XVI. *On the Anatomical and Optical Structure of the crystalline Lenses of Animals, particularly that of the Cod.* By Sir David Brewster, *LL.D. F.R.S. V.P.R.S. Ed.*

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Having observed very singular phenomena in the crystalline lenses of fishes and quadrupeds when exposed to polarized light, I was led to examine their anatomical structure, with the view of ascertaining if it had any relation to these optical appearances. Leeuwenhoek and Sattig had previously made some progress in this research, but their methods of observation were ill fitted for so delicate an inquiry, and experience soon convinced me that the structure of the lens could not be thoroughly investigated either by the microscope or the scalpel.

Anatomists had long regarded the crystalline lens as composed of concentric laminæ, and these laminæ of minute fibres; but M. Soemmerring, in his work on the Human Eye, published in 1804, regards this structure as the effect merely of maceration in alcohol, and maintains that it does not exist in the recent or the living eye*. This decision, which its author has supported by many plausible but unphilosophical and inefficient arguments, appeared to set aside all the results which had been obtained by preceding inquirers, and rendered it necessary for me to adopt a new mode of investigation, which should not be liable to the same criticism.

The crystalline lens of the cod, like almost all globular lenses, has the form of a prolate spheroid, the axis of revolution being a little longer than the equatorial diameter. This axis is the axis of the eye, or of vision.

The body or substance of the lens is inclosed in an exceedingly thin and transparent membrane, called its capsule; and this membrane is so elastic

* Lens, post mortem ita tractata, etiamsi in segmenta sphærica, laminas et fibras dehiscat, tamen minime inde sequitur, lentem recentem seu vivam ex ejusmodi fibris, lamellis et segmentis sphæricis conflari, aut per vitam lentis sanæ fabricam zeolitidi ullo modo similem esse.—pp. 67, 68.

that when it was stretched upon a plate of glass, the extended portion polarized a blueish white tint of the first order. If we puncture the capsule, a thickish fluid flows from the opening; but upon removing the capsule altogether, this fluid is found to constitute only the outer coat of the lens, the substance of the lens growing denser and harder as we approach to the centre of it.

The body of the lens is not connected with the capsule, as Dr. YOUNG supposed, by any nerves or filaments whatever: on the contrary, it floats as it were within the capsule; and in holding the lens in my hand, I observed its axis of revolution take a horizontal position whenever it was placed in an inclined direction. This observation I repeated many times with the same lens, though I have not been able to do it with others.

When the lens is taken out of its capsule, and the softer parts removed by rubbing it between the finger and the thumb, we obtain a hard nucleus, the structure of which we shall now proceed to examine. In order to get rid of SOEMMERRING's objections, I have often removed the recent lens from a newly caught fish, and taken out the nucleus without exposing it to any process of maceration or induration. I then detach a film or two from the nucleus, and find it to consist of regular transparent laminæ of uniform thickness, and capable of being separated like those of sulphate of lime or mica. The surface of these laminæ is perfectly smooth, and reflects light as copiously as any other polished substance of the same refractive power.

When we look with a microscope at the surface of any lamina, before it has been detached, it has the appearance of a grooved surface, like mother-of-pearl, or one of Mr. BARTON's iris surfaces; and in large lenses it is often easy to trace these apparent grooves or lines to the two poles of the axis of revolution, the lines being widest at the equator, and growing narrower and narrower as they approach the poles. In small lenses, however, it is extremely difficult, and often impossible, to follow these lines to their points of convergency by the use of the microscope; and hence both LEEUWENHOEK and SATTIG maintained, that in fishes the points of convergency formed a line at each pole, the line at the one pole being perpendicular to the line at the other. These lines are bisected by the polar point, and the parts of the line on each side of the pole are called septa. Hence the lines or fibres which compose the laminæ are related to two septa in fishes, according to LEEUWENHOEK and SATTIG.

Fig. 1.

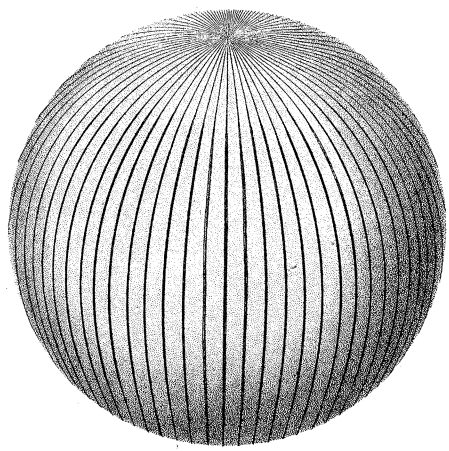
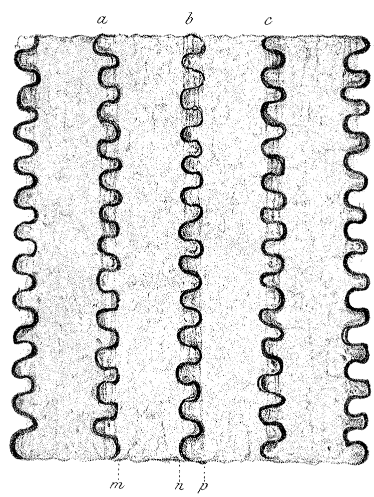


Fig. 2.



R.K. Greville del. Fig. 1.

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In examining these phenomena, I observed the surface of the laminæ sparkling with the colours of mother-of-pearl*, and upon applying a microscope, adjusted to such a focus as to show distinctly the reflected image of the candle, I observed on each side of this image one or more highly prismatic images, produced by interference, like those of grooved surfaces. As the direction of the fibres is necessarily perpendicular to the line joining the coloured images, I was enabled to trace them to their termination, or points of convergency, when the fibres themselves could not be rendered visible by the best microscope. But while this new method of observation enabled me to detect all or most of the varieties of fibrous organization which exist in the crystalline lenses of animals, it furnished at the same time a simple and accurate method of determining the diameter of the fibres at any point of the spheroid. The distance of any of the coloured images from the colourless image was a direct measure of the breadth of the fibres; and with the aid of a series of Mr. BARTON's beautiful divisions upon steel, from 312·5 in an inch to 10,000, which he was so kind as to make for me, it was easy to obtain these measures without even the trouble of calculation.

By these means I succeeded in tracing the fibres, or thin slender laminæ, to two poles diametrically opposite to each other, and coinciding with the poles of the spheroidal lens, as shown in Plate VIII. fig. 1. In small lenses, and particularly in the lenses of birds, the accurate convergency of the fibres to one focus is less distinctly seen; but it is easy to distinguish this diffused polarity, as it may be called, from the convergency of the fibres to points arranged in a straight line, and constituting the two septa already mentioned.

The distribution of the fibres now described is the simplest that occurs in the lenses of animals. Every fibre has the same length and the same form; and its curvature is, like the meridian of a spheroid, without any contrary flexure.

The perfect flatness of the surfaces of the concentric laminæ, as indicated by their power of forming a distinct image by reflexion, shows that the fibres which compose them are flat and not cylindrical; and when we look through them with a powerful microscope, this conclusion is amply confirmed by the uniform distribution of the refracted light.

* These colours may be transferred to wax, &c., like those of mother-of-pearl.

In order to measure the diameter, or rather the breadth of the fibres, I detach from the equator of the lens an extremely thin lamina, and having placed it above a small aperture in a plate of brass, I look through it at a candle, and measure the angular distance of the first coloured image from the white or central image, taking the centre of the red ray as the point from which the measurement is to be taken. When the first coloured images on each side of the central image are extremely distinct, it will be better to measure the angular distance of the red parts of their spectra, and to take half that distance as the angular distance of the first image from the central image. If we call this distance A, and put B for the breadth of each fibre, or the breadth of the transparent part, together with the breadth of the opake interval or line which separates the fibres, we shall then have $B = \frac{C}{A}$, C being a constant quantity for the red ray to be determined by experiment. According to FRAUNHOFER's experiments on Interference, C is equal to 0·0000256 of an English inch for the middle red ray; hence the formula becomes $B = \frac{0·0000256}{A}$.*

In order, however, to save the trouble of calculation, and in cases where a general estimate only is required, I use Mr. BARTON's system of grooves already mentioned; and upon looking through the lamina at the white image, or rather the central image of the iris surface, I can at once compare the distance of the first prismatic images of the one with the same distance in the other. If I am using, for example, the divisions of 5000 in an inch, and if I find the distances of the coloured images the same with the laminæ and with the steel, I infer that the breadth B is the 5000dth of an inch. This conclusion, however, is not quite correct, for we may have been comparing the effect of a perpendicular incidence on the lamina with the effect of an oblique incidence on the steel. Now, FRAUNHOFER has shown that the coloured images separate as the incidence in a plane intersecting the grooves at right angles is increased, and that the value of B, to which this increased distance corresponds, is smaller in the proportion of radius to the cosine of the angle of incidence, I. Hence the formula becomes $B = \frac{0·0000256}{A \, . \cos . \, I.}$. This property gives us the advantage of

* FRAUNHOFER found that in a system of lines where B was 0·0001223 of a Paris inch, A was 11° 25′ 20″; and in another system, where B was 0·0005919, A was 2° 20′ 57″.

a variable scale; and in making the experiment, I found that at an incidence of 25°, when the divisions of 5000 in an inch were employed, the coloured images of the laminæ corresponded with those of the grooved steel. Hence the value of the quantity B, or the breadth of the fibres, is about the 5500dth part of an inch.

I next detached laminæ from parts nearer the pole, and I found that the coloured images gradually separated as the fibres approached to the poles; thus proving, what might have been inferred from other facts, that the fibres gradually taper in breadth from the equator to the poles of the lens. In order to allow the fibres to be packed without condensation into spherical laminæ, their breadths must diminish as the cosine of the distance from the equator.

Although the prolate form of the spheroid indicates that the thickness of the laminæ, or of their component fibres, must increase slightly towards the poles, yet I have not been able to prove this experimentally, or even to determine the thickness of the fibres. I have more than once detached, by accident, a single fibre from the mass, and by an examination of the black line which forms its edges, I am satisfied that its thickness is at least five times less than its maximum breadth.

Having thus determined the form and size of the fibres, we come now to a very delicate and interesting part of the inquiry, namely, to ascertain the mode in which the fibres are laterally united to each other, so as to resist separation, and form a continuous spherical surface. The remarkable mechanism by which this is effected was first pointed out to me by an optical phenomenon. In looking at a bright light through a thin lamina of the lens of a cod, I observed two faint and broad prismatic images, situated in a line exactly perpendicular to that which joined the common coloured images. Their angular distance from the central image was nearly five times greater than that of the first ordinary prismatic images, and no doubt whatever could be entertained that they were owing to a number of minute lines perpendicular to the direction of the fibres, and whose distance did not exceed the $\frac{1}{2500} \times 5$, or the 12,500dth of an inch.

Upon applying a good microscope to a well-prepared lamina, I was delighted to observe the structure shown in fig. 2, where the two fibres, *a b*, *b c*, are united

by a series of teeth, exactly like those of rackwork, the projecting teeth of one fibre entering into the hollows between the teeth of the adjacent one. The length of the teeth, or $n p$, is equal to about one half of $m n$, and this length of course diminishes towards the pole in the same ratio with the fibre. The breadth of the teeth is such, that five of them, namely, three of one fibre together with the two teeth of the adjacent fibre, which they inclose, are equal nearly to $m n + n p$, which is the measure of the quantity B in the preceding formulæ. With an ordinary microscope, the series of teeth between any two fibres seem to form a dark line, whose breadth is $n p$; and it is in consequence of the interruption of the light thus occasioned, when the lamina is dry, and the surfaces not in optical contact, that the fibrous lamina acts upon light like grooved steel, the space $n p$ in the lamina corresponding to the groove formed by the cutting diamond point in the metallic surface.

Although the parallel sides of the teeth do not form continuous lines, yet they produce colours by interference in the same manner as if they were continuous; and it is by their influence that the secondary prismatic images are produced in a line perpendicular to the sides of the teeth. In the living as well as in the recent lens the faces of the teeth and of the fibres are all in optical contact, and light passes through them in every direction in the same manner as if the whole lens were a continuous solid.

The toothed structure which has now been described, I have found in the salmon, haddock, herring, shark, and, indeed, in the lens of every fish where I have looked for it; and in this class of animals it is generally very distinct, and almost always capable of producing the secondary prismatic images. In the salmon, however, the teeth are much narrower than in the cod, and the colours which they produce are less distinctly seen.

Having thus determined the form and magnitude of the fibres and their teeth in a given lamina, it becomes interesting to ascertain if they suffer any change in shape or size at different distances from the centre of the lens. With this view I continued to remove one coat of the lens after another, till I reduced it to such a minute nucleus that I could no longer use it. I then dried it at the fire, and having crushed it, I obtained small portions of laminæ extremely near the centre: in this way I found that the fibres gradually diminished towards the centre of the lens, and the teeth in the same proportion, so

that the number of fibres in any spherical coat or lamina was the same from whatever part of the lens it was detached.

In the lens of a cod, I found that there were 2000 fibres in an inch at the equator of a spherical coat or lamina, whose radius was $\frac{6}{30}$ths of an inch; consequently there must have been 2500 in the spherical surface*. If we now suppose that the breadth of each fibre is five times its thickness, and that each tooth is equal to the thickness of the fibre, or that five teeth are equal in breadth to a fibre, we shall obtain the following results for the lens of a cod four tenths of an inch in diameter:

Number of fibres in each lamina or spherical coat	2,500
——— teeth in each fibre	12,500
———————— in each spherical coat	31,250,000
——— fibres in the lens	5,000,000
——— teeth in the lens	62,500,000,000

or, to express the result in words, the lens of a small cod contains five millions of fibres, and sixty-two thousand five hundred millions of teeth. A transparent lens exhibiting such a specimen of mechanism may well excite our astonishment and admiration!

The magnitude of the fibres and of their teeth varies in different animals. In the lens of a South American fish, for example, called the sheep-head, there are only 613 fibres in a spherical surface†; but it will be seen in a subsequent Paper, that there are other animals in which the fibres are still more minute than those in the lens of the cod.

By means of very fine microscopes, with high magnifying powers, I have succeeded in detecting the same structure in the lenses of birds and quadrupeds; but in these classes of animals it is much less distinctly developed than in fishes. The teeth are much shorter; and when the lens belonged to an aged animal, the toothed structure was extremely indistinct and irregular, and in some parts of the fibres it entirely disappeared.

The fibrous structure represented in fig. 1, and in which the fibres converge to two opposite poles, is never found, in so far as my observations extend, in any

* The radius being $\frac{6}{30}$ or ·2, we have $3{\cdot}1416 \times {\cdot}4 \times 2000 = 2513$.

† The diameter of the lens was $\frac{1}{5}$th of an inch, and there were 975 fibres in an inch at the equator.

of the Mammalia or Cetacea. It is the universal structure in the lenses of all the birds that I have examined; and though it is the most common structure in fishes, it is not the only one which they exhibit. In the following Table, I have given the names of the different animals in whose lenses I have found the structure shown in fig. 1.

FISHES.

Cod.	Spirling.	Eel.
Haddock.	Loch-leven Trout.	Pike.
Serpent Fish.	Turbot.	Mackerel.
Diver.	Sole.	Coal Fish.
Mullet.	Sayd.	Gold Fish.
Herring.	Grey Dog.	Great Lamprey.
Holibut.	Flying Fish.	Bull-head.
Fresh-water Fluke.	Frog Fish.	Whiting, English.
Salt-water Fluke.	Sea Cat.	

BIRDS.

Cassowary.	Magpie.	Pheasant.
Albatross.	Plover.	Penguin.
Pelican.	Common Pigeon.	Cock.
Crane.	Wood Pigeon.	Hen.
Turkey.	Emberiza.	Green Linnet.
Barnacle Goose.	Alauda arvensis.	Ornithorhynchus.
Sea Eagle.	Tringa.	
Snowy Owl.	Black Grous.	LIZARDS.
Curlew.	Red Grous.	Lacerta striata.
Chaffinch.	Partridge.	Lacerta Calotes.
Thrush.	Wild Duck.	

For many of the lenses in the preceding Table, and for others which I shall have occasion to enumerate in subsequent communications, I have been indebted to the kindness and zeal of Captain BASIL HALL, Captain ROBERTSON, Professor GRANT, Mr. GEORGE SWINTON, Dr. KNOX, Mr. WILLIAM CLARK, and Mrs. GREEN of Cumberland Island.

In the Philosophical Transactions for 1816, I have described and represented

by drawings the singular structure of the crystalline lens of the cod, as exhibited by transmitting through it a beam of polarized light. I have there shown that it consists of three different structures; viz. the nucleus, which has negative double refraction like calcareous spar; the external strata, which have the same kind of double refraction; and the intermediate strata, which have positive double refraction like zircon. The axis of vision, or that of the spheroidal lens, is the axis of double refraction for these three structures. I have discovered the same structure in the lens of the haddock, the salmon, the frog fish, the skate, and the whiting, and indeed, with more or less distinctness, in all the lenses of fishes which were large enough to show the polarized tints.

A doubly refracting structure, related to the axis of vision, is distinctly seen in the human lens, and in that of quadrupeds and birds; but it differs considerably, both in its character and intensity, from that which exists in the lenses of fishes. In the paper to which I have already referred*, I have stated that in the lenses of sheep and oxen there is only one series of luminous sectors, or one structure, corresponding with the intermediate set in the crystalline of fishes. This, however, is a mistake. By nicer means of observation I can distinctly see all the three structures in the lens of the sheep, the ox, and the horse; but, what is very singular, the nucleus and outer structure have positive double refraction, while the double refraction of the intermediate structure is negative; a result exactly the reverse of that which I have obtained from the lenses of fishes. If this triple structure is intended, as I have already conjectured, to correct aberration, or to improve vision, it will be a curious problem to determine how this is effected, and to connect the one structure with the existence of a spheroidal lens without the aqueous humour, and the other with the co-existence of a flat lens and an aqueous humour.

When the lens of a cod is prepared so as to indurate and retain its form and transparency, the process of induration confounds all the three structures in one; viz. a negative doubly refracting structure many times more intense than that which exists in the recent lens. When a lens thus indurated was exposed to polarized light, I observed round the axis of the lens a beautiful system of negative uniaxal rings, seven in number, and intersected with a well-defined black cross. When the polarized light passed through any equatorial diameter

* Philosophical Transactions, 1816, p. 315.

of the lens, a system of seven biaxal rings was beautifully displayed, the principal axis being of course negative. This system of rings was intersected by the black cross, when the plane of the equator coincided with that of primitive polarization, and they displayed the two dark hyperbolic branches when the inclination of these planes was 45°. These phenomena I observed most distinctly in the lens of the boneta; and I have seen them also in the lenses of the cod, the shark, and the flying fish, which happened to have been preserved without any fissures or loss of transparency.

In looking at a candle through the indurated lens of a cod, held at a distance from the eye, and which had been preserved for three years, I observed the candle encircled with three beautiful concentric rings, red on the inside and green without. These colours were no doubt those of mixed plates.

In examining the laminæ of the crystalline lens under the microscope, we are often perplexed with a variety of colours apparently spread over the surface of the plate. These colours are not the effect of chromatic aberration, but arise from the interference of the coloured pencils produced by the two surfaces of the laminæ. If we take a thin lamina, and, holding it opposite to a candle, look at its surface with a lens about an inch in focus, we shall see the whole of it covered with the most brilliant and varied colours, not inferior to those of the richest opal. These colours vary as we incline the laminæ in a plane cutting the fibres of it perpendicularly; and when the portion of the lamina is flat, they form a series of rectilineal serrated fringes perpendicular to the direction of the fibres. When the portion of the lamina is much curved, the fringes are irregular, and form, occasionally, returning curves of every variety of form and of every imaginable tint. If we immerse one of the surfaces of the lamina in a fluid of the same refractive power, we remove, as it were, the fibrous structure of that surface, and the serrated fringes immediately disappear. This observation led me to imitate these fringes by combining two series of grooves cut on the surface of separate strips of glass*. The effects were precisely similar and highly beautiful; and in the prosecution of the subject I was led to the observation of a series of very curious phenomena, which will form the subject of a separate communication.

* These phenomena are much more splendid, when the grooves are formed upon thin plates of isinglass, by taking an impression of them from a steel surface.