ON THE MAGNETIC EFFECT OF ELECTRICAL CONVECTION. II.

By Harold Pender, Ph.D.

SINCE the publication of the results of his first experiments on the magnetic effect of a moving charged body,[1] the author has continued his investigations, with results in every way confirmatory of those of the previous experiments. A brief account of these later experiments may not be without interest, as they were performed under entirely new and more favorable conditions, and gave results which are far more consistent than those previously obtained.

M. Cremieu,[2] in criticising the previous paper of the author, suggested that the agreement between the observed and calculated values of the magnetic effect of the moving charged discs was due to the fact that the speeds and potential of the discs were of such critical values that a slight leak in the insulation would produce the observed effect. The first step then was to test this criticism by varying the speeds and potential within as great limits as possible. To do this, the same method as that previously used by the author, and first introduced by M. Cremieu, was adopted; namely, to measure the current induced in a coil when the charge on a rapidly rotating disc close to it is suddenly reversed.

The great difficulty encountered in the experiments of last year was the impossibility of shielding the needle of the sensitive galvanometer employed to detect this current, from the disturbing magnetic effects of the electric circuits in the vicinity of the laboratory, although the experiments were conducted at night after the electric cars had ceased running. Through the kindness of Professor Ames, Director of the Physical Laboratory of the Johns Hopkins University, I was enabled to move the entire apparatus to the country. The apparatus was, therefore, set up at McDonogh School, twelve

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[1] Phil. Mag., 2, p. 169, 1901; Phys. Rev., 13, p. 203, 1901.

[2] Jour. de Phys., Dec., 1901.

miles from the city of Baltimore and two miles from the nearest electric car line. Experiment showed that this car line was too distant to affect the galvanometer. Electric power for running the various motors was furnished by the school.

The room first put at my disposal was a large garret. The apparatus was set up here, and considerable time was spent in vain attempts to mount the galvanometer so as to be free from mechanical jarring. This was finally given up as impossible, as it was found that the wind caused the whole building to rock considerably. The apparatus was then taken down and set up once more in a large basement room of another building. This room was 14.5 x 19.5 meters in size and had a cement floor, which was so solid that when the galvanometer was mounted on a stout table the needle was entirely free from mechanical jarring.

The various parts of the apparatus and their general arrangement were essentially the same as employed last year. There were, however, a few changes made, which will be briefly noticed.

The disc apparatus was changed only in a minor point, which, however, obviated a source of great inconvenience. This change was the mounting of the brushes making contact with the surfaces of the discs in such a way that the insulation of the cores could be cleaned without taking the apparatus apart. Special care was taken to clean this insulation thoroughly before each set of readings.

A new needle for the galvanometer was made, having a greater sensibility than the old one, and the ground-glass scale was placed two meters from the galvanometer. With the new needle and scale thus arranged it was possible to get four times the sensibility previously secured. But it was found more advantageous to sacrifice sensibility to steadiness of the needle, so that the galvanometer was usually adjusted to have only about one and a half times the sensibility of last year, so that a current of $.7 \times 10^{-10}$ ampères gave a deflection of 1 mm. on a scale 2 meters distant. At this sensibility the spot of light was ideally steady, the zero position seldom varying more than 2 mm. during the time required for the determination of a deflection (the period of the needle was about 35 seconds), although there was sometimes a slow drift of the light to the left. Any error due to this effect was easily eliminated by taking a reading first on one side of the zero position and then on the other.

On the shaft of the combined reverser and commutator which served to reverse the sign of the charge on the discs and to commutate the galvanometer terminals, a second reverser was mounted and connected in series with a Daniell's cell, resistance boxes and the test coil *T*, on the disc apparatus. My idea was to adjust the value of the current through this coil until its effect on the large coil *I*, between the discs, was just equal and opposite to the effect of the moving charged discs, thus employing a zero method. It was found more convenient, however, to note first the deflection produced by passing a known current through the test coil with the discs discharged, then to break the circuit of the conduction current, connect in the Voss machine so as to charge the discs and note the deflection produced by the convection current; then again note the effect of the conduction current, and so on. This was accomplished by means of a set of switches operated by the observer at the galvanometer. The conduction current was adjusted so as to give about the same deflection as the convection current. Its value was determined from the known resistance of the circuit and the E.M.F. of the Daniell cell. The zero method was abandoned on account of the great length of period of the galvanometer needle, nearly a minute being required to detect any slight variation from the zero position.

The above method of procedure obviated the necessity of determining the sensibility of the galvanometer and the speed of the reverser for each set of readings and also the constant "A" of the former paper. Much trouble was experienced in getting brushes for the conduction current reverser which would make a steady contact, but finally this difficulty was overcome by making the brushes of very soft copper foil, each brush consisting of ten layers of foil. It was necessary in the course of the experiments to replace these brushes several times.

As before, a Voss machine and battery of Leyden jars were used to charge the discs. Instead, however, of connecting each pole of the Voss machine to the inside coats of three jars, one pole of the Voss was earthed and the other connected to the inside coating of all six jars; the outer coats of which were earthed. The employment of this method rendered possible the developing of a higher potential, but the convection current produced by the moving charged discs was no longer reversed, but simply made and broken by the reverser. The reverser was run at such a speed that this make and break occurred about ten times a second.

The potential to which the discs was charged was measured by a Thomson electrostatic voltmeter having a range of 0–1,200 volts. This instrument was carefully calibrated by comparison with the standard guard ring electrometer at the Physical Laboratory of the Johns Hopkins University.

The following diagram, Fig. 1, will make clear the general arrangement of the apparatus.

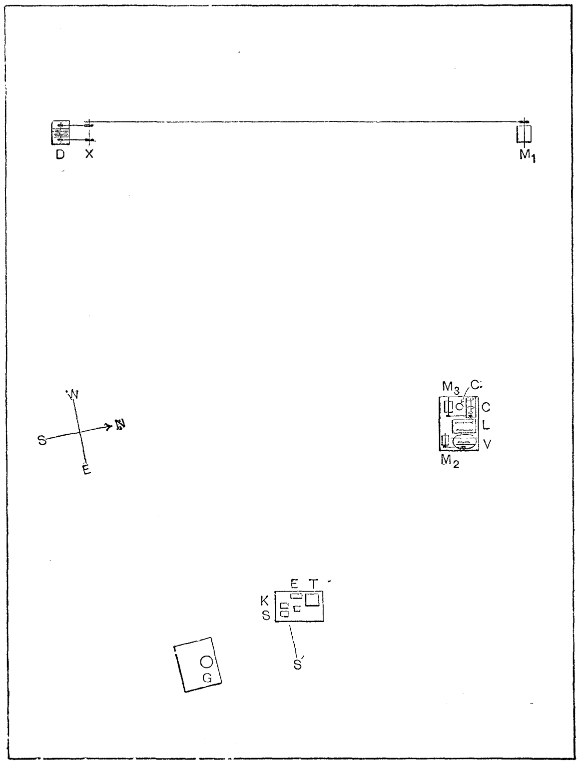

Fig. 1.
Scale 1 cm. = 2 m.

The letters indicate the following :

D the discs and induced coil.
M_1 motor driving the discs.
X countershaft.
C commutator and reverser.
M_3 motor driving the same.
L Leyden jars.
V Voss machine.
M_2 motor driving the same.
E electrometer.
T resistance boxes and switch in test circuit.
S high potential switch.
K key in galvanometer circuit.
G galvanometer.
S' scale for same.

Connections are omitted for the sake of clearness. They were essentially the same as previously used, except that a separate circuit had to be employed to carry the test current through the new reverser.

A number of sets of readings was now taken to determine the relation between the deflection d of the galvanometer produced by rapidly reversing a known current in the test coil, and commutating the galvanometer terminals connected with the induced coil, and the deflection D, produced by charging and discharging the discs at the same rate, the galvanometer terminals being commutated as before. The deflections actually measured were $2d$ and $2D$ (see preceding paper). In each set of readings five determinations of both $2d$ and $2D$ were made with the discs running in each direction. $2d$ and $2D$ were determined alternately. In the first five sets of readings the potential was kept practically constant and the speed of the discs varied from 9.9 to 92.4 revolutions a second, and in the next six sets the speed was kept practically constant and the potential of the discs varied from 905 to 5,900 volts. To show how closely the various quantities could be determined, the following table, giving all the data for one complete set of observations, is appended. A comparison of this table with Table III. of the previous paper will show how greatly the conditions of the experiment have been improved. In the latter the greatest deviation from the mean of $2D$ is 42 per cent., while in the table below it is only 4.4 per cent.

The symbols have the following meanings : E is the electrometer reading, from which is deduced V, the potential of the discs in volts, by means of the calibration curve of the electrometer ; T_1, the number of seconds required by the east disc to make 1,990 revolutions ; T_2, the same for the disc on the west side ; N the mean number of revolutions of the two disc per second deduced therefrom ; i the test current measured in ampères ; d and D as described above. The ratio of the two systems of units is calculated from these data in the manner described below.

Table I.

March 25, 1902. *Direction of Rotation : east disc* + , *west disc* — .

$2d$	$2D$	E	T_1	T_2	i
73	78	59.7	37.8	42.4	$.389 \times 10^{-4}$
75	81	61.0	38.8	42.2	
72	80	59.5	38.6	42.4	
73	82	60.5	38.8	42.0	
72	85	61.0	38.2	41.8	
73.0	81.2	60.3	38.4	42.2	$.389 \times 10^{-4}$

$V = 6310$ *volts.* $N = 49.3$. *Hence* $v = 3.00 \times 10^{10}$.

Direction of Rotation : east disc — , *west disc* +.

72	83	60.5	38.6	42.2	$.389 \times 10^{-4}$
72	79	61.0	39.0	42.6	
73	85	59.8	38.6	42.8	
72	80	58.0	38.0	42.4	
75	81	59.5	38.4	42.2	
72.8	81.6	59.8	38.5	42.5	$.389 \times 10^{-4}$

$V = 6260$ *volts.* $N = 49.1$. *Hence* $v = 2.95 \times 10^{10}$.

Mean value of v: 2.98×10^{10}.

To compare the observed values of $2D$ with those which should be expected on the assumption that the magnetic effect of a moving charged body is similar to that produced by a conduction current, the ratio V of the two systems of electric units was calculated in the same manner as described in the previous paper. No attempt was made at an accurate comparison until all the observations had been completed.

Referring to my previous paper, we have

$$v = \frac{4VN\varDelta}{(B-\beta)D}\left[\mu + \nu\frac{B}{\pi}\log_e\left(2\cos\frac{\pi\beta}{2B}\right)\right]$$

where the symbols have the meanings there given. (I take this opportunity to call attention to two misprints in my former paper, namely, the symbol π for V in the formula on pp. 224 and 225, and $4v$ for $8V$ in the formula on p. 222.) In deducing this formula, the assumption was made that the charge on the discs was reversed from a positive to an equal negative value and vice versa by the reverser. In all the experiments here described the discs were alternately charged and discharged, sometimes negatively and sometimes positively. Hence to apply to these experiments, the above formula must be written

$$v = \frac{2VN\varDelta}{(B-\beta)D}\left[\mu + \nu\frac{B}{\pi}\log_e\left(2\cos\frac{\pi\beta}{2B}\right)\right].$$

$\varDelta$ is the deflection produced by reversing unit current in the test coil at the same rate as the discs are charged and discharged. Hence if d is the deflection produced by the current i under the same conditions,

$$\varDelta = \frac{d}{i}.$$

If the potential is measured in volts and the current in ampères, the above formula then becomes

$$v = \frac{2VNd}{30(B-\beta)Di}\left[\mu + \nu\frac{B}{\pi}\log_e\left(2\cos\frac{\pi\beta}{2B}\right)\right].$$

μ and ν were determined in the manner described in the former paper. The distance between the condensing plates was kept constant. While the discs were running at a high speed one day in the early spring, the east disc flew off the axle, and was so badly damaged that it could not be used again. Instead of waiting to have it repaired, which would have taken considerable time, I went ahead with the remaining disc, making a virtue of necessity by thus varying the conditions of the experiment.

The constants in the above formula are as follows :

Mean Value for the Two Discs.	**Value for the West Disc.**
$B = 2.432$	$B = 2.469$
$\beta = .356$	$\beta = .356$
$\mu = 115.0$	$\mu = 115.0$
$\nu = 28.8$	$\nu = 28.8$

It so happened that the two discs were arranged almost perfectly symmetrically with respect to the coil, so that μ and ν for the two sides were identical within the limits of accuracy of measurement. Hence for the two discs

$$v = 4.18 \frac{VNd}{iD}$$

and for the single disc

$$v = 2.06 \frac{VNd}{iD}.$$

Below are given the mean values, determined from a series of observations similar to that recorded in Table I., of the variable quantities in the above formulæ for the various speeds and potentials employed. Those sets in which the single disc was used are marked with a *.

TABLE II.

i	$2d$	$2D$	N	V	v
$.103 \times 10^{-4}$	20.5	15.5	9.94	5690	3.03×10^{10}
.229	38.8	36.8	25.6	6250	3.08
.389	72.9	81.5	49.2	6275	2.98
.577	92.6	83.9	63.0	5960	3.00
.792	113.4	115.8	92.4	6230	2.98
From former paper.		67.2	102.2	3110	3.00
.0813	20.5	18.8	59.4	905	3.01
.134	26.0	32.7	59.6	2030	3.00
*.1005	18.7	22.0	59.2	2950	3.04
*.249	83.5	56.1	57.6	4090	2.92
*.249	47.1	38.1	57.9	5010	2.97
*.273	54.0	47.1	58.4	5900	2.98
				Mean	3.00

Surely no more conclusive refutation of M. Cremieu's criticism could be desired than that contained in the above results. Such close agreement between the observed and calculated effect under such varying conditions can not be ascribed to the effect of a conduction current caused by any leak in the insulation, for such a current would certainly, from its very nature, be independent of the speed. It is to be noted, however, that the exact coincidence of the value of v as determined from the above experiments with its known value must be considered as an accident only, for an error of at least one per cent. might readily have occurred in the determination of the constants of the apparatus.

In one of his experiments on the magnetic effect of a rotating charged disc on a magnetic needle suspended near it,[1] M. Cremieu observed a deflection of the needle when between it and the charged disc there was only a single condensing plate connected to earth, but when between the needle and this plate a second metallic plate connected to earth was introduced, no effect could be obtained. It therefore seemed worth while to try a similar experiment with the apparatus above described. In this experiment only one disc was used. Between the condensing plate next the coil and the coil itself was introduced a brass plate 1.5 mm. thick connected to earth. On setting the disc in rotation, but without charging it, a great unsteadiness of the needle was noticed. It was discovered that this was due to traces of iron in the brass plate. By gently tapping the plate when the disc was at rest the same effect could be produced. To keep the plate sufficiently steady to make any observations on its shielding effect, it was therefore necessary to run the disc at a very low speed. With the disc running at such a low speed, the Voss machine was connected in, and the deflection of the galvanometer needle observed. Then, without making any other change, the brass plate, connected to earth, was introduced, and the deflection again noted. This was done several times. The mean of a number of readings with the plate out and in were respectfully 12.8 and 13.0 mm. deflection. From this we can conclude that the introduction of the plate was without any such effect as noted by M. Cremieu. It may be of interest to note in this connection that an attempt to use a solid aluminum disc in place of the gilded disc in my first experiments was foiled by the magnetic disturbances caused by traces of iron in the aluminum, although the purest metal obtainable was employed.

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[1] C. R., 131, p. 797, 1900.

The next experiment tried was the application of Cremieu's method to the investigation of the magnetic effect of a dielectric moving in a uniform electrostatic field, or in other words, the magnetic action of a moving apparent charge. This question was first investigated by Roentgen in 1888.[1] Roentgen showed that a moving polarized disc was capable of deflecting a magnetic needle suspended near it. The maximum deflection observed by Roentgen was 3 mm. One objection offered to Roentgen's experiment was that the effect observed might have been caused by the disc assuming a real charge by leakage across from the condensing plates on each side of it. Cremieu's method precludes any such action as this, inasmuch as the condensing plates are rapidly charged and discharged, and even though there should be a slight leakage of a real charge across to the surface of the disc, this charge could produce no deflection of the galvanometer, as the charge would tend to assume a constant value, whereas the deflection of the galvanometer is due to a *change* in the electrical condition of the disc.

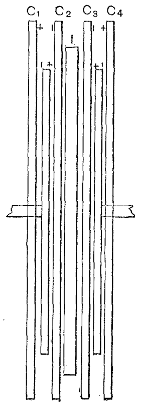

Fig. 2.
½ actual size.

For this experiment two ebonite discs were made, diameter 30.5 cm., thickness .8 cm. The gilded micanite discs used in the first experiment were replaced by these (see Fig. 2). The two condensing plates C_2 and C_3 next to the induced coil I were earthed. The other two condensing plates C_1 and C_4 were connected through the interrupter to the pole of the Voss machine so that they might be rapidly charged and discharged. Everything else remained exactly the same as in the first experiments. When the two outer plates C_1 and C_4 are charged positively, for example, the two ebonite discs become polarized so that the surfaces next to the outer condensing plates assume an apparent negative charge, and the surfaces nearer the inner condensing plates C_2 and C_3 assume an apparent positive charge. Since the positively charged surfaces are nearer the induced coil than the surfaces negatively charged, when the outer plates are suddenly discharged while the discs are rotating, there will be a slight current induced in the coil I. Since the two

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[1] Wied. Ann., 40, p. 93.

surfaces oppose each other in their magnetic action, the resultant effect is very small, being greater the thicker the discs, for the same surface density of the apparent charge. A slight deflection of the galvanometer was observed with the discs arranged as just described, but it was found that a greater effect could be obtained by mounting the two discs flat up against each other on the same axle, thus using only one side of the apparatus. This arrangement amounted to the use of a single disc 1.60 cm. thick, *i. e.*, twice the thickness of one of the discs. Also, it was possible to charge to a higher potential the single condenser thus formed than the two condensers above described, for a given speed of the Voss machine and the interrupter. (It may be here noted that the Voss machine was always run at the highest possible speed. A machine of greater capacity would have made possible the procuring of a greater deflection.)

To calculate the deflection which should be expected on the assumption that a moving apparent charge has a magnetic action, a method similar to that employed in the previous calculation was adopted. Let σ be the surface density of the apparent charge on the surface of the disc next to the coil, assumed uniform as a first approximation, N the number of revolutions of the disc per second, v the ratio of the two systems of magnetic units, r the radius of an imaginary ring on the surface of the disc with its center at the center of the disc and of width dr, δ the deflection of the galvanometer needle produced by a unit current in such a ring on the surface of the disc next to the induced coil, rapidly made and broken the same number of times a second as the disc is polarized and depolarized, δ' the same for a unit current in such a ring on the opposite surface of the disc. Then the deflection of the galvanometer needle due to the rapid polarizing and depolarizing of the rotating disc will be

$$D = \frac{2\pi N\sigma}{v}\int_0^R r(\delta - \delta')dr.$$

σ is determined from the formula (Webster, Elec. and Mag., p. 364)

$$\sigma = \frac{(\mu - 1)V}{4\pi[\mu(d_1 + d_2) + d]},$$

where μ is the dielectric constant of the disc (for ebonite 2.5), d_1

the distance between the outer condensing plate C_1 and the surface of the disc, d_2 the distance between the inner condensing plate C_2 and the surface of the disc, d the thickness of the disc, and V the potential of the outer plate, the inner plate being earthed.

The integral

$$\int_0^R r(\delta - \delta')dr$$

was determined by a "calibration of the apparatus" in a manner similar to that employed in the first experiments. A set of coils of known radii was clamped up against the surface of the disc next to the induced coil. A known current i was sent through the reverser and one of these coils. While the current was being thus reversed in this coil, the frame carrying the disc was drawn back from the induced coil a distance equal to the thickness of the disc, and the resultant change A in the galvanometer deflection noted. The frame was then pushed up into its former position, and the change in deflection again noted. A second known current i_1 was then sent through the reverser and the test coil on the frame carrying the disc, and the change in galvanometer deflection B resulting from a known change $(i_1 - i_2)$ in this current noted. i, i_1, and i_2 were so chosen that the deflection produced by the current i_1 in the test coil was equal to the deflection produced by the current i in the coil on the surface of the disc, and the change in deflection A was approximately equal to the change in deflection B. In this way the quantities A and B were measured at the same part of the galvanometer scale, thus avoiding any error due to a lack of proportion between the current and deflection, which was considerable in the galvanometer employed. Let ρ_1 be the ratio of the deflection produced by unit current flowing through the reverser and any coil on the surface of the disc next to the induced coil to the deflection produced by unit current flowing through the test coil, ρ_2 the corresponding quantity when the coil is on the opposite surface of the disc. Then

$$\rho_1 - \rho_2 = \frac{A}{i} \times \frac{(i_1 - i_2)}{B}.$$

From the observations taken as above described $\rho_1 - \rho_2$ was calculated and plotted for twelve different coils. Let Δ be the deflection produced by a unit current flowing through the reverser and test coil. Then

$$\delta - \delta' = \tfrac{1}{2}\Delta(\rho_1 - \rho_2)$$

($\delta - \delta'$ is the deflection due to the making and breaking of a current, whereas A and B are the deflections resulting from a reversal of current, hence the factor $\frac{1}{2}$). The formula for D therefore becomes

$$D = \frac{\pi N \Delta \sigma}{v} \int_0^R r(\rho_1 - \rho_2)\,dr.$$

The integral

$$\int_0^R r(\rho_1 - \rho_2)\,dr$$

was calculated graphically from the plot of $\rho_1 - \rho_2$.

A number of observations of the deflection D were made, which always agreed in direction and fairly well in amount with the deflection as calculated. A close agreement could not be expected, inasmuch as the assumption that σ is uniform at the edge of the disc is only a rough approximation at the truth, and even under the best conditions, the deflection is necessarily small. The following data, which are the mean values from one set of readings, will suffice to illustrate the capabilities of the method.

$d = 1.60$, $d_1 = .30$, $d_2 = .75$.

$V = 24.9$ C.G.S. electrostatic units (= 7,470 volts).

$\sigma = .70$ electrostatic units.

$\Delta = 2.51 \times 10^7$ mm. per electromagnetic unit.

$N = 57.8$

$\int_0^R r(\rho_1 - \rho_2)\,dr = 22.8.$

$2D$ calculated 4.85.

$2D$ observed 4.5.

$2D$ was the actual deflection measured, not D.

Considering the importance of the question as to the magnetic action of a moving static charge, the following experiment, in which was observed the direct magnetic action of a moving charged disc on a magnetic needle suspended near it, may be of interest, though similar results have been obtained by other experimenters. The uninjured one of the two micanite discs used in the first experiments was provided with a row of sixteen brass studs set at equal intervals apart in a circle of five centimeters radius around the center of the disc. The gilded surface of the disc was then divided into sixteen sectors on each side, each pair of sectors carrying a stud. The sectors were separated from one another by a strip of micanite surface 1 centimeter in width. The tin foil on both the condensing plates, with the exception of a sector on each twice the width of a sector on the disc, was removed. The tinfoil sectors were earthed, and the sectors on the disc could be connected one at a time, through a brush *B* (Fig. 3) set so as to make contact with the studs *S*, with one pole of the Voss machine, the other pole of which was earthed. The frame carrying the disc was so arranged that the disc could be set in rotation about a vertical axis. A hole about 2 cm. in diameter was cut through the upper ebonite plate C_1 diametrically opposite the tin foil segment, and so that its center came 1 cm. over the edge of the disc. This hole was covered on the side next to the disc with a thin sheet of mica. Fitting loosely into the hole so as not to touch the sides or the mica plate at the bottom, was a brass tube in which was suspended a delicate astatic needle *N*. The two magnets forming the needle were 5 cm. apart. The needle and attached mirror weighed about 3 mg., and was suspended by a fine quartz fiber. With the control magnet properly placed the needle could be given a period of 25 seconds. The case in which the needle was suspended was fixed to a frame built over the disc apparatus, having an independent support, so that when the disc was set in rotation there was no jarring of the needle. The position of the needle was read by the reflected image of an electric light filiament on a ground-glass scale two meters distant.

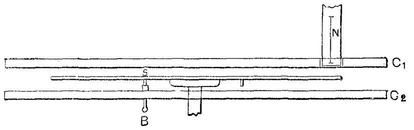

Fig. 3.

When the disc was set in rotation and the brush making contact with the studs was connected to the Voss machine, a deflection of the needle was obtained, which was in the proper direction and of the proper amount to be accounted for on the assumption of the magnetic action of a moving charge. The arrangement here adopted precludes any conduction of charge in the condensing plates or in the disc itself, two possibilities which have been suggested to account for the deflection observed with solid condensing plates and a disc of uniform conducting metallic surface. The results of one set of observations will suffice to give an idea of the magnitude of the quantities involved.

Mean distance between the two surfaces of the disc and needle, 1.61 cm.

Distance between the two condensing segments (one on each ebonite plate C_1 and C_2), 2.18 cm.

Thickness of disc, .356 cm.

Potential of the disc, 5,000 volts.

Speed of disc, 69.7 revolutions per second.

Observed deflection, 47.9.

Calculated deflection, 56.0.

The calculation was made in a manner similar to that employed in the previous experiments, the principle of it being a calibration of the disc apparatus such as above described. Only a rough calculation was attempted, as it would be a matter of some difficulty to calculate the exact distribution of the charge on the sectors. As a first approximation this distribution was assumed uniform. The agreement between the observed and calculated values of the deflection is therefore as good as could be expected.

My chief object in setting up the apparatus with the magnetic needle was to test experimentally certain criticisms made in my former paper on M. Cremieu's experiments, especially his experiments on open electric circuits.[1] However, due to unavoidable delays, it was not until the first of June that I was ready to proceed with the work. But now the damp and sultry weather of the summer had set in and put an end to all experiments with static electricity for the time being.

I wish here to express my thanks to Professor Ames, of the Johns Hopkins University, to whose kindness I am indebted for the opportunity for carrying out these experiments, and whose criticisms and suggestions have proved of great value.

BALTIMORE, MD., July 1, 1902.

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[1] C. R., 132, p. 1108.