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XXXVII. *On Double Refraction in Matter moving through the Æther.* By D. B. BRACE*.

THE FitzGerald-Lorentz † “Contraction” Hypothesis to explain the negative results of the Michelson-Morley ‡ experiment of interference between two rays, at right angles and parallel to the earth’s motion, has been tested by Rayleigh § in his experiments on the double refraction of liquids and of glass. He assumes the contraction to be $(10^{-4})^2$, and also the excess of the index above unity to be proportional to the density. The first assumption is apparently in error by a half and should be 0.5×10^{-8} . The second assumption does not seem to be entirely valid for glass, at least, when compared with the double refraction produced by a given strain. The first correction reduces his margin down to 50 times for a liquid and 1.5 times for glass. The second will reduce the margin to considerably less than unity for glass, which would thus leave us only the observations on liquids upon which to base our conclusion.

While the method of Rayleigh cannot be regarded by any means as a conclusive test of the hypothesis, it is the only experimental one attempted and can be extended so as to give a safe margin for a solid like glass.

This suggestion of the “contraction” hypothesis by Lorentz, from considerations in regard to intermolecular forces analogous to the interaction, through the mediation

* Communicated by the Author.

† *Versuch einer theorie*, Leiden, 1895.

‡ Amer. Journ. of Sci. (3) xxxiv. p. 333 (1887).

§ Phil. Mag. Dec. 1902.

of the æther, of electric and magnetic forces, is certainly plausible enough to warrant further examinations and extension experimentally. That the intermolecular forces are not altered by factors many times less than those obtained by Rayleigh, is found to be the case in the media used.

Experiments with Water.

Two arrangements suggest themselves: the one, a system rotating about a vertical axis, the other a similar system rotating about a horizontal axis so as to shift the plane of polarization from a position at 45° to the earth's orbital motion through an angle of 90° . In the matter of simplicity, sensibility, and stability the latter method would be preferable. However, the first arrangement was selected for the purpose of utilizing the same mounting for other experiments. A heavy beam was pivoted between the floor and ceiling so as to carry a trough with its horizontal axis intersecting the pivotal axis. This system could be rotated continuously so as to bring it into any desired position. This trough was 413 cms. long, 15 cms. wide, and 27 cms. deep on the inside, and built up of 5 cms. planking in order to give sufficient stability to the polarizing and mirror systems which it carried.

In order to obtain sufficient intensity through the total column, the 2856 cms. of water used, sunlight was so thrown into the trough as to keep its path the same whatever its position. The lens 1 (fig. 1) of about 2 m. focus converged the sun's rays, from a carefully adjusted heliostat, within the nicol 4, after reflexion from 2 and 3. The diverging beam was then successively reflected from mirrors 5, 6, and 7 upon the concave mirror 8. The radius of curvature of this latter was about 15 m., and it was mounted, as were the other mirrors, upon brass plates containing adjusting-screws fastened to the ends of the trough. The axis of the reflected cone was displaced in a horizontal plane, so that the return ray passed through the analysing system 9-11 placed to one side of the polarizer. The lens 12 converged the light, which would otherwise have come to a focus at a distance of about 2 m. beyond, to the eye 15 at a distance of 25 cms. from 9. Thus the eye could observe 9 directly or by means of the telescope 14. Both the heliostat-mirror and the lens 1 were diaphragmed down so that the aperture of the cone of rays was slightly less than that of the mirror 8 whose aperture was about 15 cms. This prevented diffused light from the mirror and the water reaching the nicol 11 to any serious extent, and also aided in the adjustments of the mirrors so as to keep the rays fixed when the trough was rotated.

Fig. 1.

The total-reflecting prism 2 was carried by a universal mounting passing through a rod forming the prolongation of the axis about which the system rotated. By properly shifting 1 and 2 the ray 2-3 could be brought exactly in the axis of rotation, so that when the trough was rotated the return ray at 9 remained at a definite point in the field of view. 3 and 4 were then shifted until the ray passed through them symmetrically. Any change in the direction of the incident ray at 1 would of course cause a shift, but by properly regulating the heliostat this could be avoided. However, with such a long optical lever slight irregularities might occur after a rotation, but these were always compensated for before observing the field of view by adjusting 2 until the beam of light occupied the exact position it did previous to rotation.

The polarizing nicol was either one with ends normal to the ray, or, if of the ordinary type, mounted in a cell with thin cover-glass ends so as not to affect the ray when the system was under water. The analysing nicol was a Glan-Thompson of 15 mms. aperture. The analysing and polarizing systems together with the prisms and lens were mounted within tubes to prevent access of the water and upon a common cross-piece fastened to the trough. By adjusting 8 the cone of rays could be sent into the analyser symmetrically so as to fill completely the field of view. The principal planes of the nicols were crossed and at 45° to the vertical plane. A metal diaphragm was placed lengthwise between the entering and the emerging rays and between the mirror 5 and the polarizing system so as to prevent scattered light reaching the analyser.

The following delicate method, a detailed description of which I give elsewhere*, was used for observing the slightest trace of double refraction. 9 was a thin strip of mica which I will designate as the "sensitive strip" of order $\frac{1}{100}$ or 0.0012 mm. thick, cemented with Canada balsam between two thin cover-glasses without double refraction, the latter being cemented to a brass ring carried by an arm extending from a collar slipping over the brass containing-tube of the nicol. This collar carried an arm with the scale divided into some 60 divisions representing half degrees. 10 was a similar thin section of mica of order $\frac{1}{75}$ approx., cemented similarly and covering nearly the entire aperture of the nicol 11. This system, which I will designate as the "compensator," was mounted on a collar slipping over the nicol between the collar and the strip of the first system. This

* Phys. Rev. Feb. 1904.

had an arm for rotating and also a pointer passing over the scale referred to.

In the adjustments 2 was moved until, when the trough was turned completely round, the ray as seen on a white mark did not shift. Water which had been heated to drive out air and prevent minute bubbles forming in it and upon the mirrors and thus causing diffused light was then flowed into the trough until it covered the analysing and polarizing systems. This usually caused a shift of the rays, and 2 was again adjusted until the spot of light remained fixed when the trough was rotated. 8 was then adjusted until the return rays passed through the analyser so as to give a uniform field of view when examined directly with the eye through a small circular aperture or by means of the telescope 14. The light after its passage through this 30 metres of water appeared of a beautiful light-green tint. With the mica sections removed the nicols were adjusted for extinction, which was fairly complete. The sensitive strip 9 was then thrown in and rotated to extinction, and then turned through 45° so as to bring its principal axes at 45° to the principal plane of the analyser. 10 was then placed in position and turned until the field on each side was of the same intensity as that of the sensitive strip. The eye thus saw the field of view illuminated uniformly with green light in the neighbourhood of this strip. The slightest trace of double refraction in the direction desired would at once make itself evident in the relative increase or diminution of the light from the strip.

The conditions of maximum sensibility in photometric comparisons, namely a vanishing line and a uniform field, were thus attained. A small piece of glass compressed vertically to the slightest degree with the fingers placed after the polarizer 4 showed a sharp change of intensity at this bounding line. A match could be immediately obtained by rotating the compensator 10. By noting the position of the pointer for a match and then shifting the same until such a change could just be detected, a measure of the sensibility of the system could be obtained. This angle was found to be $0^\circ.2$ under favourable conditions. At each observation the sensibility was determined. A match was obtained with, say, the trough in the meridian at noon, this was then turned through 90° into the direction of the earth's orbital motion. The position of the return image at the polarizer was noted, and if it had shifted in any way it was brought back by the adjustment of 2 into its initial position and then the field of view examined. In no case could a change be observed, *i. e.*

there was still a match indicating no double refraction. Various positions were taken in and at right angles to the meridian with the same result. Hence, we may conclude that to this order of sensibility there is no double refraction in the water due to its motion through the æther. These observations were taken during the latter part of July 1903. It is evident that a rotation of the plane of polarization due to the earth's field of force would not affect this match, as both portions of the field would vary in intensity by the same amount. To make sure of this the trough was rotated through 180° into the meridian so as to reverse the direction; but no effect could be observed. It is evident that since the rotation due to a magnetic field is always in a definite direction and independent of the direction of the ray, such a rotation of the plane of polarization would be reversed with respect to an observer moving with the trough. Hence this could not mask any effect due to double refraction.

A second check was made with a cell of turpentine 1.6 mm. thick, whose ends were made with thin cover-glasses without double refraction, which would give a rotation of about $0^\circ.5$, while if we take $0^\circ.015$ as Verdet's constant for water and 0.2 as the earth's field and a length of 30 m. we find about $0^\circ.15$ for the rotation. On inserting this cell after the polarizer, no effect could be detected.

In order to determine the relative retardation which corresponds to a given rotation of the compensator, the polarizing and analysing systems were dismantled and placed on a support with their optic axes in line. The system was illuminated by an acetylene flame, the light from which passed through green glass or celluloid of about the same tint as that obtained after passage through the water. The sensitive strip, compensator, a quarter-wave plate mounted on a vertical circle, and a vertical strip of glass capable of carrying a weight, and, in addition, a micrometer-screw carrying two horizontal cross-wires in front of a horizontal strip of glass held within a clamp so as to produce a flexure, were arranged to be placed in the path of the light. The order of the mica quarter-wave plate was found to be approximately $\frac{1}{4}$ for green light, $\lambda = 0.0005$ cm., by comparison in the usual way with a quartz or selenite wedge. With the nicols crossed and the plane of polarization at 45° to the vertical, the circle carrying the quarter-wave plate was adjusted until the light was extinguished and the mean of its positions for a number of settings noted. The sensitive strip was then thrown in with its axes at 45° to the plane of polarization, and after that the compensator which was set for a match. By rotating

the quarter-wave plate this match was destroyed, but by rotating the compensator this could again be obtained. In this way the retardation of the compensator could be at once determined in terms of that of the quarter-wave plate. Thus, a rotation of 5° of the compensator corresponds to $16'$ of that of the quarter-wave plate. It was found that the rotation of the compensator was proportional to that of the quarter-wave plate approximately for these small angles.

A further comparison was made with the vertical crown-glass strip. This was 13 mms. wide and 2 mms. thick. The quarter-wave plate was removed and this strip inserted instead and a setting made with the compensator. On adding 200 gms. a match was obtained on rotating the compensator through $2^\circ.5$. From this can be calculated the relative retardation produced in glass per unit weight and unit width. Another comparison was made with white light from the acetylene flame direct by removing both strip and compensator and inserting the micrometer and horizontal glass strip in addition to the vertical glass strip. When the clamp for producing flexure was screwed up a horizontal black band appeared between the two cross-wires. For one flexure, where the band was quite distinct, 500 gms. on the vertical glass strip gave a reading of 36 on the micrometer-screw and 200 gms. gave 14, thus showing the proportionality. A movement of the cross-wires, just sufficient to observe a shift, gave a reading of 12, which was the sensibility of the system for that flexure. On releasing the screw until the flexure was so far reduced that the band was barely visible, 200 gms. gave a shift of 23 divisions and 100 gms. gave 11 divisions as near as could be observed, and this was the smallest weight which could be observed to produce any double refraction. A direct shift of the cross-wires gave 13 divisions as the sensibility. Using direct white light and the sensitive strip and compensator $0^\circ.1$ rotation of the latter could be detected, thus giving it a sensibility of $\frac{200}{2.5} \times 0.1 = 8$ gms., or 12.5 times that of the band under similar conditions of light intensity and adjustment*. With greater intensity and more careful adjustment higher sensibility could be obtained by both methods. In fact, Rayleigh, using lime-light and a black band, has been able to detect a weight of 25 gms. on a vertical glass strip 15 mms. wide, or a sensibility over four times as great as that obtained above with the acetylene flame and a black band.

* A comparison with a Bravais sensitive-tint biplate gave 200 times the sensibility for the sensitive strip.

From the above data we may calculate the least change in the index which could be observed if the water had become doubly refracting. If θ is the angle which the plane of polarization makes with one of the principal axes of the mica then the component vibrations or the principal axes of the resultant ellipse in the quarter-wave plate are in the ratio of $\tan \theta$ to 1. For small angles then the ratio of the change of phase to the total or $\frac{\lambda}{4}$ is proportional to the angle θ . Thus 1° rotation of the mica gives

$$\frac{1}{45} \times \frac{\lambda}{4} = \frac{\lambda}{180},$$

but $16'$ of the quarter-wave plate was equivalent to 5° of the compensator, and as $0^\circ.2$ rotation of the latter could be detected, this reduces to

$$\frac{16}{60} \div 5 \times 0.2 \times \frac{\lambda}{180} = \frac{\lambda}{17,000} = 6 \times 10^{-5} \lambda$$

approx. for green. The total path of the light in the water was 2856 cms. Taking its index as 1.33, the number of waves is

$$\frac{2856 \times 1\frac{1}{2}}{.00005} = 7.6 \times 10^7.$$

As 6×10^{-5} of a single wave could be detected, the fraction of the total would be

$$6 \times 10^{-5} \times \frac{1}{7.6} \times 10^{-7} = 7.8 \times 10^{-13}.$$

This represents the greatest difference in velocity or in index between the two components which could exist referred to that of water * for green light, $\lambda = .00005$ cm.

Mascart † has shown that in the case of water under compression the increment in the excess of the index above unity is nearly proportional to the increment of its density. If in the movement of matter through æther an increase in density in this direction took place, producing a change in the natural frequency of the molecular systems similar to that which occurs in glass, say, then, to determine how great it might be from these results, it is necessary to measure the

* For carbon bisulphide Rayleigh obtained the corresponding limit of 4×10^{-11} for yellow light. His retardation was calculated from Wertheim's results. This checks with the data obtained above as 200 gms. gave $2^\circ.5$, hence 25 gms. would give $0^\circ.31$ or $\frac{\lambda_D}{13000}$ instead of $\frac{\lambda_D}{12000}$ which he gives.

† *Optique*, t. iii. p. 613.

increment in phase which represents the sensibility of the experiment in terms of the excess of the index above unity. This excess of index is $\frac{1}{3}$ while the index is $\frac{4}{3}$, hence our limit should be four times larger or 3.1×10^{-12} . The greatest change which could be expected is the difference between unity and $\sqrt{1 - \frac{v^2}{V^2}}$ where v is orbital velocity and V light-velocity or

$$\frac{1}{2} \frac{v^2}{V^2} = \frac{1}{2} (10^{-4})^2 = 5 \times 10^{-9},$$

or about 1600 times greater than the smallest effect which could be observed.

The effect of a change in the frequency of the order $\frac{v^2}{2V^2}$ on the index of the moving molecular vibrations relatively to the æther impulses in the direction of motion, is far too small to be observed. Thus the index of water for frequency 5.1×10^{14} is 1.334 and for 6.9×10^{14} is 1.341. This gives for a fractional increase in frequency of $\frac{4}{3}$ a fractional increase in index of $0.007 \times \frac{4}{3}$. Hence the fractional increase in index due to a change of frequency of order 0.5×10^{-8} is

$$\frac{0.5 \times 10^{-8}}{\frac{4}{3} \times 10^{14}} \times 9 \times 10^{-3} = 3.5 \times 10^{-25},$$

while the smallest observable change was 7.8×10^{-13} .

Experiments with Glass.

Two different arrangements were tried with glass. In the first a large slab of "optical" glass (crown) was cut lengthwise and the edges of the two halves ground square. These were then cemented together side by side so as to give approximately square end-surfaces for grinding and polishing. These end-surfaces were "built up" in the usual way so as to ensure a "flat" surface. These two prisms were then cemented end to end, giving a prism 42 cms. long with polished ends 10 cms. by 3.8 cms. These end-surfaces were silvered and a strip at the bottom and top of each removed. The system was then mounted on a support within the trough so that light from the polarizer could pass in and be reflected backwards and forwards until it passed out through the unsilvered space at the other end, where it was again reflected back into the prism by a concave mirror 3 m. radius of curvature, approximately. After the same number of reflexions it passed out to one side of the entering ray and was received by the half-shade analysing system already

described. It was found impossible to obtain a satisfactory match with the half-shade system alone without some other compensation. On examining with the analyser, vertical bands (they appeared horizontal of course) were seen which were quite regular and symmetrical on each side of a central black band. The distance apart of these bands and their distinctness were less as the number of internal reflexions were increased. The total number of passages through the prism varied from ten to eighteen, or a total distance in the glass of from 420 cms. to 756 cms. An attempt was made to compensate by means of the horizontal strip of glass with the clamp for producing flexure. This system was mounted on a universal system so as to bring the black band in the glass strip vertically in front of the analyser. In one position, under flexure, the resulting bands became narrower. On reversing it, so as to interchange the compressed and dilated portions of the strip, the bands became wider and finally disappeared as the flexure was increased up to a certain point. They then reappeared and became narrower with increasing flexure. This compensation increased the sensibility so that a moderate pinch of the prism by the fingers gave a marked shift of the central band which could be observed by means of the two cross-wires already referred to. However, the compensation was not sufficiently satisfactory to obtain good matches with the half-shade. Furthermore, the slightest flexure of the trough or deviation of the beam of sunlight caused the "match" to change in the one case or the band to shift in the other, owing to the narrowness of the beam. Observations with this arrangement would thus be likely to prove unreliable, and the system was finally given up for another which could be rendered more stable, optically, and in which artificial light could be used.

Two cylinders of flint-glass, each 22.3 cms. long and 2.4 cms. in diameter, and of mean index $n_D = 1.77$, were mounted on adjustable supports between the polarizing and analysing systems. The former consisted of the nicol and half-shade system used previously as the analysing system. This was observed through the analysing nicol by a low-power telescope. The source of light was an acetylene flame into which was injected, broadsides, a flat stream of oxygen through a fish-tail burner. This increased the brightness of the field of view several times, and extended the sensibility of the settings by a corresponding amount. The entire system was mounted on a common base, so that once a match was obtained it could be moved without disturbing it. These cylinders were especially well annealed Jena glass used a

number of years ago in experiments on the double refraction of light propagated at right angles to the lines of force in a magnetic field*. Each showed the black cross in certain azimuths between crossed nicols. In order to use this portion of the glass only, diaphragms 3 mms. to 4 mms. in aperture were placed at each of the ends of the cylinders along the optic axis of the system. One cylinder was then inserted and adjusted so as to give the most satisfactory match of the half-shade. The aperture was sufficient for obtaining a close setting, and the field could be made of nearly uniform intensity so that a vanishing-line was approximately realized. The slightest contact of the fingers, however, usually disturbed the match, in consequence of temperature changes. This match could be seen slowly to recover itself on removal of the fingers. Also the slightest flexure in the process of adjustment made itself at once manifest. This entire system was placed upon the large trough, and observations, with the polarizer at 45° to the vertical, made when the same was rotated. At first irregular changes in the match were observed, but these were found to be due to a shift of the eye and head of the observer. To eliminate this a seat was mounted so that the observer could move undisturbed with the trough, the head being steadied by means of a clamp. In this way no change in the field could be observed except in a very few instances. These were attributed to an accidental shift of the eye or to slight temperature changes. Observations were made at noon and at 6 P.M. in the early part of December. At this latter time occasional change could be detected similar to those which had been noted several times in the noon observations. The difficulty in maintaining the conditions for so high a sensibility as was attained, rendered the fictitious effects quite possible. When the greatest care was exercised no change could be detected. Under the most favourable conditions a rotation of the compensator of 0.2° approximately could be detected. This corresponds, as shown above, to a change in the relative retardation of $6.5 \times 10^{-5} \lambda$ for the mean portion of the spectrum, $\lambda = .000055$ cm. The total path in the glass was 44.5 cms., and hence the total number of waves is

$$\frac{44.5 \times 1.77}{.000055} = 1.43 \times 10^6.$$

Thus the fraction of the total becomes

$$6.5 \times 10^{-5} \div (1.43 \times 10^6) = 4.5 \times 10^{-11},$$

which is the greatest difference in velocity or in index

* Phil. Mag. p. 342, Oct. 1897.

between the two components which could exist in this kind of glass.

If we estimate the contraction from the change in density by means of the excess of the index above unity, as was done in the case of water and as assumed by Rayleigh, the above fraction would become

$$\frac{1.77}{.77} \times 4.5 \times 10^{-11} \quad \text{or} \quad 10^{-10},$$

approximately. This is 50 times smaller than $0.5 \times (10^{-4})^2$, the change to be expected on the "contraction" hypothesis, and is 30 times less than the sensibility obtained with water.

If, on the other hand, we take Wertheim's * results for glass, we have approximately for Faraday's flint, 5×10^{11} as Young's Modulus and 2.4×10^7 dynes on a millimetre cube to give a relative retardation of one λ . From above we have

$$\frac{6.5 \times 10^{-5} \lambda}{445} = 1.46 \times 10^{-7} \lambda$$

as the relative retardation for 1 mm.

Thus, the force to produce the least observable effect is

$$2.4 \times 10^7 \times 1.46 \times 10^{-7} = 3.4 \text{ dynes per 1 mm.}$$

Young's Modulus for 1 mm. square becomes 5×10^9 and the contraction becomes

$$\frac{3.4}{5 \times 10^9} = 6.8 \times 10^{-10},$$

which is seven times smaller than that expected on the "contraction" hypothesis. If we correct by $\frac{1}{4}$ for Poisson's ratio, as we should if the interference problem were done on a glass support, the calculated contraction becomes

$$0.5 \times (10^{-4})^2 \times \frac{4}{5} = 4 \times 10^{-9}$$

or six times larger than our margin for glass.

Hence, if the test is a valid one, the "contraction" hypothesis cannot explain the negative results of the interference experiments; and, with the same reasoning, we also conclude either that the æther moves with the embedded matter, or that the effect of the relative motion on the intermolecular forces and the possible consequent relative change in dimensions are very small.

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* *Ann. de Chim. et de Phys.* (3) t. xl. p. 202.

[*Note*.—These experiments were repeated during the early part of February, 1904, when the earth's orbital velocity conspires approximately with that of the solar system in space. The conditions for observation were quite as favourable as before; but no effect could be detected. With glass, the optical system was rotated through several quadrants consecutively so as to observe any possible trace of an effect. Observations were made at noon and at 6 P.M.

Hicks*, in a more rigorous discussion than that of Lorentz, of the effect to be expected in the Michelson-Morley experiment, shows that instead of a contraction of $\frac{v^2}{2V^2}$ in the direction of drift, there should be an elongation of $\frac{v^2}{2V^2}$, to account for the negative results of the observations. The experiment itself should thus disprove the FitzGerald-Lorentz hypothesis. Either, on any of the suppositions possible from Lorentz's point of view, viz. contraction along the drift and zero change at right angles, no contraction but extension at right angles to the drift or elongation along and at right angles to the drift, such that the difference is $-\frac{v^2}{2V^2}$, or, on the conclusion of Hicks, the effect to be observed by means of double refraction in the preceding experiments would be the same.—D. B. B.]

XXXVIII. *On the Occurrence of Cavitation in Lubrication.*

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[Plates XVII.-XIX.]

§ 1. **T**HE following experiments ‡ arose from an observation made when determining the refractive index of a liquid by means of Newton's rings. As Newton showed, the rings can be obtained when a liquid is run into the space between the lenses (Opticks, Obs. 10); and by comparing the radii of the rings with those obtained with the same lenses and air we have a means of measuring the refractive index between air and the liquid. The only difficulty is to arrange the illumination suitably as the rings are far fainter with the liquid than with air.

* Phil. Mag. Jan. 1902.

† Communicated by the Physical Society: read November 27, 1903.

‡ These experiments formed the subject of a Demonstration before the Cambridge Philosophical Society, November 10, 1902.