The Second Book of Opticks. Part IV (1704)

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THE
SECOND BOOK
OF
OPTICKS.

PART IV.

Observations concerning the Reflexions and Colours of thick transparent polished Plates.

THere is no Glass or Speculum how well soever polished, but, besides the Light which it refracts or reflects regularly, scatters every way irregularly a faint Light, by means of which the polished surface, when illuminated in a dark Room by a beam of the Sun's Light, may be easily seen in all positions of the Eye. There are certain Phænomena of this scattered Light, which when I first observed them, seemed very strange and surprising to me. My Observations were as follows.

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OBS. I.

The Sun shining into my darkened Chamber through a Hole $\frac{1}{3}$ of an Inch wide, I let the intromitted beam of Light fall perpendicularly upon a Glass Speculum ground concave on one side and convex on the other, to a Sphere of five Feet and eleven Inches Radius, and quick-silvered over on the convex side. And holding a white opake Chart, or a Quire of Paper at the Center of the Spheres to which the Speculum was ground, that is, at the distance of about five Feet and eleven Inches from the Speculum, in such manner, that the beam of Light might pass through a little Hole made in the middle of the Chart to the Speculum, and thence be reflected back to the same Hole : I observed upon the Chart four or five concentric Irises or Rings of Colours, like Rain-bows, encompassing the Hole much after the manner that those, which in the fourth and following Observations of the first part of this third Book appeared between the Object-Glasses, encompassed the black Spot, but yet larger and fainter than those. These Rings as they grew larger and larger became diluter and fainter, so that the fifth was scarce visible. Yet sometimes, when the Sun shone very clear, there appeared faint Lineaments of a sixth and seventh. If the distance of the Chart from the Speculum was much greater or much less than that of six Feet, the Rings became dilute and vanished. And if the distance of the Speculum from the Window was much greater than that of six Feet, the reflected beam of Light would be so broad at the distance of six Feet from the Speculum where the Rings <89> appeared, as to obscure one or two of the innermost Rings. And therefore I usually placed the Speculum at about six Feet from the Window; so that its Focus might there fall in with the center of its concavity at the Rings upon the Chart. And this posture is always to be understood in the following Observations where no other is exprest.

OBS. II.

The Colours of these Rain-bows succeeded one another from the center outwards, in the same form and order with those which were made in the ninth Observation of the first Part of this Book by Light not reflected, but transmitted through the two Object-Glasses. For, first, there was in their common center a white round Spot of faint Light, something broader than the reflected beam of Light; which beam sometimes fell upon the middle of the Spot, and sometimes by a little inclination of the Speculum receded from the middle, and left the Spot white to the center.

This white Spot was immediately encompassed with a dark grey or russet, and that darkness with the Colours of the first Iris, which were on the inside next the darkness a little violet and indico, and next to that a blue, which on the outside grew pale, and then succeeded a little greenish yellow, and after that a brighter yellow, and then on the outward edge of the Iris a red which on the outside inclined to purple.

This Iris was immediately encompassed with a second, whose Colours were in order from the inside <90> outwards, purple, blue, green, yellow, light red, a red mixed with purple.

Then immediately followed the Colours of the third Iris, which were in order outwards a green inclining to purple, a good green, and a red more bright than that of the former Iris.

The fourth and fifth Iris seemed of a bluish green within, and red without, but so faintly that it was difficult to discern the Colours.

OBS. III.

Measuring the Diameters of these Rings upon the Chart as accurately as I could, I found them also in the same proportion to one another with the Rings made by Light transmitted through the two Object-Glasses. For the Diameters of the four first of the bright Rings measured between the brightest parts of their orbits, at the distance of six Feet from the Speculum were $1\frac{11}{16}$, $2\frac{3}{8}$, $2\frac{11}{12}$, $3\frac{3}{8}$ Inches, whose squares are in arithmetical progression of the numbers 1, 2, 3, 4. If the white circular Spot in the middle be reckoned amongst the Rings, and its central Light, where it seems to be most luminous, be put equipollent to an infinitely little Ring; the squares of the Diameters of the Rings will be in the progression 0, 1, 2, 3, 4, *&c*. I measured also the Diameters of the dark Circles between these luminous ones, and found their squares in the progression of the numbers $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$, $3\frac{1}{2}$, *&c*. the Diameters of the first four at the distance of six Feet from the Speculum, being $1\frac{3}{16}$, $2\frac{1}{16}$, $2\frac{2}{3}$, $3\frac{3}{20}$ Inches. If the distance of the Chart from the Speculum was in <91> creased or diminished, the Diameters of the Circles were increased or diminished proportionally.

OBS. IV.

By the analogy between these Rings and those described in the Observations of the first Part of this Book, I suspected that there were many more of them which spread into one another, and by interfering mixed their Colours, and diluted one another so that they could not be seen apart. I viewed them therefore through a Prism, as I did those in the 24th Observation of the first Part of this Book. And when the Prism was so placed as by refracting the Light of their mixed Colours to separate them, and distinguish the Rings from one another, as it did those in that Observation, I could then see them distincter than before, and easily number eight or nine of them, and sometimes twelve or thirteen. And had not their Light been so very faint, I question not but that I might have seen many more.

OBS. V.

Placing a Prism at the Window to refract the intromitted beam of Light, and cast the oblong Spectrum of Colours on the Speculum: I covered the Speculum with a black Paper which had in the middle of it a Hole to let any one of the Colours pass through to the Speculum, whilst the rest were intercepted by the Paper. And now I found Rings of that Colour only which fell upon the Speculum. If the Speculum was illuminated with red the Rings were totally red with dark inter <92> vals, if with blue they were totally blue, and so of the other Colours. And when they were illuminated with any one Colour, the Squares of their Diameters measured between their most luminous parts, were in the arithmetical progression of the numbers 0, 1, 2, 3, 4,

and the Squares of the Diameters of their dark intervals in the progression of the intermediate numbers $\frac{1}{2}$, $1\frac{1}{2}$, $2\frac{1}{2}$, $3\frac{1}{2}$: But if the Colour was varied they varied their magnitude. In the red they were largest, in the indico and violet least, and in the intermediate Colours yellow, green and blue; they were of several intermediate bignesses answering to the Colour, that is, greater in yellow than in green, and greater in green than in blue. And hence I knew that when the Speculum was illuminated with white Light, the red and yellow on the outside of the Rings were produced by the least refrangible rays, and the blue and violet by the most refrangible, and that the Colours of each Ring spread into the Colours of the neighbouring Rings on either side, after the manner explained in the first and second Part of this Book, and by mixing diluted one another so that they could not be distinguished, unless near the center where they were least mixed. For in this Observation I could see the Rings more distinctly, and to a greater number than before, being able in the yellow Light to number eight or nine of them, besides a faint shadow of a tenth. To satisfy my self how much the Colours of the several Rings spread into one another, I measured the Diameters of the second and third Rings, and found them when made by the confine of the red and orange to be to the same Diameters when made by the confine of blue and indico, as 9 to 8, or thereabouts. For it was hard <93> to determine this proportion accurately. Also the Circles made successively by the red, yellow and green, differed more from one another than those made successively by the green, blue and indico. For the Circle made by the violet was too dark to be seen. To carry on the computation, Let us therefore suppose that the differences of the Diameters of the Circles made by the outmost red, the confine of red and orange, the confine of orange and yellow, the confine of yellow and green, the confine of green and blue, the confine of blue and indico, the confine of indico and violet, and outmost violet, are in proportion as the differences of the lengths of a Monochord which sound the tones in an Eight; *sol, la, fa, sol, la, mi, fa, sol*, that is, as the numbers $\frac{1}{9}$, $\frac{1}{18}$, **{** $\frac{1}{12}$ **}**, $\frac{1}{12}$, $\frac{2}{27}$, $\frac{1}{27}$, $\frac{1}{18}$. And if the Diameter of the Circle made by the confine of red and orange be 9A, and that of the Circle made by the confine of blue and indico be 8A as above, their difference 9A ---- 8A will be to the difference of the Diameters of the Circles made by the outmost red, and by the confine of red and orange, as $\frac{1}{18} + \frac{1}{12} + \frac{1}{12} + \frac{2}{27}$ to $\frac{1}{9}$, that is as $\frac{8}{27}$ to $\frac{1}{9}$ or 8 to 3, and to the difference of the Circles made by the outmost violet, and by the confine of blue and indico, as $\frac{1}{18} + \frac{1}{12} + \frac{1}{12} + \frac{2}{27}$ to $\frac{1}{27} + \frac{1}{18}$, that is, as $\frac{8}{27}$ to $\frac{5}{54}$, or as 16 to 5. And therefore these differences will be $\frac{3}{8}$A and $\frac{5}{16}$A. Add the first to 9A and subduct the last from 8A, and you will have the Diameters of the Circles made by the least and most refrangible rays $\frac{75}{8}$A and $61\frac{1}{2}$8A. These Diameters are therefore to one another as 75 to $61\frac{1}{2}$ or 50 to 41, and their Squares as 2500 to 1681, that is, as 3 to 2 very nearly. Which proportion differs not much from the proportion of the Diameters of the <94> Circles made by the outmost red and outmost violet in the 13th Observation of the first part of this Book.

OBS. VI.

Placing my Eye where these Rings appeared plainest, I saw the Speculum tinged all over with waves of Colours (red, yellow, green, blue;) like those which in the Observations of the first Part of this Book appeared between the Object-Glasses and upon Bubbles of Water, but much larger. And after the manner of those, they were of various magnitudes in various positions of the Eye, swelling and shrinking as I moved my Eye this way and that way. They were formed like Arcs of concentrick Circles as those were, and when my Eye was over against the center of the concavity of the Speculum (that is, 5 Feet and 10 Inches distant from the Speculum) their common center was in a right Line with that center of concavity, and with the Hole in the Window. But in other postures of my Eye their center had other positions. They appeared by the Light of the Clouds propagated to the Speculum through the Hole in the Window, and when the Sun shone through that Hole upon the Speculum, his Light upon it was of the Colour of the Ring whereon it fell, but by its splendor obscured the Rings made by the Light of the Clouds, unless when the Speculum was removed to a great distance from the Window, so that his Light upon it might be broad and faint. By varying the position of my Eye, and moving it nearer to or farther from the direct beam of the Sun's Light, the Colour of the Sun's reflected Light constantly varied upon the Speculum, <95> as it did upon my Eye, the same Colour always appearing to a By-stander upon my Eye which to me appeared upon the Speculum. And thence I knew that the Rings of Colours upon the Chart were made by these reflected Colours propagated thither from the Speculum in several Angles, and that their production depended not upon the termination of Light and Shadow.

OBS. VII.

By the Analogy of all these Phænomena with those of the like Rings of Colours described in the first Part of this Book, it seemed to me that these Colours were produced by this thick plate of Glass, much after the manner that those were produced by very thin plates. For, upon tryal, I found that if the Quick-silver were rubbed off from the back-side of the Speculum, the Glass alone would cause the same Rings of Colours, but much more faint than before; and therefore the Phænomenon depends not upon the Quick-silver, unless so far as the Quick-silver by increasing the reflexion of the back-side of the Glass increases the Light of the Rings of Colours. I found also that a Speculum of metal without Glass made some years since for optical uses, and very well wrought, produced none of those Rings; and thence I understood that these Rings arise not from one specular surface alone, but depend upon the two surfaces of the plate of Glass whereof the Speculum was made, and upon the thickness of the Glass between them. For as in the 7th and 19th Observations of the first Part of this Book a thin plate <96> of Air, Water, or Glass of an even thickness appeared of one Colour when the rays were perpendicular to it, of another when they were a little oblique, of another when more oblique, of another when still more oblique, and so on; so here, in the sixth Observation, the Light which emerged out of the Glass in several obliquities, made the Glass appear of several Colours, and being propagated in those obliquities to the Chart, there painted Rings of those Colours. And as the reason why a thin plate appeared of several Colours in several obliquities of the rays,was,that the rays of one and the same sort are reflected by the thin plate at one obliquity and transmitted at another, and those of other sorts transmitted where these are reflected, and reflected where these are transmitted: So the reason why the thick plate of Glass whereof the Speculum was made did appear of various Colours in various obliquities, and in those obliquities propagated those Colours to the Chart, was, that the rays of one and the same sort did at one obliquity emerge out of the Glass, at another did not emerge but were reflected back towards the Quick-silver by the hither surface of the Glass, and accordingly as the obliquity became greater and greater emerged and were reflected alternately for many successions, and that in one and the same obliquity the rays of one sort were reflected, and those of another transmitted. This is manifest by the first Observation of this Book: For in that Observation, when the Speculum was illuminated by any one of the prismatick Colours, that Light made many Rings of the same Colour upon the Chart with dark intervals, and therefore at its emergence out of the Speculum was alternately transmitted, and not <97> transmitted from the Speculum to the Chart for many successions, according to the various obliquities of its emergence. And when the Colour cast on the Speculum by the Prism was varied, the Rings became of the Colour cast on it, and varied their bigness with their Colour, and therefore the Light was now alternately transmitted and not transmitted from the Speculum to the Lens at other obliquities than before. It seemed to me therefore that these Rings were of one and the same original with those of thin plates, but yet with this difference that those of thin plates are made by the alternate reflexions and transmissions of the rays at the second surface of the plate after one passage through it, but here the rays go twice through the plate before they are alternately reflected and transmitted; first, they go through it from the first surface to the Quick-silver, and then return through it from the Quick-silver to the first surface, and there are either transmitted to the Chart or reflected back to the Quick-silver, accordingly as they are in their fits of easy reflexion or transmission when they arrive at that surface. For the intervals of the fits of the rays which fall perpendicularly on the Speculum, and are reflected back in the same perpendicular Lines, by reason of the equality of these Angles and Lines,are of the same length and number within the Glass after reflexion as before by the 19th Proposition of the third Part of this Book. And therefore since all the rays that enter through the first surface are in their fits of easy transmission at their entrance, and as many of these as are reflected by the second are in their fits of easy reflexion there, all these must be again in their fits of easy transmission at their <98> return to the first, and by consequence there go out of the Glass to the Chart, and form upon it the white Spot of Light in the center of the Rings. For the reason holds good in all sorts of rays, and therefore all sorts must go out promiscuously to that Spot, and by their mixture cause it to be white. But the intervals of the fits of those rays which are reflected more obliquely than they enter, must be greater after reflexion than before by the 15th and 20th Prop. And thence it may happen that the rays at their return to the first surface, may in certain obliquities be in fits of easy reflexion, and return back to the Quick-silver, and in other intermediate obliquities be again in fits of easy transmission, and so go out to the Chart, and paint on it the Rings of Colours about the white Spot. And because the intervals of the fits at equal obliquities are greater and fewer in the less refrangible rays, and less and more numerous in the more refrangible, therefore the less refrangible at equal obliquities shall make fewer Rings than the more refrangible, and the Rings made by those shall be larger than the like number of Rings made by these; that is, the red Rings shall be larger than the yellow, the yellow than the green, the green than the blue, and the blue than the violet, as they were really found to be in the 5th Observation. And therefore the first Ring of all Colours incompassing the white Spot of Light shall be red without any violet within, and yellow, and green, and blue in the middle, as it was

found in the second Observation; and these Colours in the second Ring, and those that follow shall be more expanded till they spread into one another, and blend one another by interfering.

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These seem to be the reasons of these Rings in general, and this put me upon observing the thickness of the Glass, and considering whether the dimensions and proportions of the Rings may be truly derived from it by computation.

OBS. VIII.

I measured therefore the thickness of this concavo-convex plate of Glass, and found it every-where $\frac{1}{4}$ of an Inch precisely. Now, by the 6th Observation of the first Part of this Book, a thin plate of Air transmits the brightest Light of the first Ring, that is the bright yellow, when its thickness is the $\frac{1}{89000}$th part of an Inch, and by the 10th Observation of the same part, a thin plate of Glass transmits the same Light of the same Ring when its thickness is less in proportion of the sine of refraction to the sine of incidence, that is, when its thickness is the $\frac{11}{1513000}$th or $\frac{1}{137545}$th part of an Inch, supposing the sines are as 11 to 17. And if this thickness be doubled it transmits the same bright Light of the second Ring, if tripled it transmits that of the third, and so on, the bright yellow Light in all these cases being in its fits of transmission. And therefore if its thickness be multiplied 34386 times so as to become $\frac{1}{4}$ of an Inch it transmits the same bright Light of the 34386th Ring. Suppose this be the bright yellow Light transmitted perpendicularly from the reflecting convex side of the Glass through the concave side to the white Spot in the center of the Rings of Colours on the Chart: And by a rule in the seventh Observation in the first Part of the first Book, and by the 15th and 20th Propositions <100> of the third Part of this Book, if the rays be made oblique to the Glass, the thickness of the Glass requisite to transmit the same bright Light of the same Ring in any obliquity is to this thickness of $\frac{1}{4}$ of an Inch, as the secant of an Angle whose sine is the first of an hundred and six arithmetical means between the sines of incidence and refraction, counted from the sine of incidence when the refraction is made out of any plated Body into any medium encompassing it, that is, in this case, out of Glass into Air. Now if the thickness of the Glass be increased by degrees,so as to bear to its first thickness, *(viz*. that of a quarter of an Inch) the proportions which 34386 (the number of fits of the perpendicular rays in going through the Glass towards the white Spot in the center of the Rings,) hath to 34385, 34384, 34383 and 34382 (the numbers of the fits of the oblique rays in going through the Glass towards the first, second, third and fourth Rings of Colours,) and if the first thickness be divided into 100000000 equal parts, the increased thicknesses will be 100002908, 100005816, 100008725 and 100011633, and the Angles of which these thicknesses are secants will be 26′ 13″, 37′ 5″, 45′ 6″ and 52′ 26″, the Radius being 100000000; and the sines of these Angles are 762, 1079, 1321 and 1525, and the proportional sines of refraction 1172, 1659, 2031 and 2345, the Radius being 100000. For since the sines of incidence out of Glass into Air are to the sines of refraction as 11 to 17, and to the above-mentioned secants as 11 to the first of 106 arithmetical means between 11 and 17, that is as 11 to $11\frac{6}{106}$, those secants will be to the sines of refraction as $11\frac{6}{106}$ to 17, and by this Analogy will give these sines. So then <101> if the obliquities of the rays to the concave surface of the Glass be such that the sines of their refraction in passing out of the Glass through that surface into the Air be 1172, 1659, 2031, 2345, the bright Light of the 34386th Ring shall emerge at the thicknesses of the Glass which are to $\frac{1}{4}$ of an Inch as 34386 to 34385, 34384, 34383, 34382, respectively. And therefore if the thickness in all these cases be $\frac{1}{4}$ of an Inch (as it is in the Glass of which the Speculum was made) the bright Light of the 34385th Ring shall emerge where the sine of refraction is 1172, and that of the 34384th, 34383th and 34382th Ring where the sine is 1659, 2031, and 2345 respectively. And in these Angles of refraction the Light of these Rings shall be propagated from the Speculum to the Chart, and there paint Rings about the white central round Spot of Light which we said was the Light of the 34386th Ring. And the Semidiameters of these Rings shall subtend the Angles of refraction made at the concave surface of the Speculum, and by consequence their Diameters shall be to the distance of the Chart from the Speculum as those sines of refraction doubled are to the Radius that is as 1172, 1659, 2031, and 2345, doubled are to 100000. And therefore if the distance of the Chart from the concave surface of the Speculum be six Feet (as it was in the third of these Observations) the Diameters of the Rings of this bright yellow Light upon the Chart shall be 1'688, 2'389, 2'925, 3'375 Inches: For these Diameters are to six Feet as the above-mentioned sines doubled are to the Radius. Now these Diameters of the bright yellow Rings, thus found by computation are the very same with those found in the third of these

Observations by measuring <102> them, *(viz.* with **{**$1\frac{11}{16}$**}**, $2\frac{3}{8}$, $2\frac{11}{12}$,and $3\frac{3}{8}$ Inches, and therefore the Theory of deriving these Rings from the thickness of the plate of Glass of which the Speculum was made, and from the obliquity of the emerging rays agrees with the Observation. In this Computation I have equalled the Diameters of the bright Rings made by Light of all Colours, to the Diameters of the Rings made by the bright yellow. For this yellow makes the brightest part of the Rings of all Colours. If you desire the Diameters of the Rings made by the Light of any other unmixed Colour, you may find them readily by putting them to the Diameters of the bright yellow ones in a subduplicate proportion of the intervals of the fits of the rays of those Colours when equally inclined to the refracting or reflecting surface which caused those fits, that is, by putting the Diameters of the Rings made by the rays in the extremities and limits of the seven Colours, red, orange, yellow, green, blue, indico, violet, proportional the Cube-roots of the numbers, 1, $\frac{8}{9}$, $\frac{5}{6}$, $\frac{3}{4}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{9}{16}$, $\frac{1}{2}$, which express the lengths of a Monochord sounding the notes in an Eight : For by this means the Diameters of the Rings of these Colours will be found pretty nearly in the same proportion to one another, which they ought to have by the fifth of these Observations.

And thus I satisfyed my self that these Rings were of the same kind and original with those of thin plates, and by consequence that the fits or alternate dispositions of the rays to be reflected and transmitted are propagated to great distances from every reflecting and refracting surface. But yet to put the matter out of doubt I added the following Observation.

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OBS. IX.

If these Rings thus depend on the thickness of the plate of Glass their Diameters at equal distances from several Speculums made of such concavo-convex plates of Glass as are ground on the same Sphere, ought to be reciprocally in a subduplicate proportion of the thicknesses of the plates of Glass. And if this proportion be found true by experience it will amount to a demonstration that these Rings (like those formed in thin plates) do depend on the thickness of the Glass. I procured therefore another concavo-convex plate of Glass ground on both sides to the same Sphere with the former plate. Its thickness was $\frac{5}{62}$ parts of an Inch; and the Diameters of the three first bright Rings measured between the brightest parts of their orbits at the distance of 6 Feet from the Glass were 3. $4\frac{1}{6}$. $5\frac{1}{8}$. Inches. Now the thickness of the other Glass being $\frac{1}{4}$ of an Inch was to the thickness of this Glass as $\frac{1}{4}$ to $\frac{5}{62}$, that is as 31 to 10, or 310000000 to 100000000, and the roots of these numbers are 17607 and 10000, & in the proportion of the first of these roots to the second are the Diameters of the bright Rings made in this Observation by the thinner Glass, 3. $4\frac{1}{6}$. $5\frac{1}{8}$ to the Diameters of the same Rings made in the third of these Observations by the thicker Glass $1\frac{11}{16}$. $2\frac{3}{8}$. $2\frac{11}{12}$, that is, the Diameters of the Rings are reciprocally in a subduplicate proportion of the thicknesses of the plates of Glass.

So then in plates of Glass which are alike concave on one side, and alike convex on the other side, and alike quick-silvered on the convex sides, and differ in nothing <104> but their thickness, the Diameters of the Rings are reciprocally in a subduplicate proportion of the thicknesses of the plates. And this shews sufficiently that the Rings depend on both the surfaces of the Glass. They depend on the convex surface because they are more luminous when that surface is quick-silvered over than when it is without Quick-silver. They depend also upon the concave surface, because without that surface a Speculum makes them not. They depend on both surfaces and on the distances between them, because their bigness is varied by varying only that distance. And this dependance is of the same kind with that which the Colours of thin plates have on the distance of the surfaces of those plates, because the bigness of the Rings and their proportion to one another, and the variation of their bigness arising from the variation of the thickness of the Glass, and the orders of their Colours, is such as ought to result from the Propositions in the end of the third Part of this Book,derived from the Phænomena of the Colours of thin plates set down in the first Part.

There are yet other Phænomena of these Rings of Colours but such as follow from the same Propositions, and therefore confirm both the truth of those Propositions, and the Analogy between these Rings and the Rings of Colours made by very thin plates. I shall subjoyn some of them.

<105>

OBS. X.

When the beam of the Sun's Light was reflected back from the Speculum not directly to the Hole in the Window, but to a place a little distant from it, the common center of that Spot, and of all the Rings of Colours fell in the middle way between the beam of the incident Light, and the beam of the reflected Light, and by consequence in the center of the spherical concavity of the Speculum, whenever the Chart on which the Rings of Colours fell was placed at that center. And as the beam of reflected Light by inclining the Speculum receded more and more from the beam of incident Light and from the common center of the coloured Rings between them, those Rings grew bigger and bigger, and so also did the white round Spot,and new Rings of Colours emerged successively out of their common center, and the white Spot became a white Ring encompassing them ; and the incident and reflected beams of Light always fell upon the opposite parts of this white Ring, illuminating its perimeter like two mock Suns in the opposite parts of an Iris. So then the Diameter of this Ring, measured from the middle of its Light on one side to the middle of its Light on the other side, was always equal to the distance between the middle of the incident beam of Light, and the middle of the reflected beam measured at the Chart on which the Rings appeared: And the rays which formed this Ring were reflected by the Speculum in Angles equal to their Angles of incidence, and by consequence to their Angles of refraction at their entrance into the Glass, but yet their Angles of <106> reflexion were not in the same planes with their Angles of incidence.

OBS. XI.

The Colours of the new Rings were in a contrary order to those of the former, and arose after this manner. The white round Spot of Light in the middle of the Rings continued white to the center till the distance of the incident and reflected beams at the Chart was about $\frac{7}{8}$ parts of an Inch, and then it began to grow dark in the middle. And when that distance was about $1\frac{3}{16}$ of an Inch, the white Spot was become a Ring encompassing a dark round Spot which in the middle inclined to violet and indico. And the luminous Rings incompassing it were grown equal to those dark ones which in the four first Observations encompassed them, that is to say, the white Spot was grown a white Ring equal to the first of those dark Rings, and the first of those luminous Rings was now grown equal to the second of those dark ones, and the second of those luminous ones to the third of those dark ones, and so on. For the Diameters of the luminous Rings were now $1\frac{3}{16}$, $2\frac{1}{16}$, $2\frac{2}{3}$, $3\frac{3}{20}$, *&c*. Inches.

When the distance between the incident and reflected beams of Light became a little bigger, there emerged out of the middle of the dark Spot after the indico a blue, and then out of that blue a pale green, and soon after a yellow and red. And when the Colour at the center was brightest, being between yellow and red, the bright Rings were grown equal to those Rings which in the four first Observations next encompassed them; <107> that is to say, the white Spot in the middle of those Rings was now become a white Ring equal to the first of those bright Rings, and the first of those bright ones was now become equal to the second of those, and so on. For the Diameters of the white Rings, and of the other luminous Rings incompassing it, were now $1\frac{11}{16}$, $2\frac{3}{8}$, $2\frac{11}{12}$, $3\frac{3}{8}$, *&c*. or thereabouts.

When the distance of the two beams of Light at the Chart was a little more increased, there emerged out of the middle in order after the red, a purple, a blue, a green, a yellow, and a red inclining much to purple, and when the Colour was brightest being between yellow and red, the former indico, blue, green, yellow and red, were become an Iris or Ring of Colours equal to the first of those luminous Rings which appeared in the four first Observations, and the white Ring which was now become the second of the luminous Rings was grown equal to the second of those, and the first of those which was now become the third Ring was become the third of those, and so on. For their Diameters were $1\frac{11}{16}$, $2\frac{3}{8}$, $2\frac{11}{12}$, $3\frac{3}{8}$ Inches, the distance of the two beams of Light, and the Diameter of the white Ring being $2\frac{3}{8}$ Inches.

When these two beams became more distant there emerged out of the middle of the purplish red, first a darker round Spot, and then out of the middle of that Spot a brighter. And now the former Colours (purple, blue, green, yellow, and purplish red) were become a Ring equal to the first of the bright Rings mentioned in the four first Observations, and the Rings about this Ring were grown equal to the Rings about that

respectively ; the distance between the two beams of <108> Light and the Diameter of the white Ring (which was now become the third Ring) being about 3 Inches.

The Colours of the Rings in the middle began now to grow very dilute, and if the distance between the two beams was increased half an Inch, or an Inch more, they vanished whilst the white Ring, with one or two of the Rings next it on either side, continued still visible. But if the distance of the two beams of Light was still more increased these also vanished: For the Light which coming from several parts of the Hole in the Window fell upon the Speculum in several Angles of incidence made Rings of several bignesses, which diluted and blotted out one another, as I knew by intercepting some part of that Light. For if I intercepted that part which was nearest to the Axis of the Speculum the Rings would be less, if the other part which was remotest from it they would be bigger.

OBS. XII.

When the Colours of the Prism were cast successively on the Speculum, that Ring which in the two last Observations was white, was of the same bigness in all the Colours, but the Rings without it were greater in the green than in the blue, and still greater in the yellow, and greatest in the red. And, on the contrary, the Rings within that white Circle were less in the green than in the blue, and still less in the yellow, and least in the red. For the Angles of reflexion of those rays which made this Ring being equal to their Angles of incidence, the fits of every reflected ray within the Glass <109> after reflexion are equal in length and number to the fits of the same ray within the Glass before its incidence on the reflecting surface; and therefore since all the rays of all sorts at their entrance into the Glass were in a fit of transmission, they were also in a fit of transmission at their returning to the same surface after reflexion; and by consequence were transmitted and went out to the white Ring on the Chart. This is the reason why that Ring was of the same bigness in all theColours, and why in a mixture of all it appears white. But in rays which are reflected in other Angles, the intervals of the fits of the least refrangible being greatest, make the Rings of their Colour in their progress from this white Ring, either outwards or inwards, increase or decrease by the greatest steps; so that the Rings of this Colour without are greatest, and within least. And this is the reason why in the last Observation, when the Speculum was illuminated with white Light, the exterior Rings made by all Colours appeared red without and blue within, and the interior blue without and red within.

These are the Phænomena of thick convexo-concave plates of Glass, which are every where of the same thickness. There are yet other Phænomena when these plates are a little thicker on one side than on the other, and others when the plates are more or less concave than convex, or plano-convex, or double-convex. For in all these cases the plates make Rings of Colours, but after various manners; all which, so far as I have yet observed, follow from the Propositions in the end of the third part of this Book, and so conspire to confirm the truth of those Propositions. But the Phæno <110> mena are too various, and the Calculations whereby they follow from those Propositions too intricate to be here prosecuted. I content my self with having prosecuted this kind of Phænomena so far as to discover their cause, and by discovering it to ratify the Propositions in the third Part of this Book.

OBS. XIII.

As Light reflected by a Lens quick-silvered on the back-side makes the Rings of Colours above described, so it ought to make the like Rings of Colours in passing through a drop of Water. At the first reflexion of the rays within the drop, some Colours ought to be transmitted, as in the case of a Lens, and others to be reflected back to the Eye. For instance, if the Diameter of a small drop or globule of Water be about the 500th part of an Inch, so that a red-making ray in passing through the middle of this globule has 250 fits of easy transmission within the globule, and that all the red-making rays which are at a certain distance from this middle ray round about it have 249 fits within the globule, and all the like rays at a certain further distance round about it have 248 fits, and all those at a certain further distance 247 fits, and so on; these concentrick Circles of rays after their transmission, falling on a white Paper, will make concentrick rings of red upon the Paper, supposing the Light which passes through one single globule strong enough to be sensible. And, in like manner, the rays of other Colours will make Rings of other Colours. Suppose now that in a fair day the Sun shines through a thin Cloud of such <111> globules of Water or Hail, and that the globules are all of the same bigness,and the Sun seen through this Cloud shall appear incompassed with the like concentrick Rings of Colours, and the Diameter of the first Ring of red shall be $7\frac{1}{4}$ degrees, that of the second $10\frac{1}{4}$ degrees, that

of the third 12 degrees 33 minutes. And accordingly as the globules of Water are bigger or less, the Rings shall be less or bigger. This is the Theory, and experience answers it. For in *June* 1692. I saw by reflexion in a Vessel of stagnating Water three Halos Crowns or Rings of Colours about the Sun, like three little Rain-bows, concentrick to his Body. The Colours of the first or innermost Crown were blue next the Sun, red without, and white in the middle between the blue and red. Those of the second Crown were purple and blue within, and pale red without, and green in the middle. And those of the third were pale blue within, and pale red without; these Crowns inclosed one another immediately, so that their Colours proceeded in this continual order from the Sun outward: blue, white, red; purple, blue, green, pale yellow and red; pale blue, pale red. The Diameter of the second Crown measured from the middle of the yellow and red on one side of the Sun, to the middle of the same Colour on the other side was $9\frac{1}{3}$ degrees, or thereabouts. The Diameters of the first and third I had not time to measure, but that of the first seemed to be about five or six degrees, and that of the third about twelve. The like Crowns appear sometimes about the Moon; for in the beginning of the Year 1664, *Febr*. 19th at night, I saw two such Crowns about her. The Diameter of the first or innermost was about three degrees, and that of the <112> second about five degrees and an half. Next about the Moon was a Circle of white, and next about that the inner Crown which was of a bluish green within next the white, and of a yellow and red without, and next about these Colours were blue and green on the inside of the outward Crown, and red on the outside of it. At the same time there appeared a Halo about 22 degrees 35′ distant from the center of the Moon. It was Elliptical, and its long Diameter was perpendicular to the Horizon verging below farthest from the Moon. I am told that the Moon has sometimes three or more concentrick Crowns of Colours incompassing one another next about her Body. The more equal the globules of Water or Ice are to one another, the more Crowns of Colours will appear, and the Colours will be the more lively. The Halo at the distance of $22\frac{1}{2}$ degrees from the Moon is of another sort. By its being oval and remoter from the Moon below than above, I conclude, that it was made by refraction in some sort of Hail or Snow floating in the Air in an horizontal Posture, the refracting Angle being about 58 or 60 degrees.