4*). It appears from our observations that the failure of the earlier experiments, ours included, to produce a self-stabilizing vortex discharge system can be attributed to the electrode geometry that was used: two vertical metal rods, one above the other, in the axis of the apparatus. Such an arrangement does not give rise to a stable vortex, apparently because it imposes the requirement that the axis of the vortex must coincide with the axis of the electrodes and the vortex chamber. We find that invariably the vortex first forms about halfway between the axis and wall of the chamber. Because the vortex is so far removed from axial electrodes, the discharge will break off before it can stabilize in the axis of the vortex and migrate to the center of the chamber.

In one respect our conclusions differ markedly from those drawn by Wilkins from his similar experiments (*5*). He states, "Under the most favorable assumptions the vortex might lengthen the discharge re-strike time by a factor of 10 to 50 (from 5 μsec to 50–100 μsec). . . ." Our experiments suggest a re-strike time that is 10^4 times longer. This estimate of the life of the plasma in our experiments is confirmed by the photographs showing that the plasma in the axis between the electrodes remains luminous for approximately 4×10^4 μsec after the electric current ceases to flow. We find our observations to be consistent with Uman and Voshall's view (*9*) that the channel conductivity decay is dependent on the rate of heat transfer. They show that for channels several centimeters in diameter the temperature of the lightning channel will decay sufficiently slowly so that the electrical conductivity will persist for a typical interstroke period of 4×10 μsec.

We believe that a possible explanation for the large difference between Wilkins' findings (*5*) and our own may be that the critical ionization times of 0.5 msec that he observed are characteristic not of the vortex-stabilized discharge, as he has assumed, but rather of small sparklike discharges, similar to our feeder spark, which carry the current flowing from the two electrodes to the vortex-stabilized discharge and which are subjected to a continuous flux of fresh, cold, and un-ionized air.

Several important differences must be taken into account in any attempt to extrapolate our laboratory results to phenomena taking place in the atmosphere. It must be recognized that our electrodes are producing a much higher concentration of metal ions than would be found in the natural atmosphere and that these ions may affect the properties of the plasma. In our laboratory experiments, the potentials of only a few kilovolts were capable of initiating a spark no more than a few centimeters long, so that it was necessary to bring the electrodes almost into contact to initiate the discharge. Once the discharge had been drawn out, even a very brief interruption in the current flow causes a flameout, for the voltage is insufficient to form a new ionized part to bridge the gap between the plasma in the vortex and the electrodes. In the thunderstorm we would not expect this circumstance, for the potentials are such that lightning sparks can jump distances of several kilometers.

Our experiments show that a laboratory vortex can be formed and maintained by electrical heating alone under a variety of conditions. The vortex-discharge combination is a stable, compatible system; the vortex stabilizes the discharge, which in turn drives the vortex by electrical heating. The velocities of a few meters per second and the pressure drop of a fraction of a millibar, which we measure, are of the order of magnitude calculated to result from a heated chimney about 1 m in height. Similar discharges occurring in severe storms, in which the current was of the same order of magnitude but with a voltage three or four orders of magnitude greater than our laboratory discharge and with a heated chimney several kilometers high, might generate and maintain a vortex that had all the properties of a mature tornado.

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Visual Receptor Potential: Modification by Injected Current in the Limulus Lateral Eye

Abstract. *The latent period of the light-evoked receptor potential was increased by hyperpolarizing currents injected directly into doubly impaled retinular cells. Indirect hyperpolarization of these cells by injection of hyperpolarizing current into the eccentric cell or other intraommatidial retinular cells either shortened or did not change the latent period. The modification of the latent period may depend upon the direction of current flow across some regions of the membrane system constituting the rhabdomere. The reduction in magnitude of the receptor potential obtained with strong hyperpolarizing currents may also depend upon the direction of current flow. The results support the conclusion that the receptor potential originates in retinular cells within the membrane system of the rhabdomere.*

Our study was undertaken to determine whether extrinsic currents injected into retinular cells of the lateral eye of *Limulus polyphemus* can alter the latent period of the light-evoked receptor potential. Excised lateral eyes of *Limulus* (*1*) were impaled with independently manipulated KCl-filled micropipettes. Since we could not check impalement visually and dye-marking was not used, the following criteria had to be met for a cell to qualify as impaled by both electrodes: a change in membrane potential of at least 10 mv for 4×10^{-9} amp of hyperpolarizing current; synchrony and similarity of wave form and magnitude of spontaneous potential fluctuations detected by both electrodes; similarity of wave form and magnitude of the receptor potential; equality of latency of the receptor potential; and equality of the resting membrane potential. Additional qualifications for acceptance were stability of the doubly impaled cell for 1 hour or longer, a resting membrane potential of 40 mv or more, and a typical (*1*) receptor potential. Many double penetrations did not meet these criteria and were either discarded or recorded as combinations of retinular cells or of retinular and eccentric cells, depending on the response characteristics (*1, 2*), the magnitude of

Table 1. Changes in latent period and membrane potential produced by hyperpolarizing current injected into a doubly impaled retinular cell.

Hyperpolarizing current (na)	Latent period (msec)	Increase in membrane potential (mv)
0—Control	46	0
1.8	52	54
2.2	56	69
3.0	63	119