ART. LIX.—*On Electrical Discharges through poor Vacua, and on Coronoidal Discharges* ;* by M. I. PUPIN, PH.D., Columbia College. With Plate XIV.

INTRODUCTION.

THE behavior of electrical discharges through poor vacua does not seem to have received the attention of experimental investigators which it deserves. This may seem strange in view of the uncertainty of our knowledge of the process by which the transfer of electricity through gases takes place. Considering, however, that it was generally customary to employ in experimental investigations of this kind a vacuum jar with metal electrodes in connection with an electric generator of small capacity, it is easily explained why the discharges through poor vacua should have received so much less attention than the discharges through high vacua and the spark discharges through gases at ordinary pressures. Neither the vacuum jar, nor the working of the electric generators ordinarily employed, admitted of rapid, easily adjustable, but essential variations in the conditions of the experiment; as for instance, variations of the size and shape of the electrode, of the frequency of the discharges, of the strength of the electromotive force, etc. But, as I shall point out in the course of this paper, it is through these very variations that certain fundamental features in the character of an electrical discharge through poor vacua are brought out prominently.

The fact that electrical discharges in poor vacua resemble in many characteristic details the appearance and behavior of the solar corona attaches additional interest and importance to that class of experimental investigations which are pointed out, only, in this paper. Neither time nor facilities permitted me to aim at anything approaching completeness. The principal aim in my presenting this paper was to recommend my subject and my method of investigating it to those who command over a larger experience and skill in experimental investigations, and who also have more leisure and greater experimental facilities than I could even pretend to possess.

DESCRIPTION OF THE EXPERIMENTAL METHOD.

A brief description of the method by which I obtained my vacuum discharges seems in place now. It consists in producing an electrical current in a vacuum by means of the con-

* Read before the National Academy of Sciences, Washington, April 22nd, 1892.

denser effect of tinfoil coatings or other conductors placed on the outside of a vacuum jar.

The following experiment which I performed over a year ago will explain my meaning more fully. The poles *f g* (fig. 7,) of a small Ritchie induction coil were connected to two glass

beakers *a b* containing water. The primary was fed by a $\frac{1}{4}$ h. p. alternator A, giving an alternating current of about 80 periods. A resistance box R, regulates the strength of the primary current. The speed of the motor which drives the alternator regulated the periodicity of the current.

A vacuum jar *c d*, consisting of two glass bulbs (each about 8 cm in diameter) connected by a tube of narrow bore, was immersed into the beakers, one bulb in one beaker the other into the other. The jar contained rarefied air at about 5 mm pressure.

As soon as the bulb reached a certain depth a discharge took place producing a perfectly steady and continuously diffused crimson luminosity. The intensity of the luminosity increased with the increase of the surface of contact between the water and the bulbs. The same effect was produced by substituting

a Holtz machine for the induction coil and the alternator. In this case the effect was due, of course, to the oscillations produced by the spark discharge between the poles of the machine. The two vacuum bulbs with the water surrounding them act like two condensers connected in series by the narrow tube. It seems superfluous to describe the obvious experiments which I had to perform to prove the following relation :

The intensity of the luminosity increases with the condenser surface of the bulbs, with the frequency of alternations, and with the effective electromotive force of the charging apparatus. Other things being equal the total amount of light produced will increase with the increase of the conductivity of the vacuum. This relation may have been understood before, but to my knowledge it was never clearly stated.

The luminous effects which I succeeded in producing in the manner described were so powerful, that I thought it worth while to construct an electrical lamp on this principle. I mention this for the purpose of pointing out that this method of producing very powerful vacuum discharges was worked out by me several months before the publication of Nikola Tesla's and Professor J. J. Thomson's magnificent experiments. A considerable number of results which I obtained in my experiments are simply repetitions, on a small scale, of the results obtained by these scientists. There is, however, one line along which there seems to be but very few points of contact between their work and mine. This line runs in the direction of investigating the relation between the character of the discharge, the pressure in the vacuum, and the effective e. m. f. which produces the discharge. The following experiments will show some of the characteristic features of this relation.

I. ON THE CRITICAL POINTS OF THE DISCHARGE.

A vacuum jar of the form and dimensions as given in fig. 8, was substituted for the small double bulb *c d*, in fig. 7. The bulbs A and B were totally immersed in large glass beakers containing clear, distilled, acidulated water. The air pressure in the bulbs was a little less than 2^{mm} . Instead of the small alternator a large alternating current machine fed the primary. On closing the primary circuit the discharge between the bulbs started long before the resistance box R, indicated that the e. m. f. in the secondary coil had reached its maximum. The crimson luminosity was very soft, steady, and distributed in accordance with the distribution of the potential which one would expect in an electrical system of the above description.

Touching the narrow tube at any point increased the luminosity below the point touched; evidently due to the increase

of the static capacity at that point. Diminishing gradually the e. m. f., the luminosity of the discharge diminished with it and then stopped suddenly as if a critical point had been suddenly reached. Reducing the e. m. f. gradually to zero

and then gradually increasing it again, it was found that the discharge would cease at a point much lower than the point at which it would start again, the difference between the two points diminishing considerably with the rapidity with which these variations were made. The discharge will start at a much lower e. m. f. if solicited, that is to say if the long tube is touched at one or more points. A wire bent in the shape of a Leyden jar discharger does very good service as a discharge "solicitor."

The discharge was similarly affected by varying the capacity. Performing the last experiment, but with the small vacuum jar *c d* given in fig. 7, it was found that with a given potential (just above the critical point) the discharge did not start until the bulbs *c d* had reached a certain depth and then it started suddenly. Raising the bulbs gradually, and therefore diminishing the capacity, the discharge became fainter and fainter, but it did not cease until the bulbs were entirely lifted out of the water. On immersing again, the discharge did not start until a certain depth was reached. The depth at which the dis-

charge would start this time was smaller than in the first case and the smaller the shorter the interval between the time of taking the bulbs out and immersing them again. This difference is, of course, due to the improved conductivity of the gas and this again may in a certain measure be due to the rise in temperature of the gas on account of the heating effect of the discharge; but only in a small measure, for the bulbs were under water, so that the rise in temperature must have been very small. Besides, heating the bulbs with a Bunsen burner before immersion did not diminish the depth at which the discharge would start nearly as much as a previous discharge would, no matter of how short a duration. As stated above, the discharge may be started far below the critical point by touching the connecting tube. But if the touch lasts only a very short time (a fraction of a second) the discharge ceases as soon as the touching conductor leaves the tube. In this manner the vacuum tube may be made to blaze up in quick successions.

This behavior of the discharge at all pressures, but very much more striking at pressures higher than the pressure under consideration, seems to support the dissociation theory of Prof. J. J. Thomson (*Phil. Mag.* 1891, vol. xxxii, pp. 329, 454, 455).

II. PHENOMENA INDICATING A DISSOCIATION OF THE MOLECULES.

The following phenomenon appears to be an additional support of this theory :

A close inspection of the discharge going on in the bulbs A and B, fig. 8, seemed to reveal the strange fact that the electrical flow was confined to a thin layer of the rarified gas which is in immediate contact with the inside surface of the bulbs, especially when the e. m. f. was not too far above the critical point and therefore the supply of the current not too plentiful. To all appearances there was a gliding film of luminous gas in each bulb extending from the mouths of the connecting tube, spreading over the inside surfaces and ending at the bottom of the bulbs in violently agitated luminous clouds which gave the discharge a hazy appearance. When the vacuum was very good both the film and the clouds were absent. There was no suggestion of a motion on the part of the gas, and the discharge had a clear luminosity. To study this phenomenon more closely the following experiment was performed :

A glass bulb *a*, fig. 9, blown out at one end of a thick glass tube of narrow bore was filled with acidulated water and

Fig. 9

placed at the center of a large glass bottle, as indicated in the figure.

A wide strip (*c b*) of tinfoil was placed on the outside of the bottle, covering about one-third of the surface. The air was exhausted through the tube *d*, until the pressure was about 3^{mm} . The liquid in the bulb *a* and the tinfoil were connected to the secondary poles of the induction coil. When the e. m. f. was not too far above the critical point the discharge was in form of numerous, quivering streamers, which looked like the generators of a conical surface with the center of bulb *a* as vertex and the edge

of the tinfoil as directing curve. There was no visible discharge between the bulb and the central parts of the tinfoil. But the discharge spread out and gradually approached these parts and at the same time the streamers became less numerous and steadier, giving the discharge a more diffused appearance as the potential gradually increased. When the e. m. f. was gradually brought back to its original value the discharge diminished in intensity but did not return to its original form of distribution. It did that when the e. m. f. was considerably lowered below its initial value, which showed that the original distribution was not altogether due to the fact that at any moment the density of the electrostatic charge of the tinfoils was considerably larger near the edges. In this experiment as well as in the preceding one the number of streamers, their definition, their quivering motion, and their preference for the paths along which the discharge started, increased with the increase of pressure in the vacuum. A discharge (especially in vacua of poor conductivity) will always start between parts of highest electrical density and each successive discharge prefers the passage along the path of the first discharge on account of the increased conductivity along this path.

But if this increase in the conductivity is due to a rise in the temperature of the gas along the path of the first discharge and to nothing else, how can the fact be explained that a long, thin, discharge streamer when forced through a poor vacuum can be maintained steady, and permanent in form, even if the discharge continues for several minutes? It should broaden out continually and become more and more diffused as the adjacent particles of the air get heated. In my experiments on solitary discharge streamers in poor vacua (see this Journal, April, 1892), I did not observe any appreciable widening out, but I did observe a phosphorescent halo around the streamer which, as Prof. J. J. Thomson assumes, (l. c.) was *very probably* due to dissociated oxygen molecules that were ejected from the path of the discharge. (See further below the effect of a blast on a discharge streamer).

Still another experiment which shows that something of the nature of a dissociation of the gas molecules is going on along the path of the discharge. A thick German silver wire, 60^{cm} long, was bent zig-zag fashion into 12 zig-zag parts and placed in horizontal position at the bottom of a bottle like the one in fig. 9. A wire passing through a rubber stopper in the neck of the bottle connected this zig-zag electrode to one of the poles of the induction coil. The other electrode, a small brass sphere, was vertically above the zig-zag electrode, immediately under the rubber stopper. The shortest distance between the two was about 30^{cm}. The vacuum was about 3^{mm}. The discharge started between *the nearest points of the electrodes*, that is between the lowest point of the sphere and one extremity of the zig-zag electrode. It had the form of a band about 3^{cm} wide, intensely luminous at each end, but only very faintly luminous along the intervening three-fourths of its length. The length of the less luminous interval increased with the decrease of the e. m. f., but diminished with the increase of the gas pressure; it also seemed to have a different color, but I did not care to examine this point more closely. The phenomenon that interested me more was the gradual creeping of the discharge along the zig-zag electrode from one of its extremities towards the other. It did not increase in breadth but left its trail along the zig-zag electrode in form of a faintly luminous halo which surrounded this electrode just like a narrow luminous tube. Both the color and the gradual lateral motion of the discharge reminded me very much of the aurora borealis of Feb. 13th, 1892. (In this connection it is well to remark that when the e. m. f. is below the critical point this auroral discharge can be started by powerful disruptive discharges of a Leyden jar in its vicinity. This in connection with observations on coronoidal discharges given in the

latter part of this paper may perhaps furnish a clue in tracing the connection between sunspots and auroral discharges).

III. PHENOMENA INDICATING A TRANSLATIONAL MOTION OF THE GAS.

An interesting phenomenon was observed in the experiments with bulbs A, B, fig. 8, when the vacuum was diminished by turning a stop-cock C several times around. The vacuum pressure was about 20^{mm} . The induction coil had to be strained considerably to force a discharge through the long glass tube. The discharge looked like a luminous jet shooting from the tube into the bulbs, and in its path around the corners it seemed to strike against the necks of the bulbs at *a* and *b* from which points it was reflected and glided along the surface towards the points *e* and *f*. Inside of the bulbs the jet oscillated rapidly; it was also split up in several parts, each part consisting of numerous more or less intense streamers. A slight modification in the curvature of the necks modified the general outline of the luminous jet without changing its general character. With the increase of the gas pressure the phosphorescence appeared and seemed to be strongest at *a* and *b*. It was very strong in the tube C, leading to the stop-cock, although this tube was entirely free from the discharge proper. The height to which the phosphorescence rose in this tube increased with the current. Every slight variation in the current strength caused a simultaneous variation in the height of the phosphorescent column in C. (When the discharge ceased there was a strong phosphorescent after-glow all along the long tube). A similar behavior on the part of the phosphorescent gas, which I observed in the experiment described in this Journal, April, 1892, leads to the conclusion that the phosphorescent gas must have a translational motion due to its being ejected from the path of the discharge proper. This strengthened my belief in a translational motion of the gas along the path of the discharge proper, which belief was due to the phenomena in the experiment just described. It was also strengthened by the phenomenon observed in the experiment described by me in the paper cited above, the phenomenon namely that a discharge streamer made to curve out (by the repulsive action of another parallel streamer) so as to strike against the walls of the vacuum jar will rebound from this wall just as a curved jet of water would if it struck against a rigid surface. In another experiment with an apparatus similar to that described in the above paper a thin rectangular sheet of mica was suspended between and parallel to two discharge streamers and it was found that it prevented their action which I described in that paper, but

it was made to swing back and forth as if acted upon by a wind coming from the path of the discharges. This action was hardly perceptible in high vacua but increased quite considerably with the increase of the gas pressure. It may, however, be due to a great variety of causes, like peculiar distribution of pressures due to a peculiar distribution temperature; so-called apparent (in my case continually varying) electrostatic charge over the surface of the mica, etc.

IV. ON CORONOIDAL DISCHARGES.

Wishing to perform additional experiments which could throw some more light on this particular feature of the discharge, I constructed the apparatus given in fig. 10. A large

Fig. 10

glass bulb was coated with tin foil along those parts of its external surface which would approximately correspond to its temperate zones, its neck being one of the poles. This tinfoil coating had a wire *g* attached to it by means of which it could be connected to the pole of the induction coil, and serve as an electrode of the bulb. The other electrode was a brass sphere *a* attached to a brass rod *b*. This brass rod was surrounded by a glass tube *c d* and the space between the two was filled with sealing wax. In this arrangement the pressure could be varied between very wide limits (up to about 100^{mm}) without running the risk of refusal on the part of the induction coil to force a

discharge through. A camera was placed in front of the bulb as indicated in fig. 10, and the discharges photographed. Figs. 1, 2, 3, 4, 5, 6, (in the plate facing p. 462) are photographs of the discharges obtained in this manner but in various degrees of rarification.

I shall discuss the discharge given in fig. 6 first. In this case the vacuum was very poor (about 60^{mm} pressure). The discharge started in the form of four large streamers together with a very large number of short luminous jets, which were more or less uniformly distributed over the sphere. In consequence of these jets the appearance of the sphere reminded one very much of the granular structure of the sun's disc as revealed by Rutherford's, Janssen's, and Vogel's photographs of the sun. Very luminous spots appeared from time to time at several points of the surface, which reminded one very much of the sun's faculæ. Both the jets and the large streamers rotated rapidly. This rotation is indicated very plainly in the photograph; for the number of streamers in each wing represents the number of maxima in the alternating discharge during the time of the exposure, which was a small fraction of a second. The thickest streamers indicate the place where the discharge started. It is evident that the streamers were distributed nearly symmetrically over the sphere at the start of the discharge and that then one-half of them were gradually and almost uniformly displaced in the direction of motion of the hands of a watch, the other held in the opposite direction. The peculiar curvature of some of these streamers indicates the presence of two kinds of motion, one a translational along the prolongation of the radii of the small sphere and the other a rotational. It was this rotational motion which led me to assume that there must be some sort of repulsive action between the streamers of a vacuum discharge. The existence of this action was demonstrated conclusively by the experiment described in the paper cited above. Additional researches in this direction lead me to the conclusion that two discharge streamers tend to blow each other out owing to the motion of the cooler gas between them, this motion being produced by the enormous heating effect of the discharge. The result is that the particles of the gas which at any moment form the path of a discharge are continually displaced (particularly in a discharge through a poor vacuum), and since every successive discharge prefers the particles through which the preceding discharge passed (for reasons given above) it follows that a sort of rotary motion is set up in the various parts of the discharge.

An additional evidence in favor of a translational motion along the paths of the streamers is furnished by the fact that

all along the inside surface of the large glass bulb, which is below the tinfoil coating, there is a hazy luminosity which increases with the increase of the discharge, and which to all appearances is due to an accumulation of incandescent gas molecules which had impinged against and were reflected by the surface of the bulb.

If the inside end of the exhaust tube *e*, fig. 10, is lowered, so that it reaches the region of the discharge it is observed that from time to time the incandescent gas shoots through this tube toward the stop-cock way out of the bulb.

EFFECT OF A BLAST ON A DISCHARGE STREAMERS.

Granting that there is a translational motion along the path of the streamer it follows that a rectilinear streamer may be transformed into a curved one by imparting to the gas in each part of its path a component velocity perpendicular to its original velocity. This inference was confirmed by the following experiment :

Two bulbs A B (fig. 11) coated with tinfoil on the outside (the electrodes of the system) communicated with a reservoir (which I call the principal reservoir) by means of glass tubes

b c of narrow bore. An L-shaped tube *a* with a small orifice was fitted by means of a rubber stopper into the neck of the reservoir. By means of this tube and the tube *d* of the principal reservoir communicated with two other reservoirs, which I call the external reservoirs.

The external reservoir connected with *d* communicated with a mercury pump. When the exhaustion had reached the point at which a steady rectilinear discharge could be forced from *b* to *c*, a stopcock connecting *d* to its external reservoir was shut off and the exhaustion continued until a good vacuum was obtained in the external reservoir *d*. The discharge was then started. It was a perfectly steady, narrow, rectilinear column of crimson luminosity, surrounded by a phosphorescent ellipsoidal column. But as soon as the above mentioned stopcock was turned on, the blast coming from the orifice *a* played up the column and the rectilinear path became curved at the point where the blast was acting. The discharge acted as if it bent around to get out of the way of the blast. The observation that the effect of the blast upon the phosphorescent column was incomparably stronger than upon the crimson column needs no comment. The weaker the discharge the stronger is the effect of the blast, and *vice versa*. The effect of a blast upon the oscillatory spark discharge of a powerful Leyden jar battery is not perceptible.

In discharges through very poor vacua the heating effect is very unequally distributed throughout the vacuum jar. The temperature at certain points is enormously higher than at others. The result is that a very violent motion of the gas is set up, which motion may sometimes, on account of the effects pointed out in the last experiment, produce streamers of double curvature.

During an experiment with the apparatus given in fig. 10, which I performed on February 8th, 1892, before the astronomical section of the New York Academy of Sciences, a leak occurred so that the vacuum was exceedingly poor by the time I was ready to start the discharge. Finding that the discharge gave no sign of starting, I risked turning the whole power of the 10 h. p. alternator on the induction coil. Long sparks shot immediately from almost every point of the edge of the tin-foil. The discharge between the brass sphere and the tin-foil looked like a black-faced Medusa with fiery serpents dancing all around her head. On repeating this experiment I found that in very poor vacua the discharge streamers very often assume the form of spirals of very long pitch.

All these phenomena suggested to my mind a very strong similarity between the streamers of an electrical discharge

through poor vacua and those of the solar corona, and for the purpose of pointing out this similarity to others otherwise than by verbal description, only, I resolved to photograph these discharges under conditions similar to those under which the solar corona is observed. Photographs 1, 2, 3, 4, 5, 6 are the result.

The discharges were obtained with the apparatus given in fig. 10. The only additions were that a circular tinfoil disc was pasted on the outside of the large bulb, in the line of sight between the camera and the brass sphere *a*. The diameter of this disc was about equal to that of the brass sphere. Also, the inside surface of the large bulb which formed the background of the brass sphere was blackened by means of camphor smoke to avoid reflections. The discharge in fig. 1 is that of a good vacuum (about 2^{mm}), the succeeding ones represent discharges in poorer vacua, the pressures varying between 2^{mm} and 60^{mm} .

The bearing which these experimental results may have upon the theory of the solar corona I prefer to leave to others to decide. That they may prove a suggestive guide in the study of solar phenomena seems not unreasonable to expect.

I am greatly indebted to Professor John K. Rees for the interest which he took in my work, and to Mr. Mann of the Columbia College Observatory, for the very valuable service which he rendered me in photographing the coronoidal discharges.

Department of Electrical Engineering, Columbia College,
March 31st, 1892.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6