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ART. XXXII. — *On the Action of Vacuum Discharge Streamers upon each other*; by M. I. PUPIN, Ph.D., of Columbia College. With Plate XII.

VARIOUS phenomena which I observed in the course of an investigation on the coronal effects produced by electrical discharges through rarefied gases, led me to the belief that under certain conditions two electric current filaments in a rarefied gas may act upon each other oppositely to the direction of their mutual electrodynamic action, and that this additional action may sometimes be far predominant over the electrodynamic action; that is to say, we have a strong repulsion where electrodynamic action would produce an attraction. A brief account of these investigations was given on Feb. 8th, before the Astronomical Section of the New York Academy of Sciences. The following paper is limited to the description of the experiments by means of which the existence of the above mentioned action was definitely proved.

Fig. 1 represents the apparatus first employed. Four glass bulbs, A, B, C, D, each having a capacity of about a liter, are connected by four glass tubes of small bore to a glass reservoir E. A stopcock F serves to connect the apparatus to a mercury pump. The reservoir has a diameter of 10^{cm} and a length of 22^{cm}. The mouths *e*, *f*, *g*, *h*, of the four narrow-bore tubes form a square whose side is 10^{cm} long. The bulbs are covered with tinfoil and the tinfoil is then well coated with paraffin.

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Each tinfoil covering has a well insulated copper wire attached to it.

Fig. 1.

After producing a 2^{mm} vacuum in the apparatus the bulbs A and B were connected to the secondary poles of a small Ritchie induction coil, whose primary was fed by an alternating current of 125 periods per second. The electromotive force in the secondary coil was varied by varying the current in the primary; this was done by means of a resistance box in the primary circuit. The electric flow between the bulbs is, of course, due to the condenser effect between the tinfoils and the vacuum.

At the pressure of 2^{mm} the discharge was easy, steady and very diffuse along its path through the reservoir. Disconnecting AB and connecting CD to the induction coil the discharge was the same in character as before. Connecting both pairs of bulbs in parallel to the induction coil, that is, the bulbs A and C to one pole and B and D to the other pole, the two discharges, going on simultaneously, were the same in character as before, except that they were somewhat convex towards each other.

The pressure was then increased by turning the stopcock once around and allowing some air to get in. The discharges were less diffuse but more luminous, and less convex toward each other.

With the increase of pressure the discharges became less and less diffuse and their convexity towards each other diminished until, when a certain gas pressure was reached, it disappeared. At this point the discharges were very little diffuse and when allowed to pass through the reservoir simultaneously they remained rectilinear, but somewhat unsteady, oscillating quite appreciably about their rectilinear paths through the reservoir,

but the oscillations were always in the plane common to their rectilinear paths.

The pressure was still increased by turning the stopcock once around and allowing some more air to get in. The discharges became still less diffuse along their path through the reservoir and when allowed to pass one at a time they were quite steady and rectilinear. Both being allowed to pass through the reservoir simultaneously they were appreciably concave toward each other, but the concave arcs were in the plane passing through their shortest path in the reservoir. There was evidently a repulsive force acting between the discharges. This repulsive force increased continually with the increase of pressure in the vacuum, but with the increase of the force the steadiness of the discharges along their paths through the reservoir when they were both passing simultaneously gradually diminished. Fig. 3 (Plate XII) is a photograph of the discharges when taking place simultaneously in a vacuum in which the repulsive force just described was moderate. Fig. 2 is a photograph of the same discharges, but when taking place one at a time. Fig. 2 indicates that there is a repulsion between the discharge and the nearest wall of the reservoir, but this repulsion is very small in comparison to the repulsion acting between the streamers, when they take place simultaneously, as fig. 3 indicates. The photographs were taken by very short (1 to, $1\frac{1}{2}$ second) exposure, so strong is the luminosity of these discharges. They were taken when the repulsion was moderate, because when the repulsion is very strong the discharges oscillate very rapidly, so that they could not be well photographed with the apparatus employed. When the repulsion was so strong as to cause the streamers to curve way out and from time to time strike the nearest wall of the reservoir, the vibrations became very violent every time the streamers struck against the walls. They rebounded against the walls just as if they were luminous vibrating strings.

At this pressure in the vacuum it was very difficult to start the discharge and I had to strain the alternating machine and the induction coil to their utmost to make the start.* But when once started the discharge continues without any interruption even if the potential at the tinfoils is lowered 15 to 20 per cent.

The rate at which the temperature of these discharges increased with the increase of pressure in the vacuum seems to be much more rapid than the increase of the pressure; (the impressed *c. m. f.*, of course has to be increased with the pressure) and with the increase of the temperature the luminosity

* A gentle touch of the apparatus with a conductor will sometimes start the discharge at once when all other means of making this start fail.

of the discharge increased also. With the increase of luminosity the color of the discharge changed from the pink color, which is the characteristic color of the ordinary Geissler tube discharges through rarefied air, to a color which inclined more and more toward the white. With the increase of the pressure the diffuseness of the discharge disappeared, but instead of the diffuse pink color there appeared a beautiful green phosphorescent light which filled the whole reservoir. This phosphorescent light is so strong, that even an almost instantaneous exposure is sufficient to give it time to act upon the sensitive plate, as appears from the photographs in figs. 2 and 3. At some future date I shall describe experiments which seem to be a strong proof that phosphorescence produced by electrical discharges depends on the temperature and only in so far on quantity of the discharge and on the vacuum, as the temperature of the discharge depends on them. The investigations of Crookes, Goldstein, and others lead to the conclusion that a high vacuum with its cathode rays is most favorable if not indispensable to the development of strong phosphorescence. In my experiments a good vacuum (of about 2^{mm}) gave no phosphorescence whatever, whereas a poor vacuum (even with as high a pressure as 100^{mm}) gave very strong phosphorescence, and that too not only in places where the discharge struck the walls of the vessel but also in places which were far away from the discharge. Presently I shall describe an experiment which shows that the gas as well as the glass becomes strongly phosphorescent. My observations cannot, therefore, be well reconciled to those of Crookes, Goldstein, etc., unless the cathode rays be supposed to be very thin and very hot discharge filaments. I have several experimental facts which speak in favor of this hypothesis, but a discussion of them would lead me beyond the limits of this paper.

I find that some astrophysicists assume the existence of a repulsive force acting between the streamers of the solar corona; it was the peculiar behavior of the corona-like vacuum discharges which, in addition to other phenomena that came under my observation, forced me to assume that repulsive forces must be active between the filaments of these discharges, although at that time I was perfectly ignorant of the details of the various electrical theories of the solar corona. The streamers of these discharges are very unsteady and very much split up when the vacuum is poor. A photograph of a discharge of this kind is given fig. 4. As the vacuum improves the corona-like discharges become a great deal steadier, less torn up and quite diffuse, but never uniformly distributed over the whole spherical electrode. Fig. 5, represents the photograph of a discharge in the vacuum of about 20^{mm} pres-

sure. These photographs belong to my collection of photographs of corona-like vacuum discharges, an account of which I expect to give at some future time.

The question arose then, naturally, what is the cause of this repulsion? Electrostatic action suggested itself first, of course. But various observations which I made during my investigations on vacuum discharges made me favor another view, the view namely that the repulsive force between vacuum discharge streamers is due to a strain in the vacuum produced by the peculiar distribution of the gas pressure resulting from the peculiar distribution of temperature. If this view is correct then there should be no action between two vacuum streamers passing in two separated vacua. This suggested the following experiment:

Investigate the action of two discharge streamers upon each other when two separate discharge reservoirs are employed. Fig. 6, represents the apparatus (with its dimensions in cm.

marked), containing one of the reservoirs, two of which were placed side by side in the experiment. The bore of the capillary tubes *e*, *c*, *d*, *f*, was about 1.5mm. The bulbs AB were coated with tinfoil and the whole arrangement was the same as in the experiments with the apparatus given in fig. 1. The two apparatus communicated with each other by means of a stopcock, so that the pressure was the same in each. The discharge in one apparatus did not influence the discharge in the other, no matter what the pressure was, up to the limit at which I could still obtain a discharge, which was about 60mm. From this I conclude that the repulsion which I observed in the previous experiments was probably not due to electrostatic

action. The probability of the correctness of the other view is therefore considerably strengthened.

The apparatus for this experiment was constructed with two other objects in view, which ought to be mentioned here.

1st. To locate the phosphorescence. In this I was quite successful. It surrounded the hottest parts of the discharge, and therefore it was most intense in the narrow parts of the apparatus. Within the reservoir it extended from *c* to *d* in form of something like an ellipsoid of revolution, with the extremities of its longest axis at *c* and *d*, and at times this ellipsoid did not fill out the reservoir at all, which proves that the phosphorescent light in this part of the apparatus is due to the phosphorescence of the rarefied air and not to the phosphorescence of the glass, although in the narrower parts of the apparatus where the hot discharge was very near the glass the glass was also phosphorescent.

2d. To study what I call the ramification of the discharge. As soon as the pressure reached a certain limit the luminosity in the bulbs (which at low pressures was more or less uniformly diffused throughout the bulbs) became streaked, and at still higher pressures the whole discharge in its path through the bulbs divided itself into a number of distinct streamers, the number of streamers diminishing with the increase of pressure; given pressures produced invariably the same number of streamers. In this experiment I did not succeed in reducing the number of these streamers to less than two. The streamers rotated more or less uniformly in one direction or the other. The angular velocity of rotation seemed to increase considerably with the current of the discharge.

An exhausted glass bulb without electrodes when brought into the vicinity of these discharges emits a faint yellowish light which looks very much like the light of some forms of the aurora borealis. The bulb seems to remain perfectly cool. Lack of time and facilities have prevented me from determining the spectrum of this cold glow.

My thanks are due to Professors W. P. Trowbridge and J. K. Rees for the interest which they took in my work; also to Mr. Mann, of the Astronomical Observatory, for the very valuable service which he rendered to me in photographing these discharges.

I hope to continue this work with improved facilities as soon as time will permit.

Department of Electrical Engineering, Columbia College, February 28th, 1892.

Fig. 2

Fig. 3

Fig. 4

Fig. 5