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very long sheets of ebonite: indeed that which I used had to be specially rolled. But it is not necessary for the tubes and sheets to be continuous; a succession of short lengths could be employed. I think, however, that a practical limit must exist to the total length of tube that can be advantageously employed, for the definition was always better when the tubes were removed, and was better with tubes 1 foot long than with tubes 5 feet long, a fact which must, in part at any rate, be attributed to reflexion of diffracted and scattered light, at grazing incidence from the partition into the field of the eyepiece. It was to diminish the effect of such reflexion that in some experiments the slits D D were set wider apart and the beams subsequently brought nearer together by the parallel-plate Jamin device. But the gain was apparently more than compensated by the loss due to the dispersion, by refraction, of each beam in traversing the Jamin plates, since the light was not homogeneous. With a homogeneous source, if one bright enough can be found, this would not happen.

July 22, 1905.

XLV. *The Æther "Drift" and Rotary Polarization.* *By* D. B. Brace *.

MASCART †, some thirty-five years ago, first examined the effect of the motion of the earth on double circular refraction, using R- and L-quartz, from which he concluded that the rotary power of quartz is not altered by the $\frac{1}{20000}$ part when the ray is *reversed* in the direction of motion of the earth.

Lord Rayleigh ‡ recently repeated this experiment, also using quartz, in which he found that such a *reversal* does not alter the rotation by $\frac{1}{100000}$ part.

By using an active oil—the oil of caraway—and reversing the ray so as to compensate for rotary dispersion, I have been able by means of a sensitive-strip analyser, giving a much higher accuracy, to carry the limit certainly twenty-five and probably fifty times as far, so that we may conclude that the effect of the motion of the earth on the rotation in active substances is certainly less than $\frac{1}{5000000}$ and probably less than $\frac{1}{10000000}$ of the total rotation.

Lorentz §, in his early analysis, gives two first order terms,

* Communicated by the Author.

† *Ann. de l'Ecole Normale*, vol. i. p. 157 (1872).

‡ Phil. Mag. Aug. 1902, p. 215.

§ *Versuch einer Theorie*, Leiden (1895), p. 118.

in one of which this coefficient is the ratio of the velocities of light in quartz and in space, or approximately two-thirds. The presence, however, of two first order terms might imply still a zero first order effect if these terms completely compensated one another. It is difficult, however, to see how this could be; and hence, from such a mode of reasoning, we might still expect to find a residual first order effect which would be represented by the aberration term with a small coefficient, and which even the refined experiment of Rayleigh could not show. In a later paper, Lorentz*, in a reply to a criticism of Larmor†, gives the relation of the action between two elements arising from the electric forces which must obtain in order that the earth's motion may not influence the rotation of the plane of polarization to the first order. As this is not the only possible mode of action, and as further it is only true when second order terms are neglected, a definite conclusion can only be reached by direct experimental examination.

While the following test does not fully attain a second order sensibility, it does establish the absence of first order terms, or, at least, a compensation up to one part in five hundred and probably to one part in one thousand. Instead of quartz, which both Mascart and Rayleigh used, I employed finally an active liquid, the oil of caraway-seed ($\alpha_D = +103^\circ 33'$ per decimetre). Although its rotary power is much less than quartz ($\alpha_D = 21^\circ{\cdot}67$ per millimetre), I found it preferable in the arrangement used. Both Mascart and Rayleigh point out some of the difficulties in such an experiment, involving as it does such enormous rotations. Thus, with the five pieces of quartz which Rayleigh used, the total rotation for sodium light was more than 5500°, and this would give a difference of rotation for the two D-lines of 11°, thus making the use of such a source impossible. He actually used the yellow helium line. Even then the field in his half-shade plane polarizer was "decidedly inferior to that obtainable when the quartzes were removed." This inferiority due to residual light in the field seems to have originated more largely in imperfections in the quartzes themselves. We should infer from this that, even if the dispersion due to the actual rotation were compensated for, the field would, on account of such imperfections, be far less dark than that attainable with a perfectly homogeneous substance. This was borne out by

* Amsterdam *Akad. v. Wet.* March 29, 1902, p. 669.

† 'Æther and Matter,' Cambridge, 1900, pp. 214–215; also Phil. Mag. Sept. 1902, p. 367.

my own experience in attempting to use quartz successfully in the experiment.

It is well known that if the direction of propagation of a ray in an active substance is changed by a single reflexion, the rotation is completely compensated for after passing over the same distance. If such a compensation could be brought about and still allow the influence of the earth-motion to be unaffected, we could use white light, and hence approximate to the normal polariscopic sensibility of say $0^{\circ}\!\cdot\!01$ or less, a sensibility usually some ten times that attainable with homogeneous light from the same radiant under like conditions. My first plan was to mount two equal lengths of the active substance (in this case, quartz cylinders) at right angles to each other, with one in the direction of drift, and then rotate the system through 180°. This arrangement would give complete compensation if the details of the system could be realized. As this plan involved a change in the direction of the ray of 90°, reflecting surfaces were necessary; and since, with white light, the azimuths of the various vibrations would be at different incidence on the reflecting surface, the rotations produced by this surface would, in general, follow a different law from that of quartz, so that, to this extent, compensation would be prevented. If, however, these rays should all strike a second surface at the same incidence, but in azimuths which are the complements of those at the first surface, the effect due to reflexion would be completely compensated for. This of course may be realized by making the planes of incidence at right angles to one another. Thus, if the plane of the paths within the active media is horizontal, the plane of incidence of the first mirror may be vertical, for example, and the ray be sent upward and then horizontally from the second mirror, the plane of incidence of the latter being also vertical but in an azimuth of 90° to the incident plane of the first. Since now a single reflexion reverses an axial displacement, *i. e.*, a right-handed to a left-handed one, a second reflexion would reverse this to a right-handed one again, thus restoring the relative order, and so on. An odd number of reflexions therefore reverses the relative axial displacement, while an even number restores it* This

* Mascart, in his experiment, realized a reversal by means of a half-wave plate, following the method of Fizeau and Foucault, who used the two parallelepipeds of Fresnel instead. He was in this way able to use consecutively R- and L-quartz, their effects being added together. The total rotation which he thus obtained was approximately 6300° for the green thallium line. This rotation is somewhat greater than that obtained by Rayleigh, but the former's polariscopic sensibility was several times less, depending, as it did, on the appearance or disappearance of the thallium line as seen with a spectroscope between crossed nicols.

principle of reversal is often lost sight of in connexion with rotary polarization problems. Thus it is true that by a single reflexion the rotation of a ray is neutralized in returning through an active substance and doubled in a magnetic one. If, however, two reflexions were used, as may sometimes occur, the relative rotation for the different colours would be doubled in active substances and destroyed in a magnetic field. The total rotation of any one ray, however, would depend on its azimuth, which changes sign with respect to the normal to the incident and reflected rays, at each reflexion. The resultant rotation would be the sum of the initial and final azimuths of the vibrations on entering and leaving the reflecting system. White light, returned through an active substance by two mutually perpendicular surfaces, would not show a recomposition, as it does with a single reflexion. Thus, in the arrangement proposed (fig. 1), equal lengths of right- and left-handed substances, *e.g.* quartz, would give perfect colour neutralization, as well as plane-polarized light, if the double-mirror compensation, described above, were used. As a length of one metre for each cylinder was contemplated, the question of the realization of the normal sensibility of a half-shade system had to be answered. This requires, for its application, a uniform field of sensible area, a condition apparently unrealizable with paths of such great lengths in double-refracting substances. In this case, we should have the well-known spirals resulting from the passage of white light through equal lengths of R- and L-quartz, since the number of reflexions is even in this case and they do not enter. However, these spirals, at the centre, intersect each other at right angles, and a partial compensation at this point of the field might be realized by means of a crystal of opposite sign placed so as to form a "crossed" system with the quartz cylinder, the cross in the former being tangent to the spiral of the latter for a short distance from the optical axis. It was proposed to use Iceland spar of the proper thickness to give the best result, if this mode of compensation should prove effective. Quartz is positive and the difference in index between its two rays is only about one-twentieth that of spar, which is negative, so that a cylinder of the latter of much less length would be sufficient. As the area available in the field would necessarily be small, the amount of material for cutting could be reduced by using a small cross-section. Samples of both R- and L-quartz crystals of various sizes were secured, mainly from the Hot Springs region of Arkansas. These were cut into prisms (something over a total length of one metre for each kind) approximately parallel to the

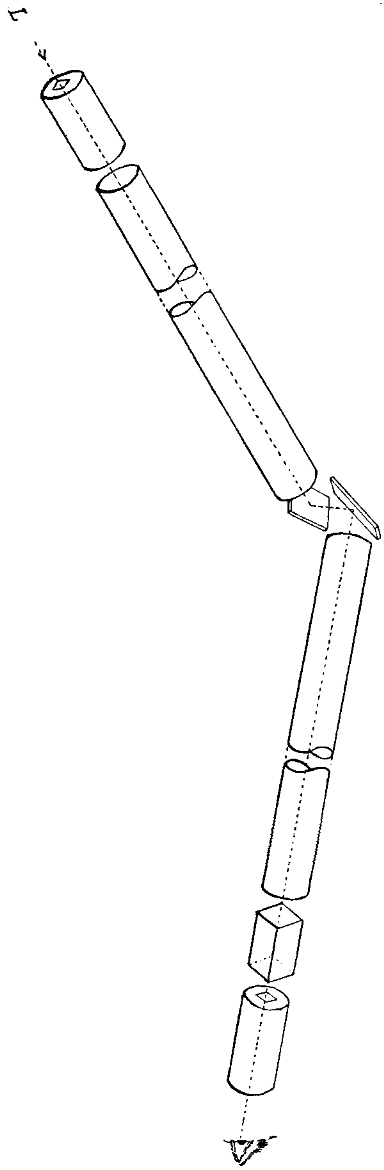
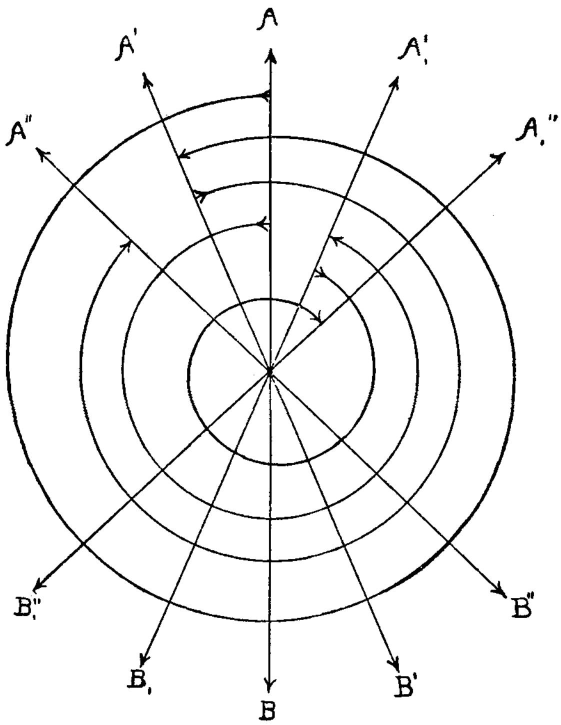


Fig. 1.

optic axis, and their ends polished in order to make a preliminary examination of their optical qualities. Many of these showed traces of the double spiral over various points of their end faces, indicating the presence of both R- and L-formations to a greater or less extent, so that perhaps less than a third of the cuttings could be used. The entire lot was finally sent to an expert cutter, who declined to undertake, with this material, the making of cylinders which should give the optical conditions necessary for realizing the normal polariscopic sensibility. Cylinders one-fourth as long, built up from sections some 5 cm. in length of purer material from Swiss sources, were proposed. Even then the final outcome as to the polariscopic sensibility was much in doubt, while the importance of the extension of this test did not seem to me to warrant the great expense which the proposal contemplated. The use of quartz was finally abandoned for other available active materials. These I sought among the active oils.

The success of the same plan, as proposed for quartz, seemed somewhat doubtful, since we should need two R- and L-substances which for suitable lengths—not necessarily equal—would give identical rotary dispersions. With the great rotations proposed, any slight relative irrationality would at once make itself evident by the corresponding increase of the residual light in the field of the half-shade, which would present the same order of difficulty as that from impure quartz. Such oils would also have to be very clear indeed to allow the passage of sufficient light through the much greater distances necessary to produce the same total rotation as in quartz. Several of the commercial oils fulfil these conditions to a greater or less extent. Two of these, caraway oil, $\alpha_D = +103°33'$, and eucalyptus oil, $\alpha_D = -52'22''$, as prepared by Schimmel & Co., Miltitz-Leipzic, are quite colourless and suited to the above arrangement. The expense of the latter (8 marks per pound) precluded its use, but the former (1 mark per pound) was entirely available, if the optical conditions referred to above could be met by a single substance. It did not at first occur to me that an arrangement for testing the "drift" was possible with a single substance which would allow the use of white light, thus giving the normal polariscopic sensibility. Both of the previous experimenters had failed to make use of this idea. If the motion of the earth produces an effect on the rotation of the plane of polarization, we should of course expect this effect to be reversed on changing the direction of motion. Thus the plane of a ray propagated along the drift would show a slight increment, say; then, if it be reflected back, there would be a corresponding decrement over what would occur if either there were no motion or the direction of propagation were across the drift. Thus in fig. 2, if AB is the initial direction of vibration, and if the active substance rotate it through a whole number of circumferences without motion, it would be

Fig. 2.



slightly increased, if propagated along the drift say, and the emergent vibration be in the direction of A′ B′. If now this ray is reflected back by a single reflector against the drift, it would be rotated in the opposite direction (to a fixed observer) by the same number of circumferences less the angle between AB and A′B′, vibrating on emerging in the direction of A″B″. Hence we should have a recomposition of all the colours to this extent. If now the optical system be turned about through 180°, the first passage would make the emergent vibration along $A_1'B_1'$, since now the propagation is against the drift. On reflexion the final vibration would be along $A_1''B_1''$. Thus, on reversing the optical system, we double the effect. Hence we are entitled to reflect the ray backward and forward, compensation being attained when the total distance in the liquid in one direction is equal to that in the other. Such an arrangement contains at once the possibilities of far greater sensibilities than any previous attempts.

The same mounting for the optical system was used as in my former experiment "on the Double Refraction of Matter moving through the Æther"*. The optical system, however, was somewhat different.

Instead of using plane-reflecting mirrors, as before, which allowed the beam of light to spread too much, with the considerable distances gone over, concave reflectors mounted with adjusting screws were used instead; their centres of curvature being approximately at the axis of rotation of the mount (fig. 3). The distance between the two sets of mirrors at the end of the trough was 410 cm., and it required some 60 to 70 pounds of the oil to fill the trough. This arrangement conserved the light without allowing it to spread out continuously, which would have required a much larger trough and consequent amount of liquid. This would have produced greater distortion in the ray by its passage through larger portions of the liquid. A brass trough whose section was like the lower half of an octagonal cylinder was mounted within the wooden trough, used in the experiment referred to. This was just large enough to carry at its ends three mirrors of two inches aperture arranged together with their centres at the points of an equilateral triangle with its vertex down. In order to avoid depolarization from reflexion and double refraction, the polarizing and analysing systems were mounted in the bottom of brass L tubes, which could be partly immersed in the oil. The vertical axis of the first L was coincident with the axis of rotation of the trough. A circular beam of sunlight from a heliostat H, converging at the axis of rotation E, was reflected downward by the prism R, mounted on an universal carrier fixed to an arm I, coaxial with the axis of rotation. The prism T reflected the ray horizontally through the polarizing nicol P, thence through the thin cover-glass C out into the liquid to the first concave

* Phil. Mag. April 1904, p. 317.

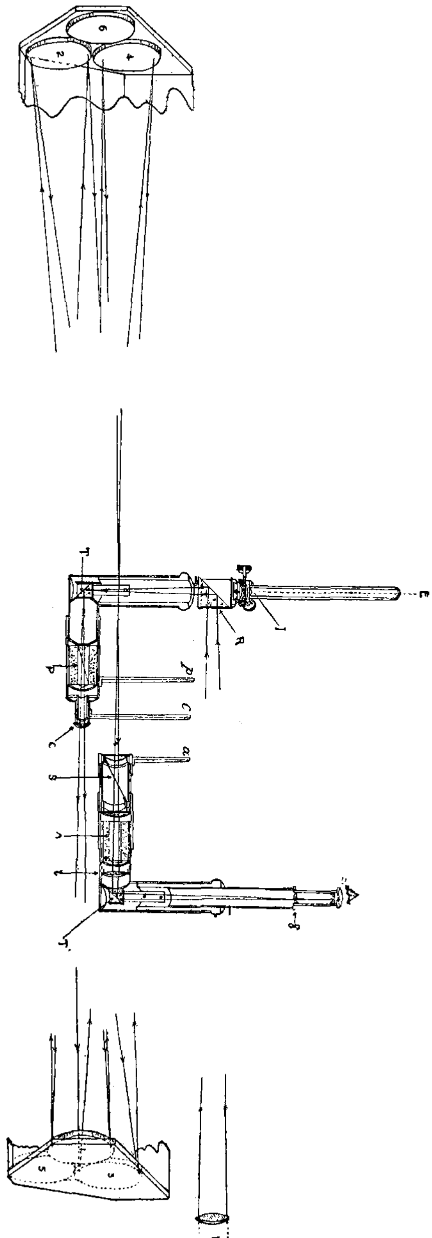


Fig. 3.

mirror 1. This reflected it back, through a convergence point in the axis of rotation below the brass L, to the second concave mirror 2, and so on; the last mirror reflecting it, through its point of convergence, successively into the sensitive-strip cell S, the analysing nicol A, the condensing lens *l*, the total reflecting prism T′ and the focus *f* of the lens *l*, and, finally, either into the eye or the observing telescope. The tube carrying the thin cover-glass C could be adjusted by the arm *c* so that the latter was exactly in the plane of the front face of S, thus giving complete rotary compensation for the two opposite paths of the rays within the liquid. The polarizing nicol P could be rotated by means of an arm *p*, attached to its retaining tube, so that it might be crossed with the analyser A or varied at will. An extension arm, some 73 cm. long and carrying an index, could be fastened to this, and its rotation measured on a scale fixed upon the trough. The strip S, upon which my sensibility depended, I have already described*. This particular strip, which was mounted so as to cover half the field of view, was 15 mm. wide and 45 mm. long and 0·1 mm. thick, and was remarkable in the sharpness of its edge. It was cut so that its plane of greatest length made an angle of 70° with the optic axis, and placed in the cell in such a way that the ray traversed the strip at right angles to its optic axis. Instead of using α-monobromonaphthaline, whose index is exactly that of the ordinary ray, I used carbon disulphide, which had been carefully clarified. The index of the latter is only slightly below the ordinary ray, but not enough to cause total reflexion for any of the ordinary rays. This liquid is much clearer than the former, and gives superior definition and a better vanishing line. The end plates, which were of the thinnest cover-glass, were carefully tested for double refraction, after being cemented on, and the cell filled with liquid. To this cell was fastened an arm, *a* (fig. 3) with which it could be rotated so as to vary the azimuth made by the principal plane of the strip with that of the analysing nicol, and thus the intensity of the field of view, settings for a match being made with the arm *p* of the polarizer. The submerged joints were cemented with a mixture of glycerine and gelatine to prevent ingress of the oil to the nicols and prisms. Preliminary adjustments of the beam of light were usually made before filling the trough with liquid, after which the ray had to be readjusted in order to bring it back into the field of view again. Much care had to be exercised in

* Phil. Mag. Jan. 1903, p. 161.

the axial adjustment of the system and the beam of sunlight, as, if the latter were not perfectly uniform in intensity over its section, a rotation of the trough would show a spurious effect in the half-shade, destroying the match. This difficulty was many times greater than would have been experienced with an artificial source which could have moved with the system; but the increased light allowed a much smaller azimuth of the strip and a consequent increase in the sensibility. It was found that the light, when it reached the analyser, was slightly depolarized; and I sought to correct this with a thin mica compensator, in the way I have already described*, placed over the end of the cell S; but this did not eliminate it, showing that the light was irregularly depolarized. The compensator was therefore dispensed with. A portion of this residual light came from diffusion, by the liquid, of the intense initial beam of sunlight within the same. The rest was due to imperfect compensation of all the rays arising from differences in density. The disturbing effect on the field of this residual light was, however, small, and did not interfere seriously with the settings for a match. At the beginning of a set of observations, the two halves of the field might show complementary colours on rotating the polarizer, indicating inequality between the combined paths. The arm *c* was then shifted until the complementary colours disappeared on rotating P in both directions, the entire field having a bright orange hue.

To avoid magnetic effects due to the earth's field, the trough was placed normal to the mean magnetic meridian. A compass, mounted in a slide upon the edge of the trough, could be set at equal intervals along its length and the position of the needle noted. This was found to vary by several degrees. The mean for the various positions was taken and found to be 21° N.E., so that the effect of the drift could be reduced only a few per cent. The trough was then set at right angles and always reversed in this direction.

Much difficulty was experienced on account of the ingress of the oil to the nicols and other optical pieces. On this account, and also because the oil, if left in contact with the air for some time, turns a yellowish colour, the trough was always filled and emptied at each observation. The residue on the mirrors and optical pieces also produced a scattering of the light, reducing the final sensibility perhaps by a half; so that all pieces had to be dismounted, cleaned, and recemented, before remounting and refilling the trough for a

* Phil. Mag. *l. c.*

second set of observations. Notwithstanding these precautions, the mirrors had to be resilvered and the oil gained access to the nicols and the strip and attacked the cement. This showed itself by a thin capillary line gradually encroaching on the field of view of the nicol and the final loosening of the sensitive-strip within its cell. This placed a definite limit to the number of observations which I was able to make and also to the extent of the paths within the trough, on account of the time necessary to make adjustments with the entire number of mirrors.

In most of the observations, I used a small telescope of some two or three diameters. I found that my eye was most sensitive if removed from the telescope during a reversal of the trough, thus relieving it from fatigue during the interval. On account of local disturbances within the liquid, the trough was turned very slowly, the time occupied in a reversal being usually a minute or more. It was then noted whether the beam of light followed exactly the same path as before and adjustments made, if necessary. This could be determined by its position with reference to a definite mark. The eye was then placed at the telescope, and the field carefully examined for any change in the two halves at some selected point in its centre, on the dividing or vanishing line. Settings for a match were also made by means of the arm p, and the index read by an assistant. While the edges of the field might show a slight contrast in the two halves, the central portion was very uniform and the bounding line, practically, a vanishing one, so that settings could be made to a high degree of accuracy. The strip used was the finest I have ever seen, and gave a dividing line far superior to any half-shade plane-polarizing system I have had the opportunity of working with. A half-shade "Lippich," placed in the same position, was entirely inadequate to the sensibility required. This was partly due to the fact that such a system, to give a vanishing line, must have in general a much larger source than a point radiant. It might also be mentioned that, if the half-shade system had been next to the polarizer, instead, definition would have been impossible through such a length of liquid. The use of such a thin strip, *e. g.* 0·1 mm., in a liquid of the same index, makes it possible to invert the order with respect to the active substance and still obtain a vanishing line as well as perfect definition; just as was done in my previous experiment with a half-shade elliptical polarizing strip placed after the substance examined. In the preliminary observations made during April, light was sent only twice through the trough. Although the liquid appears perfectly clear and colourless, the absorption through this length was very marked and the intensity much reduced. That a large part of the light was due to internal scattering, was made evident by the bright shaft of light, seen in the liquid between the polarizer and first mirror, showing along its length the various orders of colour corresponding to the reflexion of plane-polarized light in successive azimuths from small particles.

The light, however, was sufficient to make successive settings to 1/120°, and the quality of the rotatory compensation of the liquid indicated that greater lengths were practicable. Such observations were taken on different days between 11 A.M. and 1 P.M. and at 4.30 P.M., the entire apparatus having been previously dismounted and cleaned; as with all the precautions the surfaces became fogged and the quality of the definition reduced.

In the final test I used better mountings for my mirrors, and examined the light after it had passed four times through the liquid. The adjustments in this case were much more tedious, but I finally succeeded in getting a field with a sufficient intensity and uniformity to attain a high degree of sensibility. Under conditions which seemed to be freest from residual disturbances, I could observe no change on reversing the trough. With an unusually brilliant sun, I was able to detect a change in the plane of polarization, by rotating P, of less than 0°·01, or one tenth of a division of my scale = 1/120°. I also made several successive settings in the two positions, but did not note them down, as I treated them as preliminary to more extended systematic observations at another time. I am not therefore able to reproduce them definitely, but the differences between the means of the averages of individual sets of four or five, which I calculated mentally as the positions of the index were read off by my assistant, were perhaps one half of this. The observations upon which I based my conclusions were taken on May 10th at the noon hours 11–1 and at 4.30 P.M., which was as late as I could obtain the sun. I did note occasionally, while observing with the trough at rest, a gradual change in the field amounting in one or two instances to 0°·05, apparently due to internal motions of the liquid and relative changes of temperature. Observations at reversal were taken, however, when no gradual change could be detected. Slight changes were also noted due to a shift in the reflected beam from the heliostat. This disappeared when the proper adjustments were made to bring the beams back to the reference mark. Similar effects were noted late in the afternoon.

My next attempt was to obtain observations with light which had traversed the liquid the full number of times,—six, which I had provided for. To do this, I took precautions to exclude extraneous light, in order to obtain the full optical sensibility, by immersing screens made of tubes, within which the successive rays should pass. These adjustments were very tedious, and before I succeeded in getting the light from the last mirror into my field, the noon hour had passed. On dismounting my half-shade system, I found that the nicol A was seriously impaired by the presence of a capillary film of oil and the strip of spar had become detached. On removing the latter, I found it broken. In attempts to remount the remainder I destroyed it still more, beyond hope of further use. These strips are very fragile, ground as they are to 0·1 mm. thick, so as to give as near a vanishing line as possible. Mr. Halle of Steglitz-Berlin has, however, succeeded in making strips with square ground edges, in lengths of 45 mm., as thin as this. As it was quite doubtful whether I could obtain a proportionately greater sensibility with six as with four passages, even if I should be fortunate enough to secure again so fine a strip, and as it was probable that I would have to renew all the optical pieces as well as redistill the oil, I concluded to discontinue the experiment, although I had not obtained the final sets of systematic observations as originally planned. The likelihood of attaining a second order sensibility in this test seems very remote indeed, although these observations have carried the test probably a thousand times beyond the first order and within a factor of ten of the second order.

Thus assuming white light and a rotation varying as the inverse square of the wave-length, we may take 130° per decimetre as the mean rotation of the oil. Considering the total length to be 410 cm. $\times 4 = 1640$ cm., we have a (compensated) rotation of 21300°. As I should have been able to detect a direct change of 1/120° on reversal, or one half this, if the mean readings mentioned be allowed, the total effect of the motion of the earth in space on the rotation of the plane of polarization is certainly less than 1/5000000, and probably less than 1/10000000.

Physical Laboratory, University of Nebraska,
June 7, 1905.